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Transformation Towards Sustainability

A Novel Interdisciplinary Framework from RWTH Aachen University

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Springer

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ISBN 978-3-031-54699-0 ISBN 978-3-031-54700-3 (eBook)
https://doi.org/10.1007/978-3-031-54700-3

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

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Preface

Humanity is facing immense challenges that will change the way we live together, the way markets work in many sectors, and the way organizations operate. These challenges cannot be met without societal transformations, which are already playing a major role in the actions of organizations and in public debates. These societal transformations are driven on the one hand by technological developments, such as digitization and the use of artificial intelligence, and on the other hand by mounting problem pressure, for example with regard to climate change or other problems of environmental and social sustainability.

Universities can play a key role in societal transformation processes. Not only do they generate new knowledge, but they are often linked to almost all relevant stakeholder groups and thus have an influence on transformational developments themselves. However, successful transformation efforts require a change in the traditional concept of universities and in the way they act. Societal problems can hardly be solved in a disciplinary way from an ivory tower perspective. Instead, scientists from different disciplines need to work closely together and open up to the outside world. This requires a new scientific culture of cooperation, which must be meaningfully advanced by a variety of organizational measures, such as interdisciplinary platforms, new forms of communication, and, above all, mutual appreciation and tolerance of the particularities of individual scientific disciplines.

However, universities can only successfully contribute to societal transformation processes if they understand and help to shape these transformations and also change the way they do research. Therefore, the triad of transformation research (understanding transformations), transformational research (enabling and shaping transformations), and research transformation (transforming universities) allows for the best possible contribution of universities and other research institutions to societal transformation processes. The three pillars "transformation research," "transformational research," and "research transformation" therefore form the basis of the Aachen Transformation Model, which has been developed over many years in small and larger steps from the strategy of RWTH Aachen University.

The present book is structured according to this three-pillar model. After the interdisciplinary framework for transformation research at RWTH Aachen University is presented in two overarching contributions, the remaining three parts are each dedicated to one pillar of the Aachen Transformation Model. The individual contributions provide interesting insights into the understanding of transformation at RWTH Aachen University, into concrete projects with sometimes considerable transformative effects, and into the processes of change that affect the research itself. Taken together, the articles included in this book paint a multifaceted picture of the Aachen Transformation Model. With this in mind, we hope that all our readers enjoy reading this book and gain many new insights, which may even help them to leverage their own transformation efforts.

Aachen, Germany
October 2023

Peter Letmathe
On behalf of all the editors of this book

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Introduction

Societal Transformation: Transformation Research, Transformational Research, Research Transformation: A Novel Framework from RWTH Aachen University

Peter Letmathe, Maren Paegert, Christine Roll, Almut Balleer, Stefan Böschen, Wolfgang Breuer, Agnes Förster, Gabriele Gramelsberger, Kathrin Greiff, Roger Häußling, Max Lemme, Michael Leuchner, Frank Piller, Elke Seefried, and Thorsten Wahlbrink

Abstract The global environmental crisis, technological developments, the COVID-19 pandemic, and ongoing economic and political globalization are just a few of the developments that are massively increasing the pressure for transformation on regions, companies, and society as a whole. In addition, the digital age is accelerating transformation processes that are already underway. This introductory article addresses these developments and presents a new framework for transformation research and practice that has been developed and already validated by researchers of the RWTH Aachen University. The RWTH way includes inter- and transdisciplinary approaches from many disciplines, looking at technological and societal change from different perspectives. A distinction is made between analysis,

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P. Letmathe et al. (eds.), *Transformation Towards Sustainability*,
https://doi.org/10.1007/978-3-031-54700-3_1

i.e. research on understanding societal transformation processes, impact, i.e. transformational research that aims at real-world impacts, and research transformation, i.e. paradigm changes in research methods and processes that increase the degree of innovation and the impact of research.

Keywords Transformation research · Transformational research · Research transformation · Interdisciplinarity · Transdisciplinary research

1 Introduction: An Understanding of Transformation and Transformation Processes

It is the task of science to systematically collect, expand, document, and teach knowledge. On the basis of (falsifiable) theories, science facilitates a better understanding of scientific and social phenomena, reconciling these with reality. Scientific results allow predictions about the future and provide impulses for social and technological developments. Without the foundations created by science and the innovations that have emerged from them, neither the technological level of today nor the societal and economic systems in which we currently live would be possible. Science has made humans a model of success as a species. In 2022, the total number of people alive exceeded the 8 billion mark for the first time. Life expectancy is higher than ever and continues to rise. Medical, technological, and societal developments have contributed massively to these achievements. At the same time, humanity is facing

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huge challenges to transform the current way of living. Climate change is aggravating the living conditions on earth for billions of people. The resource base of the planet is overexploited, and it is clear that a continuation of the current economic and social systems will not be possible. Modern weapons technologies and the advance of artificial intelligence endanger the functionality of social systems and the position of humans on our planet. Critics of science argue that the current organization of science, with its ever-increasing specialization and thinking in silos, is exacerbating the ongoing negative and unsustainable developments. What is needed instead are inter- and transdisciplinary collaborations that produce a better systemic understanding in order to support the necessary transformation processes with holistic solutions. In a nutshell, science needs a new mode of operation that addresses these challenges and links different scientific disciplines in a solution-oriented way. This article outlines a transformation model for research that serves as a framework for successful contributions to the major societal transformation processes of our time.

The demands on science have therefore grown even more, and it can be assumed that science is itself undergoing a comprehensive transformation process. However, the fulfillment of these requirements contrasts strongly with the results of a study by Park et al. (2023) that was published in the journal "Nature". The title of the article, "Papers and patents are becoming less disruptive over time", indicates that the degree of innovation of scientific research is tending to decrease. Although the number of published articles is higher than ever, the level of knowledge increase is often incremental, and research tends to follow research paths already taken in the past. The reasons for this lie in the increasing specialization of many scientists and the associated path dependencies. According to the authors, science represents an endogenous process or, to put it more provocatively, science "boils within itself". However, self-referential processes and specialization are not very suitable for solving the major problems of our time. Whereas inventions originating from a specialist discipline, such as the invention of Penicillin by Fleming in 1928, have significantly increased the life expectancy of people, more holistic—and thus cross-disciplinary—solutions are necessary today.

The example of the problem of climate change can be used to illustrate this necessity. In order to prevent a further increase in the average global temperature, all greenhouse gas emissions must be drastically reduced. To this end, the energy system transition that has already been initiated must be accelerated, and private households, the mobility sector, and industry must all contribute to reducing emissions (Kappner et al. 2023). Technological innovations, such as the possibility of generating electricity with renewable energies, are by no means sufficient. These technological innovations encounter established structures and path dependencies that must be broken. The expansion of renewable energies must therefore be embedded in the existing energy system in order to change the system from within and to adapt it to sustainability requirements. However, complex system changes must always include social and economic aspects in order to make them economically viable on the one hand and to address social problems at an early stage on the other. In addition, there are individual economic and country-related interests that hinder or prevent the introduction of solutions that are viable on paper. This applies both to the setting of economic framework conditions and to the adoption of international climate protection agreements. So far, solutions for either of these aspects are not in sight, and the world is hurtling toward a climate disaster. All indicators suggest that the target of constraining the human-made temperature increase to 1.5°, which is politically desired but insufficiently supported, will be missed by a wide margin.

However, climate change is only one of several problems that require comprehensive transformation processes. Other examples include advancing digitization, the role of artificial intelligence, the protection of the natural environment, growing economic inequality in many societies, and overpopulation. Inherently, transformation challenges are therefore difficult to master because they are usually subject to three basic conditions:

- *System Complexity*: Systems in which transformation processes are embedded are often highly complex, i.e. the cause-effect relationships of underlying changes are usually unclear, and understanding them is therefore an important subject of transformation research. This complexity concerns the understanding of technological, economic, ecological, and societal systems, as well as the relevant relationships among these systems. In addition, not all changes occur at the same time, but relevant patterns emerge over time and may be recognized too late when negative consequences are difficult to prevent.
- *Path Dependencies (backward complexity)*: Transformation processes often have to overcome path dependencies resulting from investments already made or established behavioral norms and value attitudes. The inertia of established systems entails that transformation processes are delayed and associated with high costs. The associated "stuck in the past" problems therefore require convincing alternative courses of action and the participation of relevant stakeholders on the basis of clearly formulated objectives. At the same time, such processes must be well structured and well communicated. If necessary, compensation mechanisms must (at least partially) offset the costs or other disadvantages of affected stakeholders.
- *Outcome Uncertainty (forward complexity)*: Due to the system complexity mentioned above, the effects of targeted system interventions are often unclear or difficult to predict. This uncertainty can relate both to the level of success of measures and to possible (unintended) side effects, encompassing technological, economic, ecological, and social systems and their interdependencies. Moreover, the uncertainty is used by transformation critics to question transformation processes as a whole or in part. The associated forward-looking complexity thus often reinforces existing path dependencies. In this vein, possible transformation paths must be analyzed and understood. Simultaneously, control mechanisms are needed to counteract undesired side effects and to strengthen desired outcomes.

Taking these lines of argumentation into account, we approach a concept of transformation that provides a basis for scientific transformation research. While in everyday language and depending on the discipline, transformation is often understood only as a change or a transition of even limited scope, the Aachen Transformation Model is based on a more comprehensive approach and we have developed the following understanding of societal transformations:

Fig. 1 Model for actively managed societal transformation processes (own figure)

Societal transformation encompasses fundamental and simultaneous or time-shifted changes of technological, economic, ecological, and social systems, which are highly complex in terms of the systems to be considered, the path dependencies, and the effects of alternative courses of action and therefore require inter- and transdisciplinary solutions.

Actively managed societal transformations based on the formulated understanding must cope with the complexity, and they call for interdisciplinary approaches. The required elements to be understood as building blocks of successful societal transformations usually take place sequentially, but they overlap in time and occur over longer time horizons. Overall, we suggest the following model, as summarized in Fig. 1:

1. Vision: A vision should contain the desired image of the future and can provide the direction for transformational change in the sense of a compass. This could be, for example, a sustainable development or selected Sustainable Developments Goals (SDGs) as the guiding vision.
2. Objectives: Applied to a defined object of transformation, for example a region such as the Rhineland area or a sector such as the mobility sector, more concrete transformation goals can then be defined. In the sense of the three-pillar concept of sustainability, these can be, for example, ecological, economic, and social goals. In fact, larger transformation projects always involve multi-objective decisions.
3. System understanding: A comprehensive understanding should ideally be established that takes the inherent complexity of the system into account. For this purpose, the entire system and its interrelationships can be modeled. In any case, the most relevant cause-effect relationships should be identified.
4. Intervention understanding: Before the actual transformation planning, possible individual interventions or intervention patterns should be systematically identified and evaluated with regard to their transformation effects. The basis for the evaluation is, on the one hand, the previously acquired system understanding. On the other hand, obstacles caused by path dependencies should be included in the

assessment with a view to the successful implementation of the interventions. Outcome uncertainties should also be included. These may be due to deficits in system modeling, unforeseen events, and influences external to the system.

5. Transformation planning: After a detailed analysis of possible interventions and intervention patterns, the most promising measures or bundles of measures can be considered. The criteria previously defined at the objective level can be used for the selection, e.g. ecological, economic, and social objectives. The potential (positive) impacts of the individual measures must be compared with their costs and other resource requirements. Appropriate capacity and budget planning is therefore an important step for the selection and implementation planning of the corresponding measures. Key indicators for measuring the success of the individual measures or bundles of measures should also be defined. On the one hand, these can be understood as minimum levels to be achieved, and on the other hand, they play an important role for the measurement of success and the analyses of deviations from the original expectations. In addition to budgets and indicators, transformation planning should also define the achievement of goals at the time level as well as the relevant responsibilities.
6. Implementation: The implementation phase then comprises the realization of the plan, including the budgeted measures and their monitoring. However, due to their societal scope and complexity, societally relevant transformations are not comparable with projects such as those carried out in companies. Neither can all the necessary measures and budgets be defined in advance nor can all the effects and interdependencies be identified in advance. But also because of the usually long planning horizon, the planning and execution phases are interrelated, and plans need to be repeatedly adjusted in order to sensibly control the ongoing transformation process. Therefore, monitoring and controlling are of great importance in addition to the execution of measures in the implementation phase.

The structure shown in Fig. 1 is not meant to suggest that societal transformations can be viewed as a step-by-step process. As already mentioned, the individual building blocks are interrelated, interdependencies must be taken into account, feedback loops must be implemented, and all relevant actors must be involved. Nevertheless, the building blocks of the model in Fig. 1 are essential for the success of transformations and have to be implemented professionally. Otherwise, there is always a risk, particularly in the case of long-term projects, that individual interests will prevail, that the process will be too fragmented, and that the end result will not only yield unnecessarily high costs but will also jeopardize the achievement of the transformation goals.

Moreover, societally relevant transformation processes cannot be left to individual actors, but must be coordinated with all relevant stakeholder groups. Appropriate participation and reflection processes must therefore be considered from the outset. These not only relate to the necessary reconciliation of interests but also increase the knowledge base for the overall process. Involving stakeholders potentially increases the acceptance of transformation processes and results, resistance can be overcome, and the participation of stakeholder groups can be motivated. Participation and reflection require governance structures through which stakeholders can engage and create opportunities for involvement.

The previous discussion indicates that societal transformations are not the equivalent to the traditional understanding of transformation as it is often used in other disciplinary contexts, e.g. for chemical or corporate production processes. What is the nature of such societal transformations? Three factors characterize the need for or the process of a societal transformation as starting points, which can also work in combination: (1) problems and challenges that have to be solved by society, (2) social and/or technological innovations, and (3) singular events that have fundamental effects on society. Here are examples for each of the three factors:

1. *Problems and Challenges*: The greatest current challenge for humanity is certainly the overexploitation of our planet with consequences such as climate change and the collapse of biodiversity in many regions of the world. In order to reverse or mitigate this negative development, the global community agreed on the guiding principle of sustainable development as early as 1992 at the Rio Conference (United Nations 1992), which is based on the Brundtland report (World Commission on Environment and Development 1987). The concept of a sustainable development does not only try to balance intra- and intergenerational justice but also has strong implications for politics as well as societal and economic forces. The pursuit of sustainability entails a whole series of societal transformations: the transition of the energy system, changes to the mobility system, the adaptation to climate change, and the modification of our economic system are just a few examples. Political movements have taken up the goal of sustainability and are massively questioning the behaviors and norms of previous social and economic systems, including established patterns of production and consumption.
2. *Social and Technological Innovations*: The most important current example, which triggers several technology-related societal transformations, is the increasing digitization of our society, including the growing importance and use of artificial intelligence. The changes associated with this process deeply affect the lives of every individual. Areas concerned range, for example, from the use of media, communication patterns, and the structure and operation of production processes (keywords: increasing automation, platform economy, and cyber-physical systems) up to the functioning of political systems. Other examples include innovations in the energy and mobility sectors.
3. *Singular Events* are not hard or even impossible to predict, but lead at least initially to hardly plannable, turbulent transformation processes. The most dramatic current example is certainly Russia's war against Ukraine. Its consequences extend far beyond the countries directly involved. They affect the importance and configuration of political institutions and systems as well as goods and energy flows around the globe, and they may involve long-term political and economic power shifts.

Of course, there are also numerous interdependencies between these factors. Problems and challenges lead to an increased focus on technologies and societal development that address these challenges. Unresolved challenges can result in "supposed" singular events that enable individuals or groups to influence the course of historical events. From a scientific point of view, societal transformations must therefore always be thought of from several perspectives at the same time. Understanding and implementing such transformations both require interdisciplinary approaches and the opposite of what prevails in many scientific disciplines: ever greater specialization and separation from other disciplines. Interdisciplinarity and transdisciplinarity oriented toward practical implementation therefore require a fundamental rethinking of how communication, collaboration, and research processes are designed. Ultimately, a cultural change becomes unavoidable, both for individual researchers and for the university as a whole. Prerequisites of this cultural change are that scientists from different disciplines interact with each other at all, that they are open to exchange, that they are able to reflect critically on methods and procedures within their own discipline, and that they can at least accept perceived ambiguities, e.g. in terminology and argumentation patterns.

Using RWTH Aachen University as an example, this book chapter shows ways in which universities can contribute to the success of societal transformation processes. In particular, the following questions are addressed:

1. How can a university be designed with a view to its organization, patterns of interaction, and operations so that it can better understand and help shape societal transformations?
2. How can a transformation-oriented research approach be designed to better understand societal transformations on the one hand and to contribute to successful transformations on the other?
3. What are successful examples of transformation-oriented research approaches and what general conclusions can be drawn for university research?

This chapter first provides an overview of the history and the strategy of RWTH Aachen University with a view to transformational research. This enables a better understanding of how and why RWTH Aachen University has developed toward an integrated interdisciplinary university. This is followed by a presentation of the Aachen Model for Transformation Research, which was decisively shaped by the Human-Technology-Transformation strategic theme group. In addition to the building blocks of the model, their interplay, including the focus and methodological shifts in the individual disciplines, is also presented. The implementation of the model is illustrated by various strategic initiatives and research projects at RWTH Aachen University. Finally, the presented transformation research model is critically reflected, including its limitations and is evaluated with regard to its further development. The future research potential of the Aachen approach and its transferability to other universities will also be elaborated.

2 RWTH Aachen University: Its History and Strategy

2.1 History and Figures

RWTH Aachen University was founded in 1870 and is today one of the largest technical universities in Europe. The university currently has more than 47,000 students, consists of nine faculties (schools), and employs nearly 7,000 scientists (RWTH Aachen University 2023a). Together with the Medical Faculty, the university has a total budget of €1.1 billion, of which more than €400 million are third-party funded. RWTH Aachen University has a strong international focus, with 30% of its students coming from abroad. Moreover, a wide range of international collaborations around the world forms an important foundation of its excellence in research and teaching. Another cornerstone is the close and established cooperative relationship between Forschungszentrum Jülich and RWTH Aachen University, which is reflected in JARA, the Jülich Aachen Research Alliance.

Originally founded as a polytechnic school in the nineteenth century, RWTH Aachen University has since grown to its present size and importance, especially following the Second World War. Today, the university ranks in the top league for many fields of research and is involved in many important societal transformation processes. The Excellence Strategy initiated by Germany's federal and state governments in the 2000s has contributed significantly to the university's development. Over the past 15 years, RWTH Aachen University has increasingly devoted itself to the expansion of interdisciplinary research. This development was particularly strengthened in the last round of the Excellence Initiative. The title of the university's corresponding application for the Excellence Initiative was "The Integrated Interdisciplinary University of Science and Technology. Knowledge. Impact. Networks". It has created further organizational and conceptual prerequisites for research and teaching at RWTH Aachen University that have a strong positive impact on societal developments (RWTH Aachen University 2019).

The successful interdisciplinary orientation of RWTH Aachen University is also reflected in figures. Two of the three acquired clusters of excellence, "Internet of Production" and "The Fuel Science Center", have an interdisciplinary orientation. This also applies to the two BMBF Future Clusters, currently located at RWTH Aachen University, on the topics of "Hydrogen" and "Neuromorphic Hard- and Software". Furthermore, numerous large-scale research projects, such as collaborative research centers (*Sonderforschungsbereiche*), research training groups (*Graduiertenkollegs und Forschergruppen*), and other collaborative projects, foster interdisciplinary cooperation.

The interdisciplinary orientation is one of the major factors why RWTH Aachen University attracts the most third-party funding among all universities in Germany. It is regarded not only by public funding bodies but also by the government and industry as an important contact for almost all societal transformation processes. Various university rankings also show that there is by no means a contradiction between an interdisciplinary orientation and disciplinary strength. RWTH is excellently represented in numerous scientific fields, especially in engineering and the natural sciences—not only in Germany but also worldwide—in various rankings, e.g. in the renowned QS and THE rankings (RWTH Aachen University 2023b).

2.2 Strategy of an Integrated Interdisciplinary University

"RWTH's vision is to further grow beyond a unique integrated, interdisciplinary university by embracing the convergence of knowledge, approaches and insights from the humanities, economics, engineering, natural and life sciences, i.e. biology and medicine. A common core activity of RWTH's research portfolio will be the comprehensive analysis, description, understanding, and design of complex systems. In the past, measures were enacted that bolstered the natural sciences. In the future, measures will be implemented that (i) strengthen disciplinary depth as well as knowledge networks accelerating the convergence of life sciences and data science in the Aachen research landscape, (ii) identify, recruit, retain, and empower excellent researches, and (iii) ensure the university's capacity for organizational renewal and ability to foster its collective creativity through an agile governance and strong alliances. These initiatives will create a unique education, research, and transfer hub with dynamic research networks crossing disciplinary and organizational borders. RWTH's ambition is to be Germany's academic cornerstone for providing sustainable solutions that impact today's and future's challenges." (RWTH Aachen University 2019, p. 2).

This vision, which is stated in the RWTH Excellence proposal, shows the commitment of the university toward interdisciplinarity and creating positive real-world impacts that contribute to a sustainable development of society. Of course, interdisciplinarity cannot simply be prescribed, but had to be painstakingly learned by RWTH Aachen University. Numerous content-related and structural measures were necessary to bring the university up to its current level. Figure 2 illustrates this development. Whereas initially, various thematic areas—such as Information and Communication Technologies (ICT), Energy, Chemical and Process Engineering (ECPE), Mobility and Transport Engineering (MTE), Materials Science and Engineering (MatSE), and Production Engineering (ProdE)—were established with an (almost) exclusive scientific and engineering focus, these have been expanded and interlinked over time.

In due course, the initial thematic focus was expanded and the need for interdisciplinarity was recognized and emphasized. Despite considerable successes, for example in the acquisition of large-scale interdisciplinary research projects, there were initially numerous structural elements still missing for promoting collaboration among scientists beyond faculty (school) boundaries. As a consequence, and after evaluating the entire strategy process of the university, the so-called profile areas were formally established in 2014 to further foster the interdisciplinary research in the core

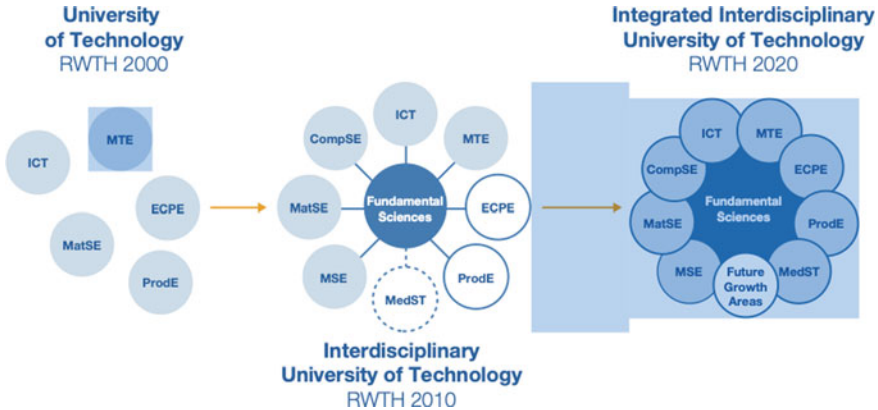

Fig. 2 Development of the RWTH Aachen. *Source* RWTH Aachen University (2019, p. 3)

research areas. The profile areas were provided with a budget, and steering committees composed of members from various faculties were established. Since then, the profile areas have been represented in the strategy-forming and advisory committees of the university and play an important role for the university's strategic development. The profile areas are now based in the original thematic areas of RWTH and have been expanded by Medical Science and Technology (MedST), Molecular Science and Engineering (MSE), and Computational Science and Engineering [CompSE, now Modeling and Simulation Sciences (MSS)] as further profile areas.

Of course, the profile areas alone do not guarantee an integrated interdisciplinary orientation. This requires the willingness of the scientists involved, appropriate incentive mechanisms, and further measures of consolidation. The key to all of this is the scientists themselves. This is problematic if they see themselves purely as disciplinary researchers and are geared toward disciplinary mechanisms of performance measurement and appreciation. Such a situation can quickly lead to the scientists involved misunderstanding each other or only wanting to push through their own ideas, which is hardly conducive to successful interdisciplinary collaboration. For this reason, RWTH Aachen University has deliberately focused its recruitment policy on hiring so-called T-shaped researchers in addition to disciplinary strength. These are scientists who are deeply rooted in their own discipline on the one hand and who have already proven that they are able to work at the edge of their disciplines and with scientists from other disciplines on the other.

T-shaped researchers are important links between disciplines. They are not only better able to analyze problems from different perspectives; they can also help to structure interdisciplinary projects, to design interfaces between disciplines, and to improve the communication within interdisciplinary teams. It is therefore a logical consequence that T-shaped researchers play an important role in the profile areas. Together with more disciplinary scientists, they are able to address and research scientific questions that are often linked to the major challenges of our time. Individual (disciplinary) and T-shaped researchers can then use the profile areas as an interdisciplinary research platform to define and elaborate research topics and to transfer them to large-scale research projects. Ultimately, not only two clusters of excellence, "Internet of Production" and "The Fuel Science Center", have emerged from this structure, but also projects and structural elements (CRC: Collaborative Research Centers) that further strengthen the interdisciplinary orientation of the university. In addition, Extramural Research Institutions (ERI) are also involved in generating ideas and applying for and implementing interdisciplinary research facilities. These research institutions are seen as strategic partners and include—but are not limited to—the Forschungszentrum Jülich (Helmholtz Center), several Fraunhofer Centers, as well as other RWTH-affiliated institutes. Figure 3 provides an overview of the interplay (depicted by the arrows) between the structural elements that contribute to the creation of collaborative research networks, resulting in many large- and small-scale interdisciplinary research projects.

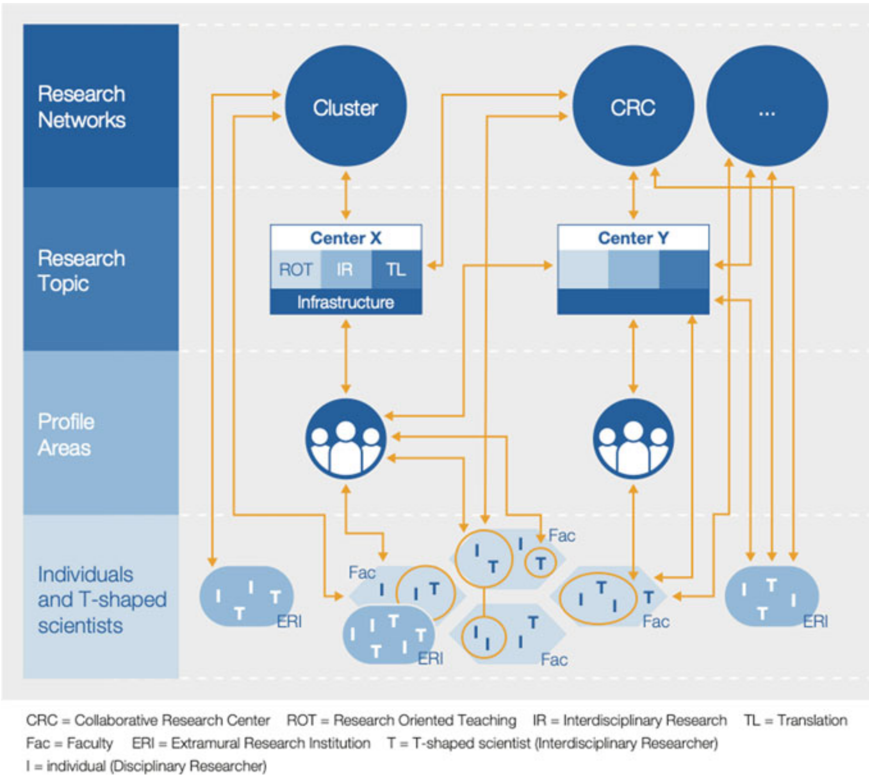

Fig. 3 Creation of research networks. *Source* RWTH Aachen University (2019, p. 25)

2.3 Organizational Elements of the RWTH for Addressing Interdisciplinary and Transformation Challenges

The strategy of RWTH Aachen University is tailored to provide answers to the major technological and societal questions and challenges of our time. Among these are challenges addressing already ongoing transformation processes, e.g. in the energy sector, in the mobility sector, in the health sector, and challenges referring to digitization and climate change. Since all these challenges call for interdisciplinary solutions, a number of measures are needed to bring together researchers from different disciplines and to increase the attractiveness of interdisciplinary research. The appointment of T-shaped researchers is by no means sufficient. The formation of networks and the generation of ideas must be promoted institutionally (see Fig. 4). RWTH Aachen University thus relies to a large extent on the intrinsic motivation of the researchers, who contribute their own ideas and network with each other. Networks and ideas can then be developed into interdisciplinary research fields, which ideally lead to the establishment of large (funded) coordinated programs, e.g. graduate schools or collaborative research centers. However, this approach can hardly be implemented via directives in a top-down manner. Rather, governance at RWTH Aachen University is based on the following pillars: organizational culture, organizational elements, incentives, and intrinsic motivation, which are also described in the following.

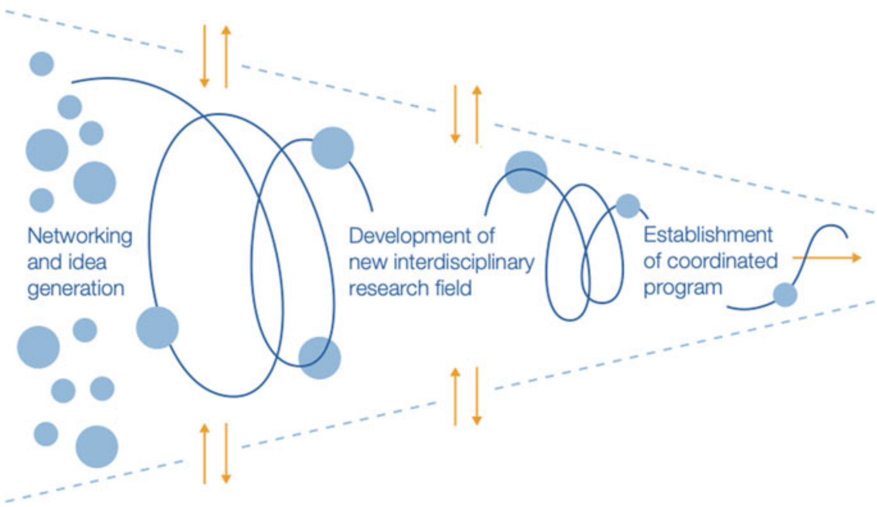

Fig. 4 From idea generation to a coordinated program. *Source* RWTH Aachen University (2019, p. 12)

Organizational Culture: RWTH Aachen as "a Place to Be"

RWTH Aachen University has set itself the explicit goal of being perceived as "a place to be" in order to create an inclusive atmosphere in which scientists enjoy working together at the highest level of research and teaching. To this end, a number of measures and tools have been established to facilitate the coaching and support of scientists at all career stages. Three elements are particularly significant: (1) the RWTH's welcoming atmosphere, (2) the RWTH Center for Young Academics and the RWTH Center for Professional Leadership, (3) the RWTH governance structure. Each of these elements is not only anchored in the overall structure of RWTH but also backed up by specific processes and measures. For example, the welcoming atmosphere begins with fair appointment negotiations, for which RWTH has also received an award from the German Association of University Professors (*Deutscher Hochschullehrerverband*). The establishment of new scientists is further supported by various on-boarding measures, such as the Welcome Workshop provided by the Rectorate (the university's executive governing body), coaching programs available to new professors, and early invitations from peer groups to participate in research projects and in several mostly interdisciplinary platforms. The RWTH Center for Young Academics and the RWTH Center for Professional Leadership provide central points of contact for information and career development at all career levels. At the same time, the internal organization of the chairs (departments) and networking for scientists are promoted with a view to the interdisciplinary and participatory orientation of the university.

The governance structure of the university is also geared toward collaboration among the various faculties and schools. Here, the Planning and Allocation Committee (PAC) should be mentioned as the most important decision-making unit of the university. The PAC is composed of the members of the Rectorate and the nine deans of the different faculties. The PAC works closely with other university committees and makes important directional decisions and related budget decisions. Unlike many other German universities, where the Rectorate has the final word with regard to such decisions, the RWTH faculties thus have a structurally secured right of participation in important decisions and can thus play a significant role in determining the strategic direction of the university. However, this governance structure obliges the faculties to cooperate among themselves and with the Rectorate, as this is the only way they can work together with the Rectorate in a meaningful way. Ultimately, therefore, this collaborative structure not only strengthens the role of the faculties, but also interdisciplinary cooperation within the university.

Profile Areas and Exploratory Research Space as Fuel for Interdisciplinarity

The aforementioned profile areas encompass the most important interdisciplinary research fields at RWTH Aachen University and were created specifically to bring together scientists from different disciplines in order to address societally relevant topics. The profile areas coordinate research activities in their respective fields and invite all scientists to participate. Each of the profile areas has its own budget and is managed by a steering committee comprising scientists from different disciplines.

The profile areas report regularly to the Strategy Council and the PAC and also play an important role in the strategic orientation and formulation of the university's Excellence Strategy. The profile areas also accompany the application of interdisciplinary large-scale research projects, in particular the clusters of excellence which are important for maintaining the RWTH's excellence status—a formal title awarded by the Federal Ministry of Education and Research (*Bundesministerium für Bildung und Forschung*).

A typical example is the profile area "Information and Communication Technology" (ICT). ICT has identified five main research areas (1) Artificial Intelligence, (2) Data Science, (3) Dependable Digitization, (4) Next Generation Computing and Communication Platforms, and (5) Quantum Computing, which are of great importance to almost all the disciplines. Since the establishment of the ICT, the AI center has been established, and the RWTH has obtained multiple ERC grants, several Alexander-von-Humboldt professorships, and has maintained a strong participation in European projects as well as top positions in several ICT-related rankings. However, the effects go far beyond participation in more disciplinary projects. For example, the NeuroSys future cluster has been successfully acquired. It conducts highly interdisciplinary research into neuromorphic hardware and software developments in various fields of application. These developments have been strengthened by several bridge professorships, e.g. by the creation of the Chairs of "Data Science" and "Hybrid Intelligence in Organizations" at the School of Business and Economics. ICT members are also involved in the ongoing interdisciplinary initiative "NextGen-Sustain" (Next Generation Sustainability), in which the creation of a sustainability engine and method apps within an open innovation approach are designed and implemented in order to better research and evaluate sustainability-related developments and decision-making processes.

Platforms and Project Houses as Facilitators of Transformation Research

While the profile areas can be seen as thematic platforms, RWTH additionally provides start-up funding for new research in new thematic areas that further strengthen the interdisciplinary profile of the university and bring together scientists from different disciplines. Most prominently, the ERS funding formats can be mentioned. ERS stands for Exploratory Research Space and is aimed at all RWTH scientists who can contribute promising, often high-risk research ideas. In this way, interdisciplinary teams are to be formed and the necessary preliminary work for the application of third-party-funded research projects is initiated. ERS projects thus start at an early stage of thematic developments with a still low degree of maturity. Within the projects, scientists get to know each other better, exchanging methods and ideas and further sharpening the thematic focus in terms of research subjects and methodologies.

The next stage includes project houses, which are intended to identify interdisciplinary growth areas in research and teaching and to anchor them structurally into the university. Project houses are initially funded by the university but later have to fund themselves through third-party funding or to acquire a budget from other sources, e.g. a faculty budget. Figure 5 illustrates the Interdisciplinary Management Factory

(IMF) as an example of such a project house. The IMF is composed of four research areas, (1) Operations Research and Management (ORM), (2) Energy, Mobility and Environment (EME), (3) Technology, Innovation, Marketing and Entrepreneurship (TIME), and (4) Managerial and Organizational Economics (MOE), which reflect the thematic profiles of the scientists already working in the faculty. At the same time, the structure of the IMF leads to a stronger internal and external networking of the faculty. Infrastructurally, the IMF is supported by various labs that further increase the research capacities of the faculty. Initially, the IMF was intended to enable and strengthen interdisciplinary connectivity of the School of Business and Economics. The funds provided were used to create four junior professorships and subsequently to establish the four research areas within the School of Business and Economics. The appointment decisions on other professorships were also influenced by the IMF structure. As a result, the school has not only initiated four master's degree programs thematically related to the four research areas, but the school's third-party funding volume has also multiplied since the IMF was founded. The IMF Project House has helped to transform the School of Business and Economics' more traditional profile to a more methodologically and technologically oriented business and economics faculty with a better fit to RWTH Aachen University. In this way, the school became an active and visible player within the RWTH, a situation which has also been reflected in visible improvements to the school's status in numerous rankings such as the Wirtschaftswoche Ranking (2023).

The elements described here were all created in the last decade in preparation for the last round of the Excellence Initiative up to 2018. They changed the character, content, and culture of the university. Collaboration across faculty (school) and disciplinary boundaries is now a part of many scientists' everyday lives. This includes

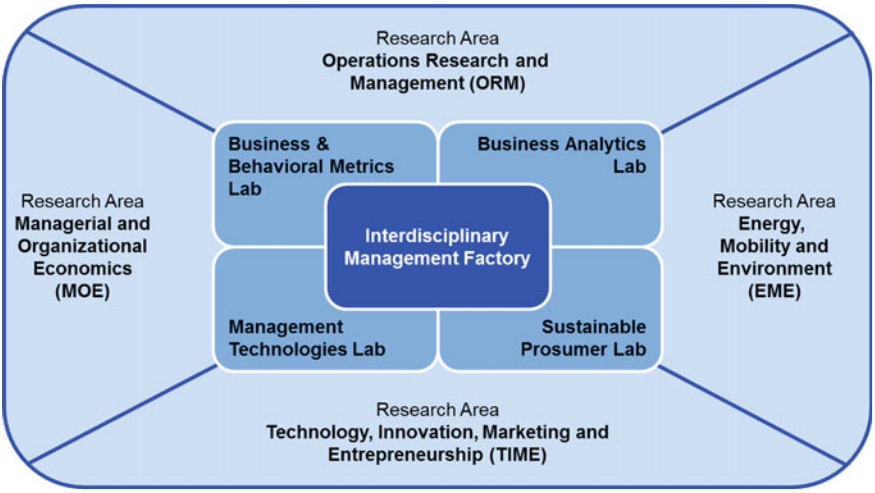

Fig. 5 Interdisciplinary management factory as an example of a project house at RWTH Aachen University (RWTH Aachen University 2015)

the ability to listen to each other, to be curious, to not cling to disciplined terminology, and ultimately to take higher risks regarding their own research and career paths. Many of the initiatives were by no means imposed; rather, they emerged from existing collaborations and thus created the basis for collegial and creative cooperation. These developments have created the foundation for making RWTH Aachen University more transformative than before, i.e. for increasing its willingness to address societal challenges and its effectiveness when doing so.

Restructuring of the School of Business and Economics and the Faculty of Arts and Humanities

In view of the developments and structures described above, it is only logical that since the last Excellence Initiative, RWTH Aachen University has increasingly turned its attention toward societal transformation processes. In addition to the large-scale research projects already mentioned, further structures have also been created here to secure the development in the direction of an integrated interdisciplinary and transformative university. Key starting points were the strategic reorientations of the School of Business and Economics and the Faculty of Arts and Humanities. Until the beginning (School of Business and Economics) to the middle (Faculty of Arts and Humanities) of the last decade, both faculties operated largely on a disciplinary basis and were detached from many of the university's strategic initiatives. There was little cross-disciplinary collaboration, and faculty-strategic directions were not tailored to the relevant contexts of a technical university. This led to considerable pressure on both faculties.

The School of Business and Economics (Faculty 8) was openly challenged with the information that it could not continue to exist in its current form unless there was a stronger alignment with the interdisciplinary orientation of the university, measured in particular by the school's participation in cross-disciplinary research projects. In addition, all future appointment decisions of the school were to be scrutinized with a view to ensuring a close fit with the university's overall strategy. Despite some criticism from various faculty members, this initiative proved to be enormously successful. Since the Interdisciplinary Management Factory was founded, participation in interdisciplinary third-party projects of Faculty 8 has grown by roughly 50% over the last decade. Today, not only does the School of Business and Economics have the highest third-party funding per professorship of German business faculties; it also participates in many strategic initiatives of the university. Since 2019, the school has been involved in both of the interdisciplinary clusters of excellence (Internet of Production and the Fuel Science Center).

The Faculty of Arts and Humanities (Faculty 7) had to undergo an even more "painful" restructuring process. Once again, a stronger focus on the strategic orientation of the university was demanded by the Rectorate. As a result of this process and against substantial resistance (change.org 2014), the faculty was obliged to reduce its capacity in Romance studies and announced five new professorships with a stronger focus on technological aspects of the social sciences. This rededication of professorships also led to a strategic reorientation of interdisciplinary research among the faculty. Existing focal points have been expanded and the portfolio of transformation-oriented topics has been significantly increased. Thematic orientations, such as science and technology research, human-technology interaction and communication research, sociology of technology and organization, governance of technical systems, technology acceptance research, and ethical aspects of technological developments, have become significantly more important.

Transformation Initiatives and Centers

In parallel, and driven in part by changes in the Faculty of Arts and Humanities and the School of Business and Economics, transformational formats have also been established university-wide. For example, the *Human Technology Center (HumTec)* embodies in a special way the linkage between specialized scientific research and interdisciplinary integration. On the one hand, interdisciplinary research about the production and use of scientific knowledge is conducted there on the basis of different disciplinary perspectives of science studies research in the humanities and social sciences. On the other hand, interdisciplinary projects are initiated that are placed precisely between different faculties. In this way, knowledge about the practice of interdisciplinarity can be deepened and, as a result, this practice can also be better shaped. Finally, all of these activities are concerned with the question of the transformation of knowledge, which not only involves epistemic problems, but ultimately focuses on the problem of democratic shaping of innovation and transformation. These research questions are dynamic in themselves. Therefore, *HumTec* is organized in an agile way according to fields of activity. One of these is the Living Lab Incubator, through which places of collaboration between science, politics, companies, and civil society actors are initialized, and innovative options can be created and tested in real-world contexts (Böschen et al. 2021). In the Leonardo lecture series, scientists from all faculties contribute and discuss topics of high societal relevance. The students should be enabled to better understand global and societal challenges, to perceive interdisciplinarity as a solution requirement, and at the same time to become aware of the responsibility of science.

In 2021, the BMBF-funded *Käte-Hamburger-Kolleg Aachen: Cultures of Research* was established as an international center for advanced studies and is dedicated to transformation processes in science itself, focusing on the following topics: (1) Complexity, Lifelikeness and Emergence, (2) Emerging Computational and Engineering Practices, (3) Histories and Varieties of Science, (4) Expanded Science and Technology Studies. Thus, an important focus lies in the reflections of science and its role in transformation processes within society. Particularly in view of the magnitude of the current challenges, e.g. with regard to climate change and digitization, it is absolutely necessary that science also questions itself and adapts its methodologies to address the increased systemic complexities and possible negative side effects of its own approaches of tackling research questions.

The *RWTH Center for Artificial Intelligence*, founded in 2019, bundles research on artificial intelligence at RWTH Aachen University and takes into account the relevance of this research field for many application areas with their transformational nature for society as a whole (AI Center 2023). For this reason, the Center has defined (1) AI Methods, (2) AI Enabling Technologies, (3) Domain-specific AI as well as (4) Ethical, Legal, Societal, and Economical Aspects as designated research fields. Hence, it is not only broadly positioned but also incorporates the great societal relevance of artificial intelligence from the very beginning. Emphasizing its interdisciplinary nature, scientists from different disciplines are involved in all of these research fields. The spectrum of research ranges from pure basic research to solving concrete application problems that concern basically all areas of our everyday life, ranging from robotics, mobility, and the energy system, across to learning technologies and computing education.

REVIERa was founded in 2019 as a transformation platform of the RWTH Aachen University to address "the complex challenge of shaping the lignite phase-out and the far-reaching social, spatial, and technological change processes this entails" (REVIERa 2023, mission statement). The format is interactive and involves actors from the university as well as all stakeholders interested in the structural change in Germany's Rhenish mining area. As an initiative of three RWTH faculties (Faculty of Architecture, Faculty of Arts and Humanities, School of Business and Economics), the platform has initiated a series of activities, ranging from a number of workshops with different groups of actors, scientific colloquia, networked teaching, across to project maps and the Temporary University Hambach in the summer of 2023. An important focus of the REVIERa platform is to reflect on the role of knowledge that accompanies transformation processes (Förster et al. 2022). Different knowledge categories are considered, starting with knowledge about transformation goals, moving on to the required system knowledge with a view to different application domains (energy, AI and information, materials and cycles, health, mobility, productive landscape) as fields of innovation, and then on to transformation knowledge (implementation knowledge). A detailed description of REVIERa's activities is provided by Förster et al. in the following chapter of this book.

The *Center for Circular Economy* (2021) was founded in 2021 as an initiative of the Faculty of Georesources and Materials Engineering and "bundles the expertise of all faculties of RWTH Aachen University on sustainable circular economy. Trans- and interdisciplinary methods are developed for the process optimization of the three main areas of the CCE: sustainable product design during production, business models during product use, and material recovery during product recycling" (Center for Circular Economy 2023, mission statement). The background is the desired transformation of the economy from linear to circular value chains. Conserving the value of products, product components, and the resources after a product's primary life can not only reduce the consumption of scarce resources but can also protect the natural environment as a sink of solid, liquid, and gaseous pollutants. Currently, 17 institutes and chairs (departments) from all the faculties and schools of RWTH Aachen University are involved as core partners in the Center for Circular Economy. The Center is also partnering with the city of Aachen, one of the 75 cities that signed the Circular Cities Declaration (2021).

The *Built-and-Lived-Environment (BLE) Group* was founded in 2020 and was initially established as an initiative of the Faculty of Architecture (Faculty 2) and the Faculty of Civil Engineering (Faculty 3). BLE research focuses primarily on the production of built environments, but also on the use of buildings and their constant adaptation to the relevant social contexts (lived environments). It quickly became clear that the guiding principle of a sustainable development is of the utmost importance to the *BLE Group*. Therefore, the group of scientists involved was logically expanded by actors from the Faculty of Arts and Humanities, the School of Business and Economics, and the Faculty of Medicine (Faculty 10). With its defined research fields, BLE targets in particular decarbonized construction, the preservation and activation of existing buildings, climate change, crisis adaptation, and healthy living spaces. As a result of this preliminary work, the *BLE Group* was defined as a growth area of RWTH with the aim of establishing BLE as a further profile area at the university. Overall, BLE is thus contributing to a paradigm shift in the construction industry and in the architecture and utilization of buildings. The transformational relevance as well as the further strategic orientation of BLE is described by Kemper and Lohrberg in this book.

The *Human-Technology-Transformation Group* was established in 2021 as a result of a strategy workshop of the RWTH's Planning and Allocation Committee. In view of the developments already described, it became clear from the discussions during the workshop that, on the one hand, the university is already involved in many transformation processes and, on the other hand, has not yet developed a clear understanding of transformation and the respective participation of research institutions. As a first step, a core group drawn from all faculties was formed under the leadership of the Faculty of Arts and Humanities and the School of Business and Economics to develop a common understanding of transformation. It quickly became clear that transformation from a research perspective should ultimately consist of three pillars: (1) transformation research to better understand transformation processes, (2) transformational research to successfully help shape transformation processes, and (3) research transformation to adapt research processes in terms of content and methodology to societal transformation requirements. At the goal level, the group quickly agreed that transformation must promote a sustainable development of society (including the natural environment) and therefore must serve economic, ecological, and social goals. In achieving these goals, technological developments play an important role in almost all current transformation processes. Successful transformation should therefore always be thought of in interdisciplinary terms. Section 3 of this article elaborates on the Aachen Model of Transformation Research that emerged from the *Human-Technology-Transformation Group* and that also forms the basis for the structure of this anthology.

2.4 Summary: RWTH Aachen University as a Transformational University?

The developments described in this chapter show how RWTH Aachen University has systematically advanced into an integrated interdisciplinary university. This puts

RWTH in a position to participate in numerous technologically and societally relevant transformations. Such participation does not only involve theoretically oriented basic research but also numerous opportunities to scientifically accompany and help shape actual economic and societal developments. It is therefore only logical that RWTH Aachen University has taken several steps that have the potential to turn itself into a transformative university—a transformation process that has changed how researchers interact, collaborate, and address important overarching research questions of our time. Figure 6 illustrates the development of the RWTH Aachen into a transformative university. RWTH Aachen University's transformation concept is based on the identified global challenges that were the focus of the first phase of the Excellence Initiative. In the following years, RWTH then developed into an integrated interdisciplinary university as described, where interdisciplinary collaborations were systematically practiced across the various platforms and in joint research projects. Building on this, the transformation idea has then steadily gained importance, particularly in recent years. This idea continues to address the major societal transformation challenges, but it can only be successfully implemented if interdisciplinarity itself continues to be successfully implemented in RWTH's research and teaching. In this sense, Fig. 6 presents the described organic development of the university, where the individual elements are mutually dependent or, to put it another way, the pieces of the mosaic fit into each other.

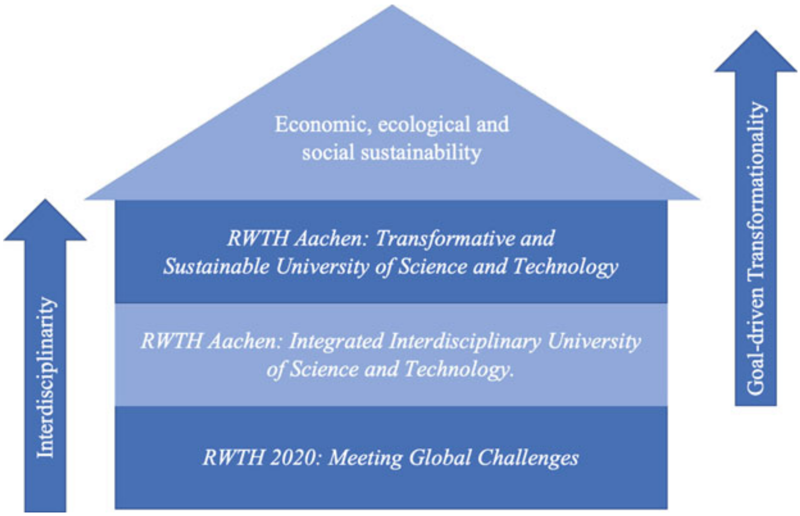

Fig. 6 Development of RWTH Aachen University toward a transformative and sustainable university (own figure)

3 Aachen Model of Transformation Research

In the introductory chapter, important characteristics of societal transformations have already been identified in the form of system complexity, path dependencies (backward complexity), and outcome complexity (forward complexity). The terminology shows that societal transformations are knowledge-intensive processes in which no perfect predictability—and thus no advance planning in a deterministic sense—is possible. Consequently, societal transformations always remain an open process. Their knowledge intensity, their inherent complexity, and their associated uncertainty justifiably qualify universities to be regarded as important actors in transformation processes. This raises the question of the role of the researcher in societal transformations. Wittmayer and Schäpke (2014) distinguish between (1) the reflective scientist, (2) the knowledge broker, (3) the process facilitator, (4) the change agent, and (5) the self-reflexive scientist. While the reflective scientist assumes a passive role by observing and analyzing the transformation process, the roles of knowledge broker, process facilitator, and change agent are active roles that change the actual transformation process. The self-reflective scientist is inward looking. The researcher questions his or her role, his or her methods, and their possible effects. These roles imply three different positionings of research in the transformation process, which also build the already mentioned three pillars of the Aachen Model of Transformation Research: (1) transformation research, which is linked to the role of the reflective researcher, (2) transformational research, which is linked to the roles of knowledge broker, process facilitator, and change agent, and (3) research transformation, which is linked to the role of the self-reflexive scientist.

This chapter introduces the Aachen Model of Transformation Research and thus presents the current state of discussion of the Human-Technology-Transformation group. First, the target level of societal transformations is discussed, and then the individual pillars of the model are presented in more detail. All other articles included in this anthology then follow the structure of the Aachen Model for Transformation Research, which also corresponds to the structure of this book.

3.1 Human-Technology Transformation

Both in the literature and in public discussions, the goal of a sustainable development is seen as prevailing for almost all transformations (Olsson et al. 2014). At the same time, the sustainability goal is very broad in terms of its content and provides numerous established patterns of justification that are accepted by a large number of stakeholders involved in transformation processes. This applies in particular to the three-pillar concept, which comprises the economic, the ecological, and the social pillars. Of course, in the sense of the introduced transformation concept, systemic relationships exist between the individual pillars, i.e. economic actions (almost) always cause effects in the ecological and social areas and vice versa.

In the literature, a wide variety of strategies for solving sustainability problems are discussed. Efficiency and sufficiency can certainly be considered as the two most influential types of strategy (Huber 2000; Jungell-Michelsson and Heikkurinen 2022). While efficiency strategies aim to achieve sustainability goals through technological advances, sufficiency strategies focus on human self-restraint in their consumption patterns. It is perhaps unsurprising that for a technical university such as RWTH Aachen University, the efficiency strategy has a high priority. By increasing resource productivity, fewer resources are needed to achieve the same output or welfare gain. As a result, the resource pool and also the natural environment as a sink of waste, wastewater, and emissions are protected without compromising the social welfare. However, efficiency strategies are viewed very critically by many environmental researchers. The consequence of more efficiency is often not a reduction in resource consumption, but rather it results in rebound effects, i.e. resources that are no longer needed are used for other purposes (Hertwich 2005; Sorrell and Dimitropoulos 2008). Rebound effects are empirically very well validated and represent a relevant problem (Stern 2020). This shifts the solution of sustainability problems from pure technological considerations back to economic and political decision-makers, i.e. efficiency and sufficiency strategies must be combined in a meaningful way in order to achieve not only selective successes but also to contribute to more sustainability on a global level, in the sense of the Sustainable Development Goals set by the United Nations (2015). This again requires an understanding of the systems underlying a societal transformation, which must always include an understanding of economic, ecological, and societal tradeoffs, since almost all transformation decisions affect all of the sustainability pillars simultaneously.

It is certainly indisputable that technological developments made the success of the human species possible in the first place. Without technological innovations, the various industrial revolutions would simply not have materialized. Medical progress has contributed massively to an increase in life expectancy in almost all countries on our planet. Today, technological advances in agriculture allow the feeding of 8 billion people. However, both the resulting population explosion and the massive increases in prosperity have also led to an overuse of ecosystems and the associated social and increasing economic problems. What was ultimately missing was the orientation of technological developments toward sustainable development in the sense of all three pillars of sustainability. The supposed contradiction between sufficiency and efficiency strategies can therefore hardly be resolved without innovative technologies and novel social solutions. However, these must consequently serve the achievement of sustainability goals. Simplified conclusions in the sense of a direct conversion of efficiency increase into benefits for the natural environment are not only inaccurate but also misleading due to a lack of systemic understanding.

A suitable metaphor could be that of the human patient. In the case of any drug, not only must the desired effects be considered with a view to combating a particular disease but also undesirable side effects that can hardly be anticipated without scientifically sound studies. At the same time, the patient must be given the opportunity to implement a healthy lifestyle so that certain disease patterns and the associated damage no longer occur. What is taken for granted for human beings, at least in the medical discussion, has been neglected in the last decades with respect to our planet. Of course, a sustainable development with regard to our natural environment must not ignore human welfare, even though it can be assumed that environmental problems and social welfare are interrelated for many people, specifically in developing countries. Hence, societal transformations must be primarily oriented toward environmental and social goals. Technological developments and economic systems are only means to an end. At least in the long term, they must contribute to the achievement of environmental and social goals. An uncontrolled development of technological and economic systems, on the other hand, is more dangerous than ever before. It is a realistic scenario where progressive environmental problems lead not only to the collapse of ecosystems but also of entire political and economic systems, including the migration due to environmental problems (Hoffmann et al. 2020). On the other hand, it is hardly possible and meaningful to think of achieving environmental and social goals without technological innovations and functioning economic systems. As a result, the Human-Technology-Transformation group at RWTH Aachen University agreed on a four-pronged approach to researching societal transformations that encompasses the domains of the environment, society, technology, and the economy, as also illustrated in Fig. 7. The figure depicts by no means a simple extension of the three-pillar concept of sustainability, but aims to include all relevant system domains. On the one hand, this approach should enable a comprehensive system necessary for achieving sustainable development and, on the other hand, it should make it possible to identify and manage possible means-purpose relationships. As mentioned, environmental and social goals are to be considered as primary goals in this context, while economic and technological goals, although important, are only secondary goals. Seeing societal and environmental goals as a priority, the Human-Technology-Transformation group operates with a taxonomy which, although not always strictly separated, is based on a hierarchy of goals.

For each of these domains, the group has defined exemplary aspects and potential goals that it considers particularly important. In the case of the *environmental goals*, these are the conservation of the natural resource pool, the reduction of emissions of all kinds, measures to limit climate change, the promotion of the ability of ecosystems to provide ecosystem services (see the chapter by Leuchner et al. in this book), and the conservation of biodiversity. All these goals are not only widely discussed in the environmental literature; there is also broad agreement on their high relevance. The situation becomes more difficult when it comes to defining target levels and measures, as these can involve deeper cuts in economic and social systems and can therefore produce profiteers, on the one hand, and individuals, groups, or organizations that are adversely affected by the pursuit of the goals, on the other hand. In addition, as the aspects and goals cannot be regarded as non-overlapping, the underlying complex system relationships and mutual influences must also be taken into account.

The definition of *social goals* is even more complex and also more controversial here, since often controversial cause-effect relationships have to be taken into account that make the achievement of social goals possible in the first place. This applies, for example, to the justice goal. Even at the conceptual level, there are numerous definitions which concern completely different aspects, for example, performance

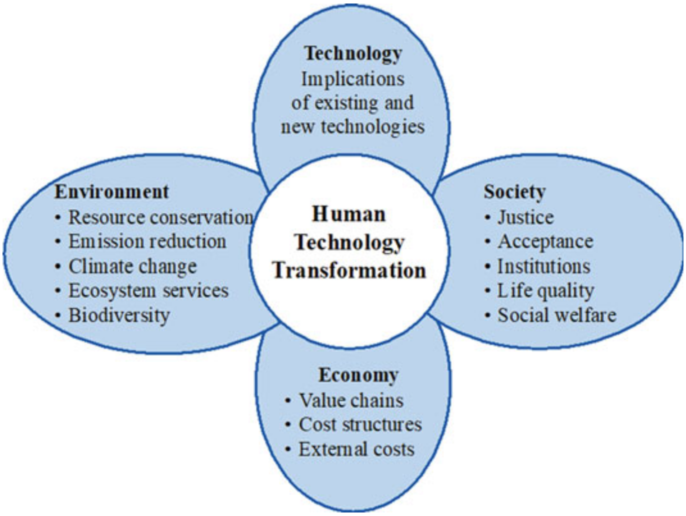

Fig. 7 Human-technology transformation (own figure)

justice, equal opportunities, and income justice. Other objectives of the societal domain concern the acceptance of measures and the institutional framework by the citizens, functioning and healthy institutions, and the increase in the quality of life and in social welfare. Since the interplay of measures and goals is extremely complex, the involvement of stakeholders and meaningfully designed participation processes are of utmost importance.

When approaching the *technological domain*, it becomes clear that basically no separate or stand-alone goals are meaningful, which is in line with the means-purpose relationship mentioned above. Of course, performance targets can be formulated for existing and new technologies, for example in terms of their efficiency. However, performance targets must always be seen in relation to the “for what?”. And this “for what?” ultimately concerns environmental and social goals. Two examples illustrate this. In the course of the energy transition, hydrogen is increasingly being discussed as a storage medium, also in order to absorb the volatility of energy generation with renewable energies, e.g. with photovoltaics and wind energy. However, in order to be able to use hydrogen in a transformed energy economy, the generation costs must be significantly reduced. This means that the economic target level is affected first. Ultimately, however, the cause-effect chain goes even further. Lower hydrogen costs are the first thing to make it possible for corresponding business models to establish themselves on the market, and for the technology to become economically feasible in the first place. In the final analysis, economic feasibility relates to both environmental and social goals. Environmental goals are concerned because economically unfeasible technologies cannot have any positive effects, for example on climate change. Social relations are affected because it is of great importance to citizens and companies that energy remains affordable and is available with sufficient security of supply (Priesmann et al. 2022). The second example concerns the diffusion of artificial intelligence solutions into many areas of people's lives. Artificial intelligence (AI) is thus becoming an important value-adding factor that can improve the material and immaterial supply of goods to society and thus contribute to an increase in the quality of life and social welfare. At the same time, AI solutions are associated with considerable risks, ranging from the role of humans in economic value creation systems to the controllability of such technologies. In both examples, therefore, technological developments cannot be classified a priori as either useful or good or bad. In the technological domain, the primary goal is thus to better understand implications of technologies for the environment and society. For this, the aforementioned system understanding of societal transformations is extremely important. On the other hand, (research) institutions are needed that are able to record and evaluate technological developments and their effects as objectively and neutrally as possible, both intellectually and free from economic interests.

The *economic domain* can be understood as a kind of coordination mechanism that, on the one hand, absorbs technological developments and, on the other, depends on functioning institutions and the natural environment as a resource pool. On the demand side, consumers should be incentivized to demand products that have fewer social and environmental impacts. In the context of market economic systems, such a coordination mechanism is often referred to as an invisible hand, through which supply and demand are brought together with the lowest possible transaction costs. Specialization and the division of labor, on which the globalization of the last decades is based, ideally lead to the maximization of the resource productivity of the overall system in the interest of all. Prices provide information about the value of a resource, which is used more frugally the higher its price. In general, it can be said that the greater the scarcity of a resource in the market, the higher its monetary value. Companies can exist if they can offer a good or service at lower total costs (including their transaction costs) than if all exchange relationships were to be facilitated via the market. For the long-term existence of enterprises, they need a revenue structure, which at least covers the arising costs of its value creation architecture, including the internal transaction costs. Due to the increasing technological complexity and in order to exploit cost advantages, a good or a service is usually produced not by one company alone, but in a value chain. For example, several hundred companies are involved in the production of an automobile. Focusing on resource productivity, it can be stated that market-based systems are more successful than others and have led to the current prosperity of many people. However, this success also has its downsides, as a price is only charged for those resources that are perceived as scarce and that can be traded on markets. This has led to an increasing overexploitation of the natural environment, and it ultimately damages not only the ecosystems but also the livelihoods of many people. In this context, economists have coined the term "externalities" to reflect such market failure. Externalities reflect situations when costs are generated in an ecosystem or in a social system that is not fully covered by either the producers or the consumer. A simple example is the emission of greenhouse gases. They are causing increasing global warming, which not only negatively impacts ecosystems but also reduces agricultural productivity in many regions due to droughts and other extreme weather events. Costs not covered by producers and consumers are also referred to as "external costs". In the interests of sustainable development, these must be internalized by companies at least in the long term. Societal transformation processes must therefore also address the economic domain by changing coordination mechanisms and by setting incentives. One important goal is to successfully establish business models and value chains that no longer generate non-compensated negative externalities.

3.2 Transformation Research

Measured by their great importance, it can be stated that societal transformations are still not largely understood in their entire complexity. It is true that plausible interpretations of transformation processes and the resulting transformation outcomes can be derived, at least in retrospect. But even here, a comprehensive consideration of all relevant factors and of their interaction is generally lacking. It is even more difficult to understand the impact of societal transformations in advance and thus to plan them. In many cases, societal transformations are therefore implemented in a learning-by-doing mode; i.e. mistakes that have already been made are corrected as far as possible and the planning must be adjusted again and again. Societal transformations thus unintentionally resemble a roller coaster ride with an uncertain outcome. This uncertain outcome affects the resources and costs as inputs of transformation processes, the implementation of the transformation processes themselves, and their outputs and impacts regarding the social and environmental domains. One reason for the high degree of outcome uncertainty is the aspects of societal transformations already mentioned in the introduction, which concern system complexity, path dependencies, the unpredictability of technological developments, and an influence of individual events. For this reason, transformation research, one of the three pillars of the Aachen Transformation Model, plays an important role. Transformation research aims to better understand societal transformations, both in terms of the relevant factors and their systemic interaction.

Before discussing further basics of transformation research, we first discuss some examples that illustrate some of the challenges of understanding transformation processes:

- *Replicability*: To date, there is no clear understanding of why some transformations succeed while others fail, at least temporarily. One example is the great success of Silicon Valley as the home region of many very successful startups and technology companies, especially in the computer industry. It is true that an excellent university infrastructure and the associated supply of skilled labor, as well as numerous other factors, such as the founding of the Stanford Industrial Park, can be identified as factors that have contributed to the Silicon Valley's success. However, these factors are also present at other locations, without the success being repeated at this level. In fact, many regions have tried to emulate Silicon Valley without even coming close to replicating its success.

- *Short-sighted, self-centered, and short-term thinking*: Even with a clear analysis and understanding of the initial problem and the resulting need for action, it is often very difficult to successfully initiate transformation processes, even when long-term success is beyond question. One example are measures that help to prevent climate change. Even though the necessary knowledge and required technologies needed are available in principle, even measures that are (almost) free and can also produce immediate results are not carried out. This applies, for example, to the introduction of a speed limit on German highways, which could save millions of tons of carbon dioxide per year. The measure would be effectively free of charge, would even reduce the risk of accidents on the highways and, as examples from other countries show, e.g. the neighboring Netherlands, would also not negatively affect the flow of traffic (ADAC 2023). Possibly due to the values of parts of the population, a small advantage (the pleasure of driving fast) is given a higher priority than the achievement of a goal that is important for the entire population. The underlying ways of thinking and logics can hardly be anticipated in advance or are difficult to bridge.
- *Power relations and understanding of the system*: Societal transformation processes always involve a number of stakeholder groups whose network of relationships often only forms in the course of the overall process and also changes dynamically. It is therefore almost always useful to identify the most important stakeholder groups in advance and to conduct a corresponding social network analysis. However, even this cannot provide a comprehensive understanding of the system, since actor constellations are constantly changing on the one hand, and on the other hand, the exchange of knowledge, interests, power relationships, and the course of decision-making processes cannot be clearly differentiated.

Figure 8 summarizes some of the aspects mentioned here for understanding transformation processes. A distinction is made between inputs, aspects of the core transformation (conversion of inputs into outcomes), and the outcomes themselves. In contrast to industrial value creation processes, transformation processes are much more complex and usually cannot be described unambiguously. However, it is precisely the understanding of these conversion processes with which societal transformations can be purposefully managed and moderated in terms of the results to be achieved.

In sum, it can be stated that to date there is no comprehensive understanding of societal transformation processes that can be used to ensure that societal and environmental challenges are successfully addressed. Much of the literature refers to or presents frameworks that aim to help solve transformation problems, either based on the use of often innovative methods, such as artificial intelligence and big data analytics, or the application of structural elements, such as participatory governance approaches and innovative organizational structures (e.g. Feroz et al. 2021; Verhoef et al. 2021; Häußling et al. 2021). However, since it is precisely these challenges that

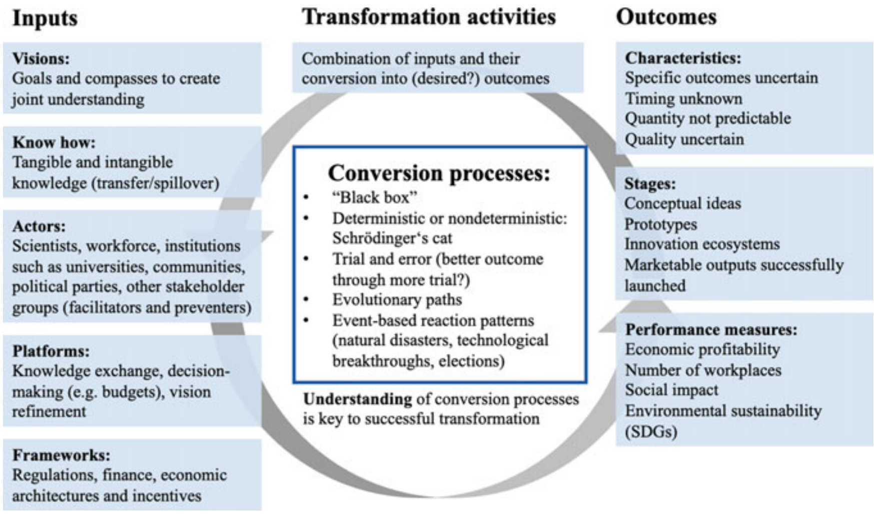

Fig. 8 Aspects of transformation processes (own figure)

will increasingly and decisively determine the future of society, it is to be expected that the field of transformation research will gain massively in importance.

3.3 Transformational Research

While transformation research focuses primarily on a better understanding of societal transformations, transformational research aims to make concrete contributions toward solving the transformation problems. Points of reference are often the major transformation challenges of our time, which Sachs et al. (2019) categorize as follows:

1. Education, gender, and inequality
2. Health, well-being, and demography
3. Energy decarbonization and sustainable industry
4. Sustainable food, land, water, and oceans
5. Sustainable cities and communities
6. Digital revolution for sustainable development.

Without going into detail here, this categorization makes it clear that all transformation challenges address social and environmental sustainability issues and require social innovation in addition to technological solutions. Customized solutions therefore always require a high degree of interdisciplinarity, the aforementioned understanding of the system involved, and the ability to work with other players to put these solutions into practice. Here are a few examples:

- Technical solutions are difficult to implement in practice if they are not economically feasible and are not supported by suitable business models. Often, they also need to be supported by economic incentives that have been set by policy-makers. Methods and frameworks to support sustainable business model innovation including their social acceptance can facilitate the successful implementation in practice (Schwarz et al. 2021).
- Universities are in a position to identify solutions and to implement them in an exemplary manner, but the solution approaches often fail to go beyond the pilot phase. It is therefore necessary to create networks in order to ensure the effectiveness of the solutions developed. Important elements here are: thinking in terms of networks of actors, open communication and innovation platforms, and the promotion of spin-offs.
- Building sufficient acceptance among stakeholders is a key factor for the success of transformation measures. Models and approaches from transformation research can make an important contribution by addressing the necessary feedback loops through stakeholder involvement, and by designing and supporting planning and implementation phases that include active stakeholder participation. Furthermore, the prominent Technology Acceptance Model (Venkatesh and Davis 2000) emphasizes perceived usefulness, perceived ease of use, plus subjective norms as important drivers of adopting new technologies which are often crucial for successful transformation processes.
- The successful implementation of transformation measures, for example the establishment of renewable energies through the expansion of photovoltaic and wind energy capacities, requires systems to be designed resiliently in order to cope with demand and supply shocks as well as singular events (Folke et al. 2010). A number of measures are being discussed specifically in the context of the energy transition. These range from energy storage, buffer capacities, servitization of the energy system, sector coupling, to smart energy consumption patterns (Jasiūnas et al. 2021).

Science can and must play an active role in transformational research. It creates tailor-made, system-relevant technological, and socio-scientific knowledge and makes it available in an adapted form on an ongoing basis during the transformation process. Moreover, science can facilitate processes by pre-structuring them, providing well-trained manpower, and being involved in decision-making processes. Particularly in difficult and controversial change processes, universities or individual researchers can help to objectify the discussion and can act as change agents or process moderators who are not bound by their economic interests. Especially during the COVID-19 pandemic, these roles contributed to the management of the associated crises and also became more apparent to a broad public, with trust in scientific institutions playing a key role (Plohl and Musil 2021).

3.4 Research Transformation

However, as researching and participating in societal transformation processes can lever the manifold impacts of universities and other research institutions, research itself is being transformed (Hölscher et al. 2021). This is happening at several levels and encompasses numerous aspects. Obviously, societal transformations affect the major problems of humanity and thus also change the scale of the problems under consideration. Climate change and the resulting necessities for the energy transition, the mobility transition, the transformation of value chains, technological solutions, and economic incentive mechanisms can neither be fully addressed by individual small-scale research projects nor is one discipline alone able to offer comprehensive solutions. What is needed is a systemic understanding of the problems, which can only be tackled through a high degree of impact-oriented interdisciplinarity. The problems to be studied are dynamic and long term in nature. Relevant planning horizons span decades and are often intergenerational. Transformative research thus contrasts with much of what characterizes the traditional university: a high degree of specialization, ivory tower research, clear delineation of disciplines, and academic careers designed for collaboration in tight academic communities with equally narrow performance measures. This is not to question what constitutes the traditional university. Rather, there is a need for greater plurality in order to give transformation research the space it deserves. The way in which RWTH Aachen University is establishing inter- and transdisciplinary researchers as an integral part of the university alongside disciplinary researchers is an important step in this direction.

The need for cultural change in science should not be underestimated. This begins at the linguistic level, in order to establish a common understanding of the phenomena under consideration, while at the same time having sufficient tolerance for different conceptual meanings and interpretations. The cultural change continues with the mechanisms of interdisciplinary cooperation that need to be established. A mutual appreciation among researchers and by the university as an institution is necessary, without compromising the required high quality of research. Such a process usually extends over years and requires institutional measures that bring scientists together and encourage interdisciplinarity. At RWTH Aachen University, it is the numerous interdisciplinary platforms and meeting places that successfully accompany this process and ultimately make the university "a place to be". Another prerequisite for the success of cultural change is that of performance measurement, which is career-relevant and influences the status and identity of the scientists involved. This is a challenge not only for the university itself but also for the funding community, especially the public funding agencies for competitive research projects. It is necessary not only to orient calls for research projects thematically toward the direction of major transformation challenges but also to explicitly demand a greater degree of interdisciplinarity. With a view to research results—even if research projects are open-ended in terms of the results achieved—content-oriented measures that strengthen research quality should be implemented and incentivized. For example, successful transformation research projects with high real-world impact could be rewarded with budgets for follow-up research. This would also strengthen the long-term research required for successful transformation processes.

Cultural change is not limited to research; it should also contribute toward opening up the university to the outside world. It is one of the essential characteristics of the major transformation problems of our time that scientific questions are linked to questions of values. These value questions cannot and should not be resolved by science. Rather, they must be clarified at a high level with all relevant stakeholder groups. In this context, science must be enabled to explain itself, including the relevant problem-solving approaches in a comprehensible way, while at the same time disclosing its own value judgments and assumptions and putting them up for discussion. This involves complex processes that will always initially involve misunderstandings and frictions. In the sense of a living democracy, such processes can help to reduce disenchantment with science and politics and ultimately to provide better solutions to the transformation challenges mentioned above. RWTH Aachen University, for example, has taken the first steps in this direction with its REVIERa transformation platform, which is geared toward structural change in Germany's Rhenish mining area and has increased the acceptance of science among citizens and various stakeholder groups.

Last but not least, transformation research is also expanding the canon of scientific methods. On the one hand, methods that enable holistic system modeling have been gaining in importance for years now. This applies, for example, to the comprehensive system modeling of our climate. On the other hand, the relevance of methods which establish the interface between science and civil society is increasing in order to meet the increased demands for participation. Living labs or field experiments also help to increase knowledge about the need for change and the impact of certain measures, without irreversibly implementing change processes (Böschen et al. 2021). Ultimately, this can also strengthen the acceptance of transformation measures.

Overall, transformational research thus has great potential to transform research itself, thereby significantly increasing the benefits of research for society. In this vein, system understanding, research cultures, participation mechanisms, and applied methods have to be improved or adapted to the specific needs of transformative research. A key element is also the learning of disciplines from each other, which requires that knowledge is exchanged much more fluidly between disciplines, with interdisciplinary collaboration being a major facilitator of such knowledge spillovers. Hence, the transformation of science through transformation research has only just begun and will certainly open up many new avenues—for new ways how to conduct science that addresses the major transformation challenges of our time.

4 Examples and Book Overview

This book is structured according to the composition of the Aachen Transformation Model. It first outlines the topic of transformation overarchingly and subsequently from the three perspectives of transformation research, transformational research, and research transformation.

Following this chapter's general introduction of the topic and the role played by RWTH Aachen University, the university's transformation platform "REVIERa", which relates to all three perspectives of the transformation model, is described and reflected. Here, the authors conclude that societal transformations in the sense of the transformation triad can be researched, shaped, and enabled via the platform approach.

As a first perspective and emphasis, this book depicts the subjects of researching transformation itself. With this, different issues are addressed, which are explored as part of the RWTH's project and/or research activities. Focus topics include greenwashing, corporate social responsibility, and bioeconomy. A systemic perspective is taken, where transformation is discussed regarding infrastructures, sociological change processes, and labor markets.

The second perspective focuses on transformational aspects of RWTH-related research. It is described, among other things, how ecosystem services can serve as a framework for transformation, including biodiversity as a crucial aspect for decision making. Ongoing transformation processes are discussed for different industries and application domains, ranging from the hardware and textile industries up to the built and lived environment as a whole. The part on "transformational research" also discusses the management of organizational change and the transformation of RWTH University's clusters of excellence.

Third, this book focuses on the transformation of research and research culture as well as concepts within universities, related institutions, and firms. The authors discuss the concept of Responsible Research and Innovation, which has been integrated into RWTH Aachen University in the form of the RRI Hub. Focusing on manufacturing, the design of antifragile systems is put into a framework, aiming to create environments which not only absorb but also benefit from stressors and volatility. Finally, the last chapter focuses on the Humboldt^n initiative, which bundles the sustainability efforts of its member universities, anchoring them via a whole-institution approach.

Naturally, the perspectives of the Aachen Transformation Model overlap, and aspects of the model are addressed in mutual connection and context in many chapters of this book. In this sense, the structure of the book aims to emphasize the different perspectives of transformation from a university's viewpoint: Which transformation topics are researched, which research topics especially trigger and shape societal transformation processes, and in which way institutions such as the RWTH Aachen (must) transform their operating principles and research cultures.

5 Conclusion and Invitation

With this book, we aim not only to establish a new model of transformation but also to encourage other universities to follow a similar path in addressing the great challenges of our time. Sustainable solutions can only be achieved if different disciplines work together, if transformation processes and challenges are sufficiently understood, if solutions are developed in an interdisciplinary way, and if scientists as well as policymakers and practitioners challenge each other methodically and in terms of content with regard to the urgent societal problems of our time. Ultimately, therefore, the Aachen Transformation Model encompasses approaches that are also relevant for other research institutions and organizations. We would like to invite the community to follow the new pathways presented in this book together with us. This also means putting aside one's own partial interests more often, not losing sight of the big picture, and ultimately developing completely new forms of interdisciplinary and transformational cooperation. We would be delighted if you would accept this invitation.

Acknowledgements Our sincere thanks go to the many scientists at RWTH Aachen University who have contributed their expertise to the development of the Aachen Transformation Model. We would also like to thank the more than 30 external reviewers who have critically evaluated the submitted contributions and provided important input for their further development. Last but not least, we appreciate the commitment of the RWTH profile areas and the university management, who have supported us financially in the development of this book.

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An Actor in the Transformation Triad: The Platform Approach “REVIERa”

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Abstract The Rhenish mining area—Europe’s largest lignite mining region—is currently undergoing a complex structural change process due to the coal phase-out that is being enacted in Germany. Researchers from RWTH Aachen University—an institution of education and research that is an integral part of the surrounding region—have founded the transformation platform “REVIERa”. Their objective is to create a forum around the lignite phase-out and to link up knowledge and activities, both inside the University and with regional partners and residents. With regard to the Aachen Transformation Model, this article reflects on the platform’s contribution to researching, shaping, and enabling the transformation process in the Rhenish mining area. We discuss the value added by the platform as well as the related challenges, limitations, interdependencies, and appropriate methods. In this respect, REVIERa can have an integrative function; however, some open questions regarding further research potential and the nature of transformation processes, institutional roles, and structures remain.

Keywords Transformation research · Transformational research · Research transformation · Collaborative research · Post-mining region

1 Introduction

The lignite coal phase-out, which has been enacted into law in Germany (Deutscher Bundestag 2020), is one example of structural change that has established an ongoing transformation process involving 2500 km^2 and more than 10,000 workplaces (RWI

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P. Letmathe et al. (eds.), *Transformation Towards Sustainability*,
https://doi.org/10.1007/978-3-031-54700-3_2

2018) in Europe's largest lignite coal field situated in the Rhine region between the cities of Köln, Düsseldorf, Mönchengladbach and Aachen in western Germany (Fig. 1). As one of Europe's leading technological universities with more than 47,000 students (RWTH 2022), RWTH Aachen University—located in the greater Rhenish mining area—plays an important role in this transformation process. Not only is the University one of Germany's 11 "Excellence Universities"; its focus on integrated and interdisciplinary research also creates beneficial conditions for participating in and contributing to the transformation process. The changing role of universities in their specific localities, their enhanced responsibility toward societal and contextual challenges as well as the setup of new learning and research environments in their cities and regions: all these issues are currently intensively debated and developed with an active involvement of RWTH, which is reflected in international projects and initiatives (ENHANCE 2023; ENIHEI 2023; Falling Walls Engage 2023; TU9 2023).

The coal phase-out in the Rhenish mining area poses both unique challenges and opportunities for regional development that will span several decades and concern many different aspects of life and work in the region (ZRR 2021). To name just a few: the preservation of jobs, the usage of the opencast mining area, regional identity, and future energy supply. Moreover, the transformation process can enhance the understanding of transformation regarding its underlying nature and its impulses for innovation. In an effort to further research, shape, and enable the transformation process taking place in the Rhenish mining area, RWTH Aachen University has created the interdisciplinary transformation platform "REVIERa", which is described in more detail below. This article aims to show the ways in which a platform of this kind can serve as a helpful actor in the coal phase-out transformation process.

Structural change entails conflict. It further marks disruption and entails challenges to citizens and firms as well as to the political terrain (Andreoni and Chang 2019; Herberg et al. 2020; Oei et al. 2020). The notion of structural change addresses processes of change on a larger scale, forsaking irreversible path dependencies or transitioning from the preservation phase into the decline phase according to the model of panarchy (Boyer 2020; Gunderson and Holling 2002). Regions with structural change problems were previously dependent on a unilateral form of value creation that is frequently linked to structural monopolies. There are three important dynamics in structural change and the related profound transformation processes that can be systematically distinguished between but which are, at the same time, related to each other. First, goal-oriented ex-novation (David and Gross 2019): How does one purposefully get out of the fixations of previous innovation activity? Second, targeted innovation: How does one develop suitable new settlements for innovation? That is, which companies should and can be located? Which impulses for transformation are made possible and which new determinations are made at the same time? Third, there is the task of tailored infrastructure development. For it is in the infrastructures that the new paths are defined—but which then also influence the future development possibilities of regions under transformation.

This article focuses on the multiple roles of science in supporting ongoing transformation processes. Particular attention is drawn to how "Doing Transformation" can

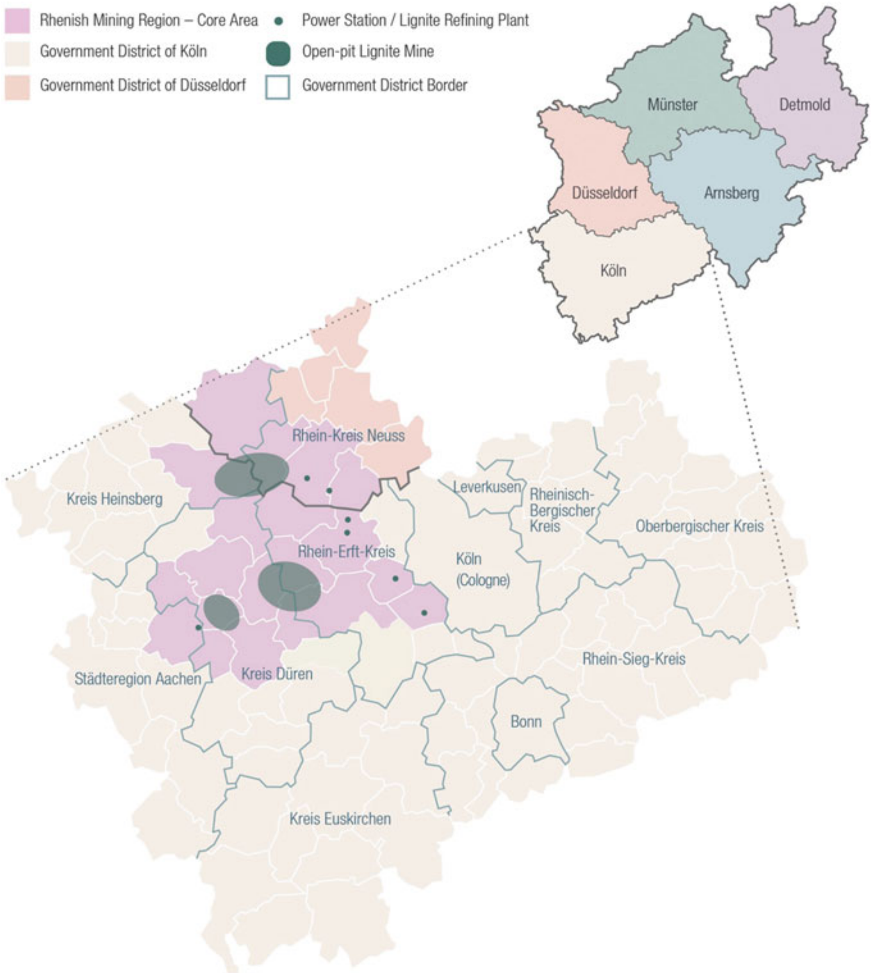

Fig. 1 Rhenish mining area in North Rhine-Westphalia and the neighboring government districts (Schubert 2021)

take place and to what possibilities and limits occur when science takes an active part in these processes. Coal exit regions offer insightful cases in point. They are characterized by specific tensions and ambiguities. First, there is an ambiguity between self-induced structural change—which is related to the notion of "crisis", often followed by a structural aid—and overarching processes of transformation which are happening anyhow. In the case of the German coal phase-out, the affected regions simultaneously face an overall scarcity of energy and material resource, demographic change, and skills shortage as well as a changing geopolitical environment with very different local, regional, national, and European impacts (Churski et al. 2021a, 2021b; Emanuela and Louis 2020; OECD 2019). This can be claimed as a tension between the intention and the evolution. Second, there is an ambiguity between the global and nationwide transformation toward sustainability (Die Bundesregierung 2021; United Nations 2015) —with the notion of transformation paths and the importance of social and cultural change—and the ambition of shaping a "model region" in a regional context. Although these remain two different phenomena, they are nevertheless interlinked.

Thus, the ambition of transforming a coal mining area into a "model region" is highly presuppositional. The underlying assumption is that "Doing Transformation" is possible and that other technologically or socially driven transformation processes can be purposefully integrated into these processes. Addressing such technologically and socially driven transformation processes is a highly complex matter, as the relevant prerequisites are usually not in place in the regions concerned (Grillitsch and Hansen 2019; Isaksen et al. 2022). This requires an overall understanding of the active and interlinked technological, social and spatial transformation processes in the region as well as an arena of actors that is willing to invest into the capacity to shape transformation—including the management of conflicts and ambiguities between different stakeholders as well as different transformation goals.

Moreover, in the course of the interaction between various actor groups also the complexity of the transformation fields and their respective challenges have to be discussed and dealt with. For example, the above-mentioned topics are often still developing fields for which no established solutions are yet available for the market. At the same time, the question arises as to how a meaningful linkage between various transformation failures can be managed. Two examples illustrate this:

1. Smart energy solutions in energy communities rely on energy from renewable resources. However, since energy is not always available in sufficient quantities, storage solutions, such as battery storage, are needed on the one hand, and clever adaptation of energy consumption to the energy supply on the other. This requires a good data and software basis to enable intelligent energy generation, storage, and use. To this end, there is increasing discussion of how car batteries, for example, can be used as intermediate storage and at what time of the day or night these batteries can best be charged (Szinai et al. 2020). This will lead to a linking of energy and mobility systems, i.e. a coupling of different sectors (Ilieva and Rajasekharan 2018). This example shows that transformation processes not only focus on the implementation of new technologies (e.g., storage systems) but also link up areas that were not previously considered together (energy system, digitization, and mobility). Therefore, such transformation processes almost always require a comprehensive understanding of the entire relevant system, which is essential for the success of the transformation.
2. The creation of new businesses, for example the establishment of circular economy approaches, often requires complex value creation architectures (Calisto Friant et al. 2020). For the example mentioned, processes regarding logistics, sorting, separating, and recycling have to be linked with each other (Dräger et al. 2021). To achieve the necessary economies of scale, various actors

must coordinate their business models and align their actions accordingly (Ghisellini et al. 2016). Particularly the application of new technologies necessitates the establishment of innovation ecosystems in which various actor constellations must be analyzed, linked, and coordinated. This would then often require new or extended infrastructures to be created, political support to be established, and potential partners to be brought together. In addition, the required competence profiles of employees in these areas must also be considered and built up.

In this article, we argue that there is a need for transformation platforms to steer within transformation processes, especially for knowledge actors such as universities. This is why the latter typically overestimate the impact of their own innovation activities while underestimating the need for aligning their innovative ideas with the goals to be reached from a citizen’s perspective. Against this background, the argument is developed in five steps. First, we lay out some main points with regard to the conceptual background, thereby the perspective of multi-level thinking is aligned with the idea of openness and the shaping of transformation (Sect. 2). Second, the idea and approach of a transformation platform interlinking the University and regional actors in the context of structural change is placed (Sect. 3). Third, to demonstrate the need for as well as the design of such a platform, three cases that focus on the components of the Aachen Transformation Model are discussed, focusing on different relevant dimensions of structural change (Sect. 4). Fourth, the insights are discussed (Sect. 5) and, finally, the main insights are highlighted (Sect. 6).

2 Conceptual Background

Generally, the term “transformation” describes a profound change process of a complex system from a status quo into a desired target state. In transformation processes, system, goal, and transformation knowledge gradually coevolve, mutually stimulating and influencing one another (Vilsmaier and Lang 2014; Wuppertal-Institut 2013). Hence, transformation processes are inherently open processes that can be kick-started and pushed in very different ways: by exacerbated boundary conditions and related crises or by intention in accordance with transformation goals (Bormann et al. 2018; BUND 2022; Sommer and Welzer 2017). In the case of longer timeframes, different occasions and impulses for transformation may overlap and merge, e.g., goals may be reset or may gain in ambition, or multiple crises may add urgency to the region under transformation. Within the transformation processes, social, economic, ecological, as well as spatial and governance-related factors mutually interplay. Hereby, the status of transformation in a specific phase shows forces, patterns, and dynamics regarding different interdependent system levels (Fig. 2).

In the case of the Rhenish mining area, transformation is self-induced, including an especially long-term perspective. According to German law, coal-based power generation is determined to end fully by the year 2038 (Deutscher Bundestag 2020) at the latest. Recently, this time limit was brought forward to the year 2030 (NWR

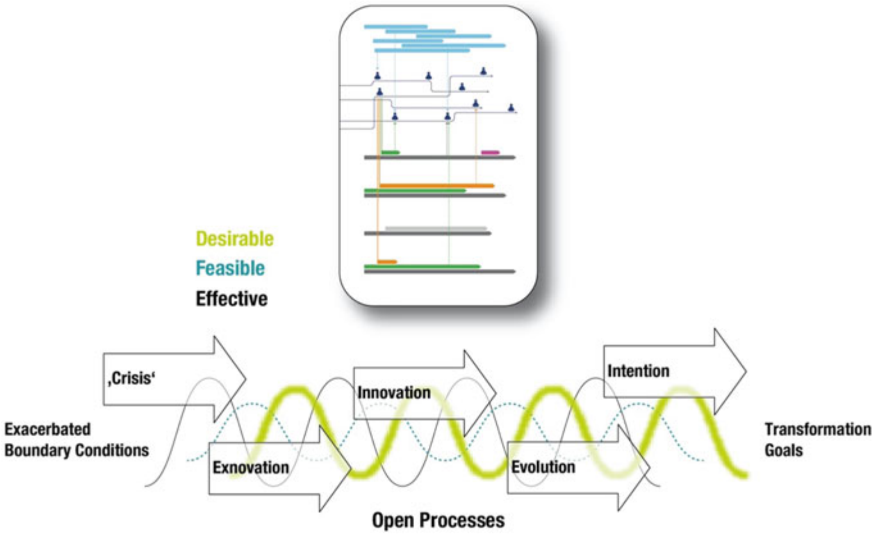

Fig. 2 Basic understanding of transformation processes (authors)

2022). This desired phase-out entails a multitude of structural, technological, spatial, and societal changes. After the closure of the opencast lignite mine in the Hambach District, another change process of lake-filling is planned, lasting several decades and posing the question of interim use of the former mining area and its surroundings. These two target states of mine closure and the presence of a lake should ideally improve the attractiveness and sustainability of the region. Globally, the United Nations has formulated the Social Development Goals, defining targets and indicators for sustainable development (United Nations 2017, 2015). Locally, projects and processes can be oriented toward these goals, with the complex task of conveying these goals to a local perspective, e.g., regarding German municipalities (Assmann et al. 2018). The coal phase-out transformation process in the Rhenish mining area is characterized by a multitude of different players and technologies. This can be illustrated by a look at the literature of transformation studies.

2.1 Understanding Transformation Through Multi-level Thinking

Transformation processes are typically embedded in complex arrangements of regimes and multi-level governance. At the same time, there are difficult questions of how to design transformation processes, if possible. Therefore, one must change the view from the reconstruction of developments toward the question of how to steer in-between developments.

Transformation processes always encounter existing structures, which are reflected in the physical environment, the competencies of existing employees, economic entities, and social and cultural norms. In this context, an important role is played by so-called path dependencies (David 2000), which should be employed as sensibly as possible, but which can also represent significant obstacles to successful transformation processes. For example, employees in the Rhenish mining area often have competencies that are important for lignite mining and the supporting industry. For this reason, it could make sense to focus on the establishment of industries in the Rhenish mining area in which competencies related to raw materials can be applied. In this regard, approaches of a circular economy could be sensible, since these also require raw material-related know-how. If, on the contrary, completely new technological areas were to be established, e.g., the creation of neuromorphic hardware and software in the Rhenish mining area, the appropriate structures must also be developed (see Smolka et al. in this book). However, in each of these cases it is necessary to detect and understand existing path dependencies, possible lock-in effects, and the necessary capacity-building measures and to address them at an early stage (Djelic and Quack 2007; Goldstein et al. 2023).

Looking at these interlinkages of actors, levels, innovation histories, and transformational change, we would like to claim such perspective, multi-level thinking. This label is inspired by, but not limited to, the so-called MLP approach (MLP = Multi-Level Perspective), which has been developed over the past two decades for the targeted study of innovation and transformation processes (Geels 2004; Geels et al. 2016; Geels and Schot 2007). It considers three levels—sociocultural landscape, socio-technical regime, and niches—and their interconnection. By linking these levels, the emergence and diffusion of socio-technical innovations can be studied in the context of transformation processes—or also: processes of structural change. According to this approach, fundamental innovations are prepared primarily in niches. However, to contribute to a regime change, i.e., to change the innovation landscape in a desired direction, specific framework conditions must prevail at the landscape level.

Geels and Schot (2007: 404) classify four possible framework conditions: In addition to “regular change”, which stands for a normal, slow, and incremental change at the landscape level and is irrelevant for the dynamic-feedback innovations in focus here, the authors identify the “specific shock” as the second: This is a sudden, strong change which, however, only affects a few dimensions of the landscape. In this respect, this rare event can lead to a serious change for one or a few dimension(s) as well as to a return to the original state. Disruptive changes occur irregularly and slowly. Like the “specific shock”, they affect only a few environmental dimensions. One could cite the environmental movement of the 1980s/1990s as an example, which gradually led to a different environmental awareness in society. The “avalanche”, or avalanche-like change, is fast-moving, intense, and far-reaching change. Think, for example, of war situations, political revolutions, or stock market crashes.

Transition is therefore not the same as transformation, according to Geels et al. (2016: 898): “The transformation pathway consists of gradual reorientation of the existing regime through adjustments by incumbent actors in the context of landscape pressure, societal debates and tightening institutions". Transition means the transition from one regime to another, e.g., the transition from a fossil to a post-fossil regime of energy production and consumption. The strength of MLP lies in the analytical discriminatory power between micro-, meso-, and macro-phenomena in connection with innovations. Weaknesses of the approach can be seen above all in the fact that the approach was originally designed only for post-festum analyses; i.e., it provided technology genesis research of innovations that had already been fully implemented. Furthermore, the connection between the levels remains vague.

Still, this approach is insightful to better understand coal phase-out processes. These are induced politically while creating a "specific shock" for regional adaptation processes. Thus, there are then a lot of niches emerging for aligning this structural change. As these evolutions are multifaceted, the problem of synchronizing the different ways of change is becoming important. In the face of these challenges, the enhancement and renewal of organizational and institutional capacities in the region is a crucial prerequisite to any transformative activities, projects, and business models. Against this background, a university may take a central meditating role and position itself as a long-term partner in regional transformation processes.

When it comes to the transformation task in the Rhenish lignite mining area, multi-level thinking may be refined and specified in three dimensions (Fig. 3). First, it relates to a time dimension: multiple levels (co-)evolve over time. This implies thinking in the form of transformation paths and in throughput rather than only in input and output, thus opening up room for change (Audretsch et al. 2021; Preda and Matei 2020; Sydow 2021). Second, multiple levels refer to different levels of spatial scales—from the individual settlement and fractions of the landscape or infrastructure to the region as a whole and its embeddedness and relations to supra-regional levels of scale, with which different transformation drivers, activities, and effects are associated (Bögel et al. 2022; Förster 2020; Lee 2022). Conditions and transformation impulses of the built and lived environment mutually interplay in between these different spatial scales. Third, transformation processes evolve through the interplay of providing a favorable framework and enabling impulses and initiatives. This means that from a regional governance perspective, top-down and bottom-up meet in a countercurrent principle (Benz 2021; Davoudi 2008; Heinen et al. 2022). Governing of transformation processes must draw special attention to the balance between the coherence of activities and investment in the region on the one hand and the diversity—and occasionally healthy competition and frictions—of players, approaches, and projects on the other hand (Böschen et al. 2021).

The operationalization of multi-level thinking in time, space, and governance is the first step to an ex-ante perspective of shaping the transformation within a region. The specific challenge, however, lies in the manifold combinations of the three different perspectives—that once again is an indication of the open nature of transformation processes and the limitations of planning for them.

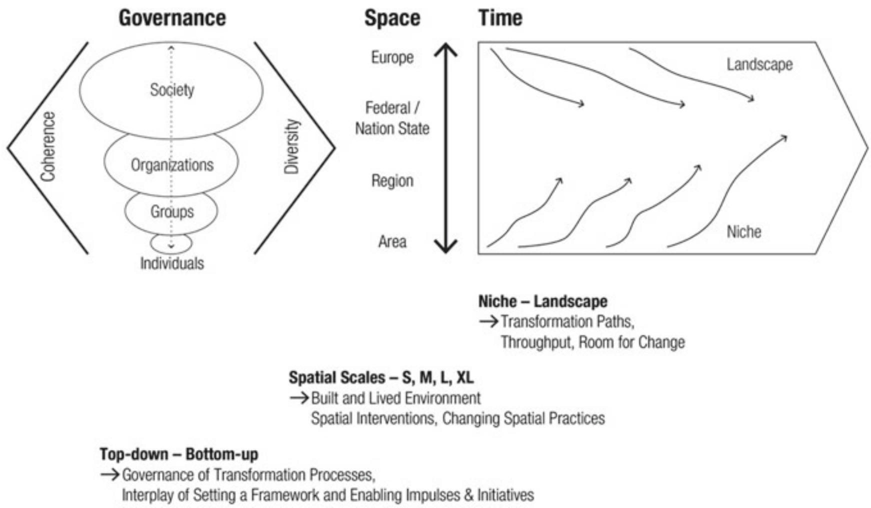

Fig. 3 Specifying multi-level thinking in transformation processes: time, spatial scales, and governance (authors)

2.2 Shaping Transformation as an Open Process

Deliberate shaping and setting of impulses into transformation processes must consider the different layers as well as the inertia and path dependency of the system that is under transformation. There are multiple entry points for effective stimuli and interventions. Beyond the thinking in precise intervention and impact cycles, transformation tends to be shaped in open processes by a multitude of more or less interrelated interventions as well as by effects on different levels. From the perspective of doing and shaping transformation, the following specification of levels and levers seems to be appropriate (Fig. 4) (Förster 2022; Köhler et al. 2019).

(i) Change can be brought about by direct interventions in the built and lived environment of the region. E.g., investments in transport or energy infrastructure are, in many cases, a precondition for attracting new enterprises, a workforce, or tourists. At the same time, the restructuring of the regional landscape—even in an early phase of the regional transformation process—can serve as a tangible impulse to enhance the quality of living in the region as well as to raise awareness among inhabitants for the post-fossil regional future (Bögel et al. 2022; Förster 2020; Förster et al. 2021; von Wirth and Levin-Keitel 2020). (ii) A second, more indirect, level of interventions can be seen in the activation, enabling, and learning of regional actors. Regional transformation processes are closely related to changing roles, ambitions, and competencies of active players—as a precondition for realizing and implementing projects and because of the profound processes of reorientation and change that influence regional stakeholders (Mezirow 2009; Singer-Brodowski et al. 2018). Bringing new players into the region or establishing new intermediaries are important success

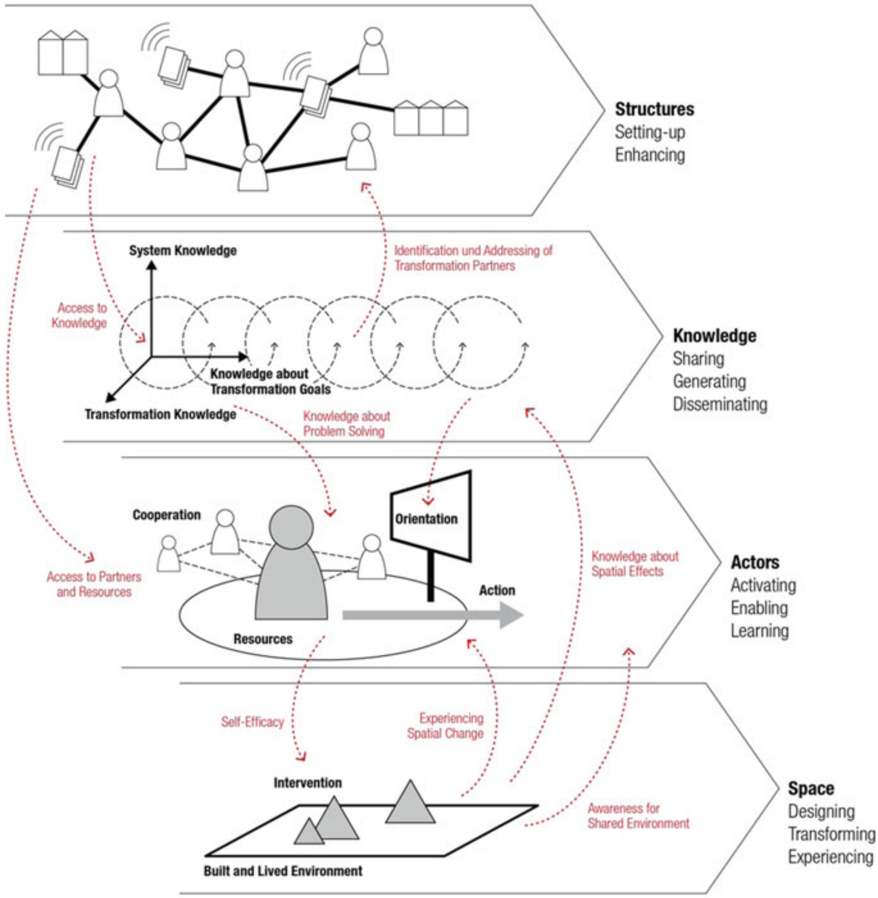

Fig. 4 Interconnected levels and levers of shaping transformation (Förster 2022: 49)

factors in regional transformation processes toward sustainability (Kanda et al. 2020; Kivimaa et al. 2019; Kundurpi et al. 2021). (iii) Thirdly, creating transformative knowledge is an important stimulus for the transformation process. The special feature of transformation processes is the simultaneous change of system, target, and transformation knowledge (Wuppertal-Institut 2013). This is often associated with high uncertainty, a lack of orientation, and even frustration and fear among local and regional communities, employers, administration, and politicians (Abbott 2005; Lamker 2016; Schweizer and Renn 2019). Hence, creating new linkages between the different knowledge domains is a key premise for organizing collective action in view of profound structural change processes. (iv) The most superordinate level of shaping transformation relates to institutions, networks, and governance. Stimulating self-transformation and learning among powerful institutions and governance arrangements is an important prerequisite for escaping path dependency and enabling ecological, economic, societal, and cultural renewal (Böschen et al. 2021).

The four levels of interventions are highly interlinked and can be initiated in different directions—from the living and economic environment within the region to the superordinate level of regional governance, and vice versa.

In the case of a region under transformation, processes on all four levels run in parallel. Within this multi-level dynamic, positive feedback as well as tensions between the different levels may occur. On-site activities may be kick-started by societies, initiatives, or companies that are capable to act in the region. From the perspective of regional planning associations or politics, such a process may be regarded as unsolicited action and impede ongoing planning and programming processes. Moreover, the generation of transformative knowledge in the face of profound transformation challenges evolves in an open and recursive process. This contradicts the high planning reliability that is demanded by local and regional administration.

These interdependencies and tensions in shaping and transforming the region under transformation go beyond the capacities and responsibilities of individual projects, disciplines, and institutions. Yet, the systemic picture of change cannot be dealt with adequately in the mode of an integrated project or a comprehensive approach. Instead, a platform approach might be an opportunity to bundle the knowledge and experience of shaping transformation at different levels—and to enhance the effective combination of transformation impulses in the region.

3 Platform Approach of RWTH Aachen University

The notion of a platform points to an interface, an arena or a physical or virtual room for communication, negotiation, and exchange. Within different disciplines, the idea of platforms plays a valuable as well as a differentiating role. For example, in computing architecture, a platform is an entity for executing programs on a common and unified ground. Or, in media studies, so-called social media constitute platforms for interaction that cause a structural change of the public (Eisenegger et al. 2021). In business, platforms facilitate economic and social activities such as online matchmakers and technology frameworks. This also includes sharing platforms (Derave et al. 2022) or "mobility as a service" platforms to increase the sustainability of transportation systems (Cruz and Sarmento 2020). In the field of cultural and creative enterprises, platform spaces emerge that are based on multi-stakeholder cooperation and link business activities to local communities and territorial development goals (Tricarico et al. 2022). Or, in education, platforms promise more personalized and adaptive approaches to learning (Kem 2022). In public policy design, platforms help to align top-down as well as bottom-up dynamics (Accordino 2013) or promise more adaptive forms of governance and resilience (Djalante 2012). Or, in city development, cities can be described as "participatory platforms for change" (Anttiroiko 2016). And beyond the smart city concept, a platform urbanism is conceived (Caprotti et al. 2022).

Based on these insights and construction designs, the idea of a transformation platform within a structural change process means enabling communication between the different stakeholders in terms of a superordinate forum, establishing a common basis of knowledge and goals, stimulating transformative learning among and between science and society, as well as networking and cross-linking ongoing transformative activities and projects.

A wide alliance of regional and supra-regional partners follows the ambition of transforming the Rhenish mining area into a model region. Since the process encompasses social, technological, spatial, environmental, and economic factors simultaneously in an outcome-open manner, an inherent and interdisciplinary approach is required. For this reason, contributions from adequately oriented research institutions and their facilities are essential. Hence, there is a need for coordination between and within the diverse research institutions.

RWTH Aachen University maintains strong partnerships and collaborations in research and industry, spanning from international research collaborations to national industry partnerships and regional clusters of innovation. In these contexts, the University fulfills various tasks that, besides training the future workforce and advancing research projects, also include research and application support for, e.g., technologies in industry.

Structural change in the Rhenish mining area reflects a diverse network, consisting of various innovation areas with corresponding projects and a wide variety of actors and stakeholders. While there are many initiatives impacting, researching, and acting within the transformation process, the linking up of these initiatives is a complex task. Hence, regional transformation requires the integration of knowledge from the University and by the University. It is the mission of RWTH Aachen University to contribute to the regional transformation process by.

- providing an integrated interdisciplinary knowledge resource,
- setting up transdisciplinary partnerships with regional stakeholders that go beyond project durations,
- strategically pushing education and career paths in direct contact with transformation issues in the region,
- coordinating and bundling the University's activities, investments, and projects in the region to generate spatial impact, and
- strengthening science communication and science engagement among the wider regional community.

Accordingly, the University takes on a broad range of different roles in the transformation process of the Rhenish mining area: Actively investing in and developing sites; it acts as an intermediary to provide knowledge; it initiates and boosts networks and activities; it educates and enables future generations and potentially raises a critical voice in the political and the societal realm (Förster et al. 2022c: 25).

3.1 Setting Up the REVIERa Transformation Platform

In the context of the challenging transformation process in the Rhenish mining area and the role of RWTH Aachen University as a local co-creator of knowledge, the REVIERa platform was established in 2019. REVIERa derives its name from the German word for district, "Revier", with the additional "a" for "Aachen", where the University is located. At the same time, the name can be associated with the French-Italian Riviera coastline, which is very popular with German tourists, creating a reference to a spatial design that combines work, daily activities, and leisure in a livable and enjoyable way.

The platform was established through an interdisciplinary collaboration between three faculties of the University. Since then, the platform and its associated group of participants have engaged in research to help understand the transformation landscape. They have created networks and open spaces, and they have enhanced their interdisciplinary cooperation. REVIERa aims to enable transformative knowledge through creating linkages between the different actors (Förster et al. 2022c).

Since 2019, the platform activities have been established in an open process in a sequence of different groups and rounds of discussion and cooperation (Fig. 5). The core team of the platform consists of researchers from three faculties that bring together knowledge and competencies from urban and regional planning, technical sociology, and business management and controlling. This team also maintains the platform with its ongoing communication process via a website and various social media. Additionally, a steering team with an enlarged circle of 10 expert researchers from different disciplines advises the core team on strategic issues.

In the first round, REVIERa invited interested researchers from all the University's faculties to share their knowledge about regional transformation and to reflect on the

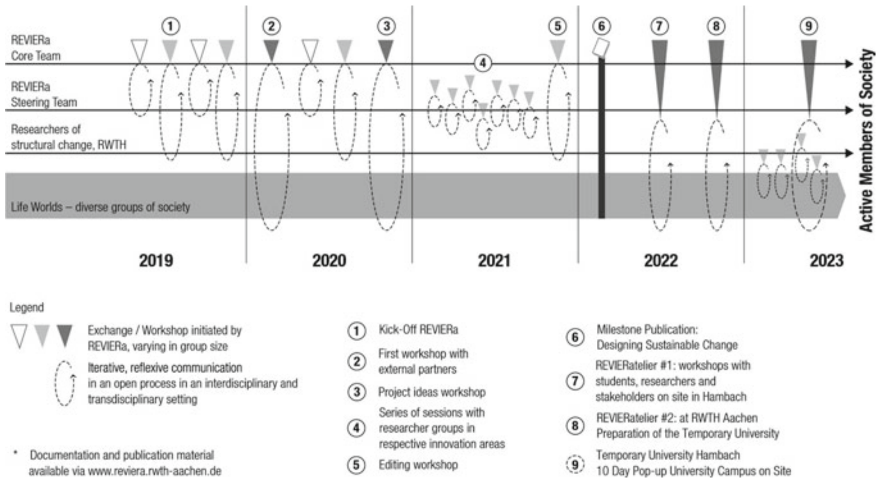

Fig. 5 REVIERa process 2019–2023 (based on Förster et al. 2022c: 32)

University's role in that process. Hence, the platform initiated an inner-University learning process. Soon after the inner-University networking, the platform gave room for encounter and exchange between science and society. From 2020 to 2022, the REVIERa process was very much based on formats such as research and practice workshops—analog as well as digital in times of the COVID-19 pandemic –, interactive forms to promote knowledge transfer and learning, as well as inter- and transdisciplinary teaching (Förster et al. 2022c). In 2022 and 2023, the focus of the platform is shifting toward more specific and on-site co-creation processes with regional players in order to bring the University's knowledge and talents into ongoing transformation activities and to speed up collaborative learning.

3.2 Contribution to the Transformation Triad

This article assesses the contribution of the REVIERa platform with regard to the three pillars of the Aachen Transformation Model (ATM) (see first chapter of this book). The three pillars are "transformation research", "transformational research" and "research transformation". In short, they relate to research concerning the subject of transformation, research which is a stimulus for transformation and the transformation of research itself.

The transformation platform can be primarily assigned to the superordinate pillar of shaping transformation that relates to institutions, networks, and governance (Fig. 4). Beyond that, REVIERa supports the creation of transformative knowledge and activates and encourages regional actors through its participatory and learning formats as well as seniors, junior researchers, and students. Also, REVIERa promotes interdisciplinary collaboration within projects, research, and teaching. Hence, the platform deliberately combines different levels and levers of shaping transformation. But what does that mean from the perspective of research in relation to transformation?

From a research point of view, the platform can be seen as an actor in the ATM transformation triad. The contribution of the University lies precisely in combining three distinct points of contact between research and transformation: to research, to shape, and to enable. Transformation research means to create scientific knowledge that supports ongoing transformation processes as well as the understanding of performed processes. Transformative research directly intervenes into the region under transformation. Research transformation points to the (self-)transformation of the University considering global and regional challenges and is hence associated with inner-University learning processes.

Considering all these aspects, this article addresses the following research question: "How can transformation processes be researched, shaped, and enabled through a platform approach? What is the added value of a platform to the three tiers of research contribution to transformation—and what limitations occur?" To answer this question, we show in the following how REVIERa, as a platform approach, acts regarding the ATM transformation triad.

4 The Dimensions of the Platform

REVIERa, as a platform, acts in and targets the three aspects of transformation research, transformational research, and research transformation. In this sense, the platform approach constitutes a superordinate construct regarding the ATM transformation triad. However, the question arises of how to practice such a platform approach. Here, we showcases for each part of the triad as an exemplary analysis on how transformation processes can be researched, shaped, and enabled.

4.1 Transformation Research ("Research")

Challenges

Transformation research aims to advance scientific knowledge on the complex social, economic, cultural, and spatial interdependencies in transformation processes. It might uncover, among other things, functionalities, operating principles and effect chains, spatial and temporal dynamics, innovation and ex-novation processes, justifications, and possibilities for action. Usually, scientific learning is very much bound to an ex-post perspective on transformation and in many cases gains rigor from comparative research approaches. Furthermore, transformation research is carried out by different scientific disciplines e.g., from social sciences, earth sciences, engineering, spatial development, history, to psychology and medicine. Hence, setting up transformation research in face of a region under transformation, poses three main challenges: First, the temporal perspective is turned from ex-post to ex-ante and real-time scientific support. Second, future-oriented transformation research must find a way to gain empirical evidence in view of the uniqueness and the non-repeatability of the region under transformation and its manifold challenges and processes that occur. Third, scientific theories and explanations of transformation from diverse scientific disciplines and communities must be aligned and interlinked.

Case

REVIERa's platform approach is based on the hypothesis that, in transformation processes, new linkages between system, goals, and transformation knowledge have to be recurringly searched for and established (Wuppertal-Institut 2013). In this process, the questions of who holds this knowledge are crucial. Therefore, actors and arenas and the related methods and processes of communication, negotiation, and cooperation lie at the heart of the platform (Fig. 6). Transformation research can be undertaken in every pillar as well as the respective interdependencies of that layout.

In the initial phase of REVIERa, the focus of transformation research was to organize a landscape of knowledge and competencies of RWTH researchers for the transformation of the Rhenish mining area. The aim was first to gain orientation on the impulses of different disciplines and profile areas and second to better understand

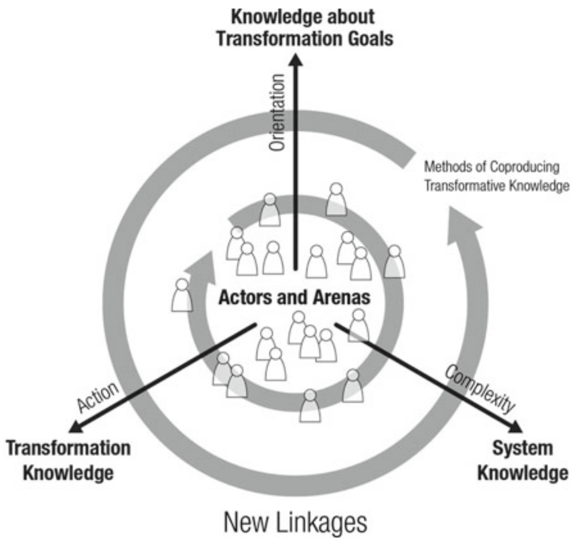

Fig. 6 Basic layout of REVIERa to link up system, goals, and transformation knowledge (Förster et al. 2022c: 31)

their mutual impact. This was a concern from within the University and from the regional partners, who were faced with a confusing multiplicity of projects and partnerships, which had applied for funding during the start phase of the regional transformation process.

REVIERa organized a process of knowledge exchange and structuring among RWTH researchers that led to a series of collaboratively edited materials that were made available open source on the platform. The first step was to gather ongoing projects as well as project ideas from over sixty teams of researchers in a booklet accompanied by a digital map of the region (REVIERa 2020a, b). On this basis and in a series of intense work sessions with researchers, seven core innovation areas for the Rhenish mining area were defined. In each area, a set of innovation stimuli with high relevance for designing sustainable change in the region were specified—and again published as open-source resources (Förster et al. 2022b) (Fig. 7). To complement the research perspective, parallel discussions with active members of society led to the creation of a baseline of perspectives and competencies in society that were also published as a map of "robust" or practical knowledge (Fazey et al. 2020; Förster et al. 2022a; Wuppertal-Institut 2013).

The further processing of the scientific knowledge gathered in the seven core innovation areas included three steps:

First, the over 50 innovation stimuli were assessed by the RWTH research teams on their contribution to the transformation goals, hence, system knowledge was combined with knowledge about transformation goals. More specifically, REVIERa introduced a transformation compass in order to link global sustainability goals to the ambition of the model region. The five dimensions of the compass include: (1) achieve environmental sustainability and climate neutrality, (2) facilitate development, (3) enhance quality of life, (4) establish new forms of value creation, and (5) ensure

Fig. 7 Landscape of the interconnected fields of knowledge of RWTH Aachen University and its research partners (Förster et al. 2022c: 28)

inclusion and participation (REVIERa 2020b, 2022). The assessment within the framework of that compass raised awareness among RWTH researchers for reflecting and positioning their activities in relation to the regional transformation process and to identify blanks as well as trade-offs in their activities between the different compass dimensions. At the same time, the regional players gained clarity on the specific relevance of the different fields of scientific expertise for shaping a sustainable future for their region.

Second, the mutual interplay of the innovation stimuli was reflected by a network analysis (Fig. 7). In this work step, relations between different fields of system knowledge were established. The resulting network reveals potentials for interdisciplinary activities, e.g., the close interplay of impulses in the areas of materials and cycles, production, and landscape with high relevance both for the economic vitality and for the achievement of environmental sustainability and climate neutrality in the region. Another nexus of interrelationships comprises health, mobility, AI, and information, which all have a strong impact on the regional quality of life. Furthermore, the interdependencies reveal possible tensions between different kinds of value chains, e.g., an inner-regional perspective with high quality of living and leisure versus an energy, resource, and production-oriented perspective of the post-mining landscape that may be shaped.

Third, the innovation stimuli were reflected against the background of a multi-level governance perspective (Fig. 8). This exercise was not performed completely, but it was discussed and developed in selected cases during a scientific colloquium. The basic concept is to further elaborate the understanding of the landscape of knowledge by linking system knowledge with transformation knowledge, i.e., knowledge about how to shape, intervene, and act in transformation processes. As a result, one can evaluate which of the innovation impulses can be supported on a local level with a high diversity of different approaches and which issues must be coordinated regionally with high attention being paid to their consistent integration with other innovation areas and impulses.

Added Value and Limitations of the Platform Approach

REVIERa's effort to elaborate a landscape of knowledge in order to support the transformation process in the region demonstrates the importance of linkages and effects between different fields of knowledge—from an interdisciplinary and a transdisciplinary perspective. The platform provides access to different forms of knowledge as well as opportunities and methods for a diverse range of scientists and regional stakeholders to actively participate in this process of knowledge sharing and networking. Analytical as well as visual approaches to support systems thinking are key to managing this interpersonal and crosscutting process.

At the same time, the ambition of achieving a tailored landscape of knowledge for the region under transformation gives the impression of a theoretically and empirically never-ending process. The possible work character of such a tool has not yet been developed adequately—a smart digital solution is needed to make the landscape interactive and to constantly update it. Such an interactive device for inter- and transdisciplinary knowledge visualization and transfer would correspond to the overall platform approach of REVIERa. Despite the ambition of providing a comprehensive view, the integration of more fine-grained qualitative data that might also reveal

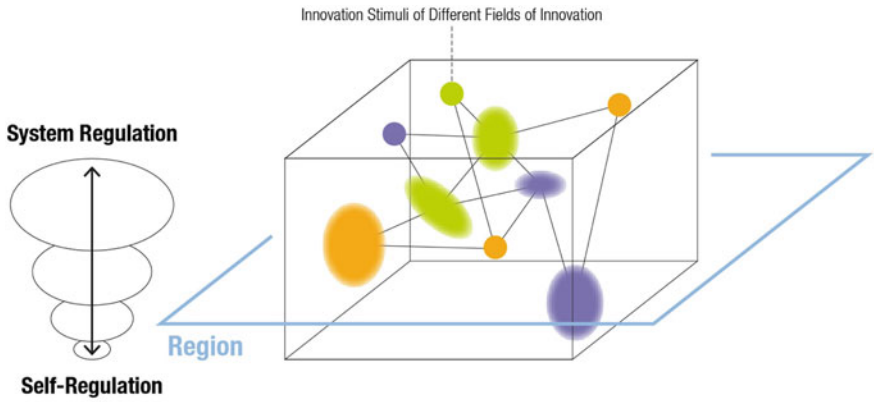

Fig. 8 Conceiving REVIERa's landscape of knowledge in a multi-level perspective (authors)

causal relations is still pending. Beyond the bird's eye perspective of the platform so far, there is a need for zooming in on specific issues, spots, or actor constellations in order to advance transformation research in—and for—the Rhenish mining area.

4.2 Transformational Research ("Shape")

Challenges

The aspect of "transformational research" describes the function of research as an impetus for further transformation. Historic great-scale technological examples would, for instance, be the invention of automobiles or the Internet. However, such transformative moments can also occur on a much smaller scale. Furthermore, the direct involvement of research in the shaping of transformation processes requires strong communicative skills and the ability to meet the motivation and needs of regional partners (Förster 2022). Beyond the motive force of funded projects, trust is an invaluable resource for any long-term cooperation between science and society. Staff fluctuation as well as work overload both within the university and the landscape of regional stakeholders may impede stable contact and confidence building.

Doing transformation can be supported on different levels and by different levers (Fig. 4), more precisely the combination of different interventions enhances the impact of research on the transformation process. For universities and their researchers, the active role in local or regional real-world processes can soon come into conflict with other commitments, such as fundamental research or international networking.

Case

The platform REVIERa aims to create transformative moments by bringing together different stakeholders and disciplines. This follows the concept that latent and tacit knowledge is activated through open-format exchange, stimulating new ideas, activities, and projects, which ultimately shape the transformation landscape. At the level of the platform, transformative research can be conceived as a chain of activities that build on one another (Fig. 9). So far, REVIERa has developed and tested some of these process modules, such as the landscape of knowledge or the transformation compass. However, there is a multiplicity of methods and approaches to stimulate transformative moments in a broad variety of interaction possibilities in the region.

Also, every single step in the chain of activities might unfold transformative power. In the genesis of REVIERa, shaping transformation started with the activation and linking up of diverse groups of science and society. Already in that phase, exchanging knowledge and competencies was a major incentive to participate. The joint debate on transformation goals was another connecting moment between the University and the region. The protected environment of REVIERa beyond political bargaining allowed for an intense and open discussion.

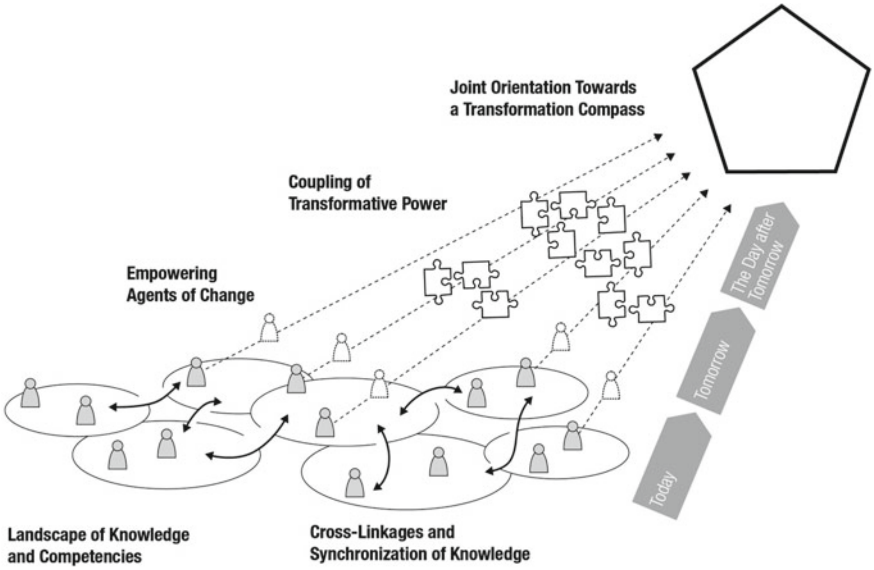

Fig. 9 Set of linkages and interrelated transformative moments in the REVIERa process (Förster et al. 2022c: 34)

Moments of reflection and learning within the REVIERa process are crucial for readjusting expectations and needs from all sides and for further developing participatory approaches. After a series of online formats in times of the COVID-19 pandemic, the request for face-to-face meetings grew. In summer 2022, REVIERa started a collaboration with an intermunicipal initiative around the open mine pit Hambach. Local stakeholders were invited to an interactive workshop format to think about instant projects that might shape the very early phase of regional transformation. The REVIERa team introduced the co-creative method "Future Synthesizer" that allows the linking up of system knowledge ("today"), transformation goals ("the day after tomorrow"), and transformative action and projects ("tomorrow"). Hence, the method enables groups of various stakeholders, researchers, and students to collectively debate and to come into action (Fig. 10). The workshop was run with five parallel groups—each of them came up with their own specific project idea to support the regional transformation process. Hereafter, REVIERa takes up the dynamic of collaboration. Therefore, the Temporary University, as one of the project ideas, is tested in summer 2023, serving as an incubator to further elaborate the transformative projects.

Added Value and Limitations of the Platform

Shaping transformation with a platform approach is an opportunity to complement the operational activities and research projects of the University. REVIERa is situated in distance to traditional funding and institutional or project-based obligations. The platform works at a preparatory level, and it provides room for encounter and

Fig. 10 Impressions from a collaborative work session using the "Future Synthesizer" in the second REVIERatelier in November 2022 at RWTH Aachen University. *Photo* Sebastian Welchlin

exchange unconstrained by tight deadlines and performance pressure. At the same time, the overarching approach is at risk of missing the specific urgency and needs within the region. That is why REVIERa's transformative research approach is—after the initial phase of setting up the platform—linked to concrete issues, sites, and players.

New perspectives of inter- and transdisciplinary teaching, meeting opportunities, and mutual visibility of recent activities turn out to be low-threshold measures to stimulate the platform's connective force between the many disciplines and societal groups. By developing and testing participative and co-creative methods, REVIERa sets the tone for more open and inclusive working formats that have since been taken up and carried forward by various stakeholders in the region. Beyond that, REVIERa's activities fuel the debate about the democratic condition and the levels of openness and inclusiveness of the regional transformation process.

In the long term, the platform will unfold its benefits in close collaboration with transformative activities and projects. Only then will the complementarities develop between focused, but temporarily limited projects and the long-term belief and trust in the platform.

The platform approach raises fundamental issues about the strategy, structure, and culture of the University (see Sect. 4.3). Shaping transformation at this level requires an institutional anchoring, either from an inner-University or from a regional partnership perspective.

4.3 Research Transformation ("Enable")

Challenges

Research transformation describes the transformation of the research culture itself, for example relating to an advancing interdisciplinary cooperation culture. Transformation processes like the structural change evoked by the end of lignite mining are characterized by a widespread involvement of many different stakeholders. This also concerns RWTH Aachen University, which is located in the Rhenish mining area, in relation to the region and its players. Considering the role of the University as a co-creator of knowledge and its aspirations of facing up to global and local challenges, the transformation in the Rhenish mining area is a challenging process which needs to be addressed from different perspectives. For example, challenges concern the ensuring of the energy supply and the maintaining of jobs after the lignite phase-out. Also, the region and the former surface mine need to be attractive for living, leisure, and/or work. The sheer scale of this challenging transformation highlights the need for collaborative efforts. From the University's perspective, activities aim to face the complex transformation process in the Rhenish mining area, which as a bigger picture can only be addressed collaboratively across disciplines. Besides the development of fitting technological and spatial solutions during and after the coal phase-out, connecting the variety of projects and stakeholders within the region is an elaborate challenge.

Case

Again, the aspect of "research transformation" describes a change in the manner of research. The REVIERa platform aims to help the progression of the research and cooperation culture following an open, interdisciplinary approach. These collaborative efforts and approaches are reflected within and supported by the platform in different ways.

First, the REVIERa platform with its three interdisciplinary co-founders has been inherently set up as a cooperation between different disciplines. In everyday operation, this structure has proven to address the challenges within the transformation process from a more well-rounded perspective than a singular discipline could. The co-founders of REVIERa from the faculties/schools of architecture, arts, and humanities, as well as business and economics are able to bring together their spatial planning, sociological, and economic perspectives. Additionally, REVIERa is supported by research assistants and other associated researchers from these and other disciplines, such as engineering. Thus, the establishment of the REVIERa platform is an example for the development of an interdisciplinary, collaborative format within RWTH Aachen University and the surrounding region.

Second, the formats and methods developed and offered by the platform support collaborations between different disciplines and actors. REVIERa's methods aim to support the analysis, visualization, and communication of topics and goals regarding the transformation process in the Rhenish mining area. Inherently, the methods are designed for inter- and transdisciplinary cooperation and knowledge exchange. For example, the "Future Synthesizer" allows not only researchers from different disciplines but also students as well as stakeholders from the municipalities within the Rhenish mining area to work collaboratively. Moreover, the methods and tools themselves were developed in a collaborative, interdisciplinary effort. This is, for instance, reflected in REVIERa's transformation compass, which was defined in a collaborative workshop in 2019 as a set of five goals for the future development of the region.

Third, these activities and the originating research network support and reflect the transformation of the research process within the University. Here, the platform serves as a meta-learning and research space for members from all faculties/schools, profile areas, and groups. With this, the platform encompasses activities of the University in different areas. In the area of teaching, REVIERa has established the umbrella of "networked teaching and learning", where lecturers and students from different courses addressing the Rhenish mining area and the coal phase-out can connect with each other in interdisciplinary meetings. This has led to the collaboration of student groups from different courses and disciplines on joint topics. Additionally, a combined and enlarged knowledge base was supported through interdisciplinary presentation of results from different courses. In the area of projects, REVIERa has made an effort to compile project ideas and enable connections between project leaders, serving as an incubator for more networked projects and initiatives. For this purpose, the platform can offer room for joint reflection on ongoing projects and transformative activities in the Rhenish mining area. Increasingly, the REVIERa platform has become a brand and a component in research proposals with its role of enabling connections and knowledge regarding stakeholders, activities, and needs in the region.

All in all, the occurring inter- and transdisciplinary knowledge and cooperation initiatives can be described as a culture of integrated interdisciplinarity. This culture is essential for enabling stakeholders to address complex challenges like the structural change due to the coal phase-out. Consequently, research transformation toward integrated interdisciplinarity, as supported by platforms like REVIERa, is necessary within any university aiming to address complex future challenges.

Added Value and Limitations of the Platform

An interdisciplinary, collaborative research and teaching culture enables complex problems to be addressed from diverse and joint perspectives. It also supports a common knowledge base and draws attention to future challenges and possible solutions. Thus, research transformation is the backbone and enabler of a desirable transformation process.

However, the efforts of integrated interdisciplinarity cannot succeed without dedicated individuals and groups, because bureaucratic boundaries as well as disciplinary language barriers have to be overcome. Moreover, funding schemes designed for interdisciplinary projects and activities are necessary. Lastly, the changing research process of enhanced inter- and transdisciplinary cooperation itself must be understood, constituting a task for the future.

5 Discussion and Reflection

The previous chapter has shown cases of how the transformation platform REVIERa acts within the transformation triad of the Aachen Transformation Model. In this section, we conclude and focus on the interplay of the triad with respect to the platform approach with its prerequisites and challenges. This yields an agenda for the REVIERa platform, targeted to enhance future understanding of the coal phase-out transformation process. Regarding the three transformation perspectives (Fig. 11), specific interdependencies, commonalities, and boundaries arise in the context of the platform, which are illustrated and discussed below.

Interdependencies Within the Transformation Triad

In the context of the REVIERa platform, we observe several important interconnections within the transformation triad. Regarding transformation research, enhancing the understanding of transformation processes themselves is a prerequisite for transformational research, meaning the shaping of transformation. Transformation research can serve as a reflective approach to ongoing transformation processes, enabling learning from current experiences and comparable regions or related processes. With this, transformation research can make a valuable contribution toward better-shaping transformation. Hence, transformation research in relation to ongoing and upcoming transformation processes needs adequate formats of knowledge transfer that could also stimulate learning among the regional players as well as the scientists involved.

Regarding transformational research, "shaping" a transformation process demands critical reflection and sound evaluation. In general, transformative research programs must carefully integrate methods and moments of reflection. Scientists whose activities shape a certain process should carefully execute and review their activities. This should also be reflected in the activity's governance structure, e.g.,

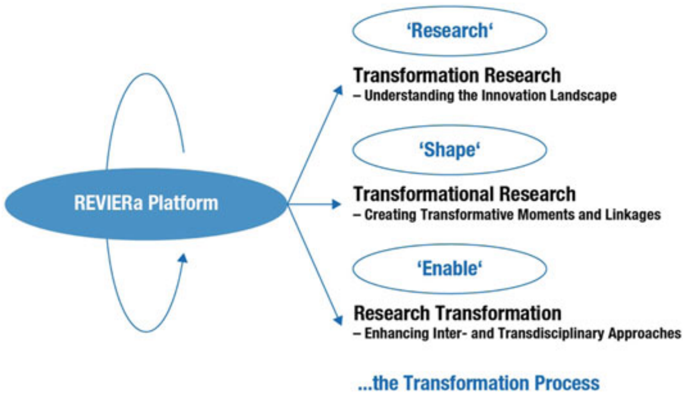

Fig. 11 REVIERa platform acting in relation to the transformation triad of the Aachen transformation model

in the form of setting up scientific teams that consider different roles and tasks and that also manage potential conflicts between them. Consequently, the transformative activities of REVIERa will have to be assessed in the future.

Regarding research transformation, the implementation of inter- and transdisciplinary formats and projects enables complex challenges to be approached, such as the structural change in the Rhenish mining area. While specific issues arising within transformation processes can be addressed from a disciplinary perspective, trans- and interdisciplinary collaboration is needed to address the complex relations within the processes and to approach one issue simultaneously from various perspectives. Given this aspiration, research transformation is a condition for collaborative transformation research.

Finally, applied research might stimulate and promote transformation processes. Thus, in our context, both research transformation and transformation research are prerequisites to be able to shape the transformation process in the form of transformational research. Moreover, ongoing transformation triggered by transformational research has a feedback function: the transformation itself feeds back to transformation research as the object of that research. Also, ongoing transformation serves as a stimulus for the further research transformation that is necessary to address new challenges. In that sense, transformational research serves as a push for research transformation.

Development of Methods

Regarding the work of the transformation platform REVIERa, we find that the development of methods is important for all three perspectives of the transformation triad. Generally, an assessment and methods relating to transformation processes need to be agile and adaptable (Böschen et al. 2022; Häußling et al. 2021). To research transformation and its impacts, it is necessary to understand systemic interdependencies, the formability and elasticity of transition processes and the processes of communication and negotiation. For this, modeling methods and dynamic visualizations can be applied. On a smaller scale, specific activities within a transformation process should be analyzed in a goal-oriented way. Here, life cycle analysis and the consideration of externalities via external costs help to understand concrete aspects of transformation and their impacts on the environment and society. REVIERa's innovation landscape (Fig. 7) is an example of a network analysis which was applied to accomplish a visual overview of innovation impulses of different areas and their interlinkage.

When it comes to research which is transformational, the transformational object, which may be a technology, a shift in mindset (e.g., environmental conscience) or regulatory commands, must be tangible in a literal or superordinate manner. Shaping a transformation process in an inclusive manner can be initiated with the help of participative methods. The goal of such methods is enabling others to handle and discuss complex and uncertain issues. In the context of REVIERa, we aim to enhance future literacy with the help of our collaborative methods and activities in order to eventually enable meaningful transformational moments (Miller 2015; Stuart 2018).

In terms of research transformation, methods and processes that enable interdisciplinary cooperation are necessary on different levels. Overall, to enable an integrated interdisciplinary research culture, appropriate structural conditions are necessary. For a university, this means enabling collaborative research and teaching by creating the opportunities within regulations and administrative structures. For inter- and transdisciplinary research and teaching itself, this means finding, testing, and combining methods for mutual work. With this, the creation of shared knowledge from different disciplines is the prerequisite for fruitful cooperation.

Learning Processes and Integrative Moments

A platform approach has the particular capacity to stimulate mutual learning within the transformation triad. Each pillar of the triad includes learning processes at different levels: "researching" advances the understanding of transformation, "shaping" entails developing the skills, methods and interventions of researchers to stimulate transformation, and "enabling" changes the conditions in which researchers as well as regional partners may research and shape transformation. In the light of the growing urgency of global as well as regional challenges, a circular and recursive approach that pushes forward learning within the transformation triad helps to speed up a university's capacity building and hence to develop as a reliable and effective player in the region.

Generally, we emphasize the need for integrative moments between the three pillars of the transformation triad, since they relate to and influence each other. In our context, the REVIERa platform can serve an integrating function. For instance, the developed "Future Synthesizer" encompasses all three aspects of the transformation triad. The content of the tool was developed on the basis of transformation research. Its application as a workshop tool creates new linkages and transformative moments between different scientific disciplines and social groups. Finally, the synthesizer itself serves as a new means of teaching and researching under the consideration of interdisciplinary perspectives and hence constitutes an occasion of research transformation. A further opportunity for integrative moments within the transformation triad is the "Temporary University Hambach" in summer 2023, taking place in a small village next to the open mine pit Hambach. Researchers, students, and a broad variety of regional stakeholders and community groups can exchange and negotiate knowledge and ambitions from different perspectives and to coproduce transformative action and projects—hence, "researching", "shaping", and "enabling" are closely related in that innovative university format.

Limitations and Open Questions

Despite the significant potential of REVIERa's platform approach for synergistically integrating three distinct points of contact between research and transformation—to research, to shape, and to enable—there are important limitations and remaining open questions that require further discussion.

First, the advancements and learning in transformation research, transformational research, and research transformation show different speeds and temporal rhythms. While transformation research follows (according to funding programs) a rather rigid scheme of a two- to six-year perspective of empirical research, "shaping" transformation requires an agile and responsive project setup, especially when it also entails social processes and learning. In many cases, the process architecture must be readjusted every three to six months—according to a changing inter- and transdisciplinary dynamic and based on moments of reflection and learning. Hence, the recommended integration of transformation research in the processes of shaping transformation is a true challenge. Furthermore, the value of shaping truly open transformational research processes and the consequences for the necessary resources and flexibility in the project design should be further discussed. Finally, “enabling” a university for transformation follows a rather long-time horizon that is significantly influenced by the career paths and cycles of the academic staff. Equally, legal framework and national funding conditions of universities strongly influence the advancements in research transformation. Open questions arise in relation to a diversification of career paths within the RWTH Aachen University and between the University and regional player institutions. How and when in their career can researchers contribute to the different pillars of the transformation triad—with what kind of permeability between the different modes of science?

Second, there are conflicting roles of the RWTH Aachen University and important lines of tensions between the three perspectives of the transformation triad. “Researching” transformation requires a critical distance between the research team and the issue and object of investigation. In contrast, when “shaping” processes, the researcher and research institution are collaborating partners—preferably at eye level—that are very much involved in the transformation process. “Enabling” processes are oriented both to the inside of the university and its disciplines, groups, researching, and learning formats and to the outside with the position and relations of a university within the scientific system—and they are hence on a superordinate and more distant level than the societal transformation processes that are researched or shaped. The preoccupation of a university with itself may be viewed critically from stakeholders of a region under transformation. With regard to the different roles of researchers in relation to transformation processes, we may ask, “What kind of knowledge and awareness do we have of these challenges? What consequences does it have for the setup and management of the platform activities? What kinds of shared as well as deliberately separated roles should be established?”.

Third, a platform is a novel approach for RWTH Aachen University. It implicates difficulties, both in its actual establishing within the University’s matrix structure of faculties/schools and profile areas, and in finding mid- and long-term funding perspectives. Funding is mostly directed toward definable projects with a limited timeframe of funding. Moreover, regional partners still find it difficult to orient and understand the setup, vision, and mission of the platform—since they perceive a polyphony of University approaches, projects, and activities with regard to the regional transformation process. So what kind of governance model is suitable to establish and run a platform like REVIERa in the mid- and long-term? Can the platform be a shared common good and be run following the principle of a cooperative society—which might also include regional partners?

6 Conclusion and Outlook

Overall, this article shows how transformation processes can be researched, shaped, and enabled by means of a platform approach, focusing on the REVIERa platform of RWTH Aachen University and the lignite coal phase-out in the region. Several main findings and further perspectives can be derived from the considerations above.

In the light of the massive ecological, economic, and social challenges, globally as well as on the level of cities and regions, a university of technology like RWTH Aachen University faces various expectations, such as enhanced societal responsibility, providing effective contributions and impulses to solve complex problems, and taking an active role in explaining, discussing, and negotiating its knowledge and innovation stimuli in many different arenas (Brennan et al. 2004; Gilliard 2020). It is becoming increasingly clear that there is a need for contributions of science that go beyond individual projects. To achieve this, however, important limitations of the research and funding systems must be overcome. Moreover, expertise and contributions from technology have to be embedded in fundamental social, economic, and spatial change processes; therefore, new ways of inter- and transdisciplinary integration are needed. A changing role of a university as a partner in transformation processes also brings with it new responsibilities and a raised importance of a university's reliability, transparency, and partnership at eye level.

In response, the transformation platform "REVIERa" was set up in 2019 during the very early phase of orientation in parallel with the political decision-making process on Germany's lignite coal exit. The ambition was to cross-link knowledge and innovation impulses within RWTH Aachen University and to engage as a long-term partner on eye level with a broad range of stakeholders in the Rhenish mining area. The University's scientists agreed that the platform approach would have a model character for other universities of technology and for regions facing other challenges of transformation.

From a science perspective, the added value of the platform is to combine different ways of how science addresses transformation: to research, to shape, and to enable (for) transformation. A platform approach has high potential for fostering learning between the three pillars of the ATM transformation triad, and hence for pushing forward knowledge, action, and implementation as well as institutional capacity for the region under transformation. To make the platform effective, it is important to develop and deploy suitable methods with regard to all three transformation perspectives as well as their interplay. Formats like the REVIERa "Future Synthesizer" have a bridging function within the transformation triad—they represent an accomplished synthesis of "researching", "shaping", and "enabling". In summary, REVIERa's platform approach opens up a broad field of inter- and transdisciplinary learning in relation to fundamental regional challenges and profound and long-term transformation processes.

In the future, it will be crucial to link the platform's activities even better to RWTH Aachen University's landscape of research and transformative projects and to enable recursive learning as well as cross-linking of the related communication and participation activities. Important open questions arise with regard to conflicting roles and lines of tension both between the different modes of science and the various groups that REVIERa addresses. Therefore, it is even more important to accompany the platform’s activities with ongoing monitoring and evaluation—and hence to make use of the capacity of transformation research.

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Transformation Research

Sustainability, the Green Transition, and Greenwashing: An Overview for Research and Practice

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Abstract Against the backdrop of increasing regulatory and societal pressure on firms to transition their activities toward more ecological sustainability, our contribution examines the role of greenwashing in corporate communication. We introduce the reader to current regulations, developments, and practices in the area of sustainability reporting. We also provide guidance for practitioners and researchers on how to detect greenwashing in single instances of communication as well as in large samples of firm-level observations. We then go on to summarize the existing evidence that greenwashing holds predominantly negative consequences for firms. We also explore potential motives behind the practice of greenwashing. Finally, we provide guidelines for firms on their communication strategies and how to avoid unintentionally misleading their stakeholders and being accused of greenwashing. Transparency along a firm's entire supply chain is key in this regard, and digital innovations—such as blockchain—might prove to be integral tools for combatting the practice of greenwashing.

Keywords ESG · Greenwashing · Sustainability

1 Introduction

Sustainability is nowadays a central concept of environmental discourses. Although origins of sustainability can be traced back to the eighteenth century, when "sustainable yield" was first coined as a forestry term referring to the careful management of resources over time, it was in the 1980s and 1990s that "sustainable development" became a guiding principle for international political and social action (Grober 2010; Barnes Hoerber 2013; Seefried 2021). The World Commission on Environment and

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P. Letmathe et al. (eds.), *Transformation Towards Sustainability*,
https://doi.org/10.1007/978-3-031-54700-3_3

Development, established by the United Nations (UN) and known as the Brundtland Commission, advocated in its report “make[ing] development sustainable—to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs” (World Commission on Environment and Development 1987). Referring to this report, the UN Earth Summit, which took place in Rio in 1992, identified sustainable development as a central standard to be adhered to in international politics. Backed up by the circulating of expertise on anthropogenic climate change, the ensuing sustainable development discourse raised the awareness that ecological and developmental problems are closely interrelated. Since then, the terms “sustainable development” and “sustainability” have penetrated into the political, the social, and the economic language with considerable success. Not only have NGOs—such as the German Federation for the Environment and Nature Conservation (BUND)—espoused sustainability, stating that it should be the carrying capacity of the earth and ecological limits that determine the use of natural resources (Macekura 2015).

What is more, firms communicate sustainability primarily in order to balance the three pillars of sustainability, which encompass environmental, social, and economic aspects (whereby the latter are usually take the form of governance targets). In order to group these pillars together, the term “environmental, social, governance” (ESG) has been coined. In fact, since the mid-1990s, firms have been developing sustainability reports and practices that are increasingly replacing traditional methods of communicating Corporate Social Responsibility (Nuhn 2013; Froitzheim 2022). Committing to ESG allows firms to gain or to maintain legitimacy among their stakeholders (Nuhn 2013; Froitzheim 2022). Thus, the corresponding engagement of firms with the three ESG pillars has become a crucial factor for research and practice. Figure 1 sums up the most important aspects of each pillar.

Fig. 1 Overview of ESG dimensions and their main aspects (own figure based on PricewaterhouseCoopers (o. D.) 2023)

The growing relevance of the topic of ESG is further highlighted by the fact that institutional programs are starting to focus on shifting the economic activities toward the integration of ESG aspects into strategic political decision-making processes, thus enabling a "green" transformation. First, in the Paris Climate Agreement of 2015, a total of 196 countries committed themselves to limiting global warming to a maximum of 2 degrees Celsius. Each of the countries then submitted their individual measures or "*nationally determined contributions*" (NDCs) as well as specific long-term low greenhouse gas emission development strategies (LT-LEDS) for achieving this goal (Paris Agreement 2023). Additionally, the United Nations launched their Sustainable Development Goals (SDGs), covering 17 different targets that focus on the commitment to address major global environmental, societal, and economic challenges of current times. These 17 goals are part of the UN's Agenda 2030 ("*Transforming our world: the 2030 Agenda for Sustainable Development*"), which was created in 2015, and they are intended to provide a framework for shaping a sustainable future. All UN member states are expected to achieve the SDGs by 2030. In their "UN SDG Tracker," the UN provide various tools for monitoring goal achievement across the different indicators (available from https://sdg-tracker.org/) (Berrone et al. 2015). In a similar vein, the European Union adopted a Sustainable Finance Action Plan (SFAP) in 2021, with the aim of ensuring sufficient funding for innovations, projects, and firms which place a particularly strong emphasis on sustainable actions. Specifically, the SFAP is primarily focused on the reallocation of financial resources to firms and projects which are having a significantly positive impact on mitigating global warming. Accordingly, the related European Green Deal Investment Plan aims to shift funds of at least 1 trillion Euros into sustainable investment until 2030 (Overview of Sustainable Finance 2021). To summarize, such major projects led by international politics demonstrate the increased regulatory and societal pressure on firms to transition their activities toward more ecological sustainability. They also mirror the rising demand within society for such initiatives.

Given the outstanding importance of transitioning the economy toward sustainability, the monitoring of a firm's performance within each individual ESG dimension is a major challenge of current times. However, it is also the vagueness of the sustainability concept that has made it so attractive for the public and in firm policy: Its meaning differs and the discourse has changed its direction, moving from degrowth to sustainable growth, from ecological concerns to ethical targets of leadership monitoring. As the concept of sustainability is open and ambiguous, it is all the more necessary to ascertain and disclose the degree to which firms communicate a pronounced (symbolic) ESG focus without actually backing such statements up with real (substantial) ESG engagement (Berrone et al. 2015). Due to the lack of audits for CSR reports and overarching mandatory disclosure, information asymmetry exists, which prevents stakeholders from validating firms' claims, and which in turn allows firms the leeway to engage in corporate misbehavior. In the context of sustainability, corporate misbehavior is often referred to as "greenwashing." More specifically, the Oxford English Dictionary defines greenwashing as "the creation or propagation of an unfounded or misleading environmentalist image" (greenwashing, n. 2023). Similarly, the Cambridge Dictionary states that greenwashing comprises the "behavior or activities that make people believe that a company is doing more to protect the environment than it really is" (greenwashing 2023).

It is the goal of this article to elaborate on the practice of greenwashing. To this end, Sect. 2 provides an overview of the state of the art of firms' sustainability reporting. Section 3 explains how practice and research can detect greenwashing. Section 4 elaborates on the consequences of greenwashing. Section 5 examines the determinants of greenwashing, and Section 6 concludes with guidelines for avoiding greenwashing.

2 Firms' Sustainability Reporting

While the importance of ESG-related engagement is constantly growing, the disclosure regulation for ESG is still insufficient to provide market participants with a sufficiently clear picture of firms' activities in this domain (Ramus and Montiel 2005). For a long time now, institutional standards for the disclosure of firm-specific ESG performance have been a rarity. This has led to stakeholders having an informational deficit, which can then cause distrust on their part with regard to firms' claims of sustainable activities. Against this backdrop, the European Union began tackling the existing information asymmetry by developing the Sustainable Finance Disclosure Regulation in combination with the respective Taxonomy for Sustainable Finance. In a nutshell, the regulation obliges financial market participants to disclose the ESG performance of their capital market products according to standards which are defined by the taxonomy. The intention of the regulation is to ease the decision-making process for investors who have an explicit interest in sustainable finance and thus to increase the flow of funds toward sustainable activities and projects (Renewed sustainable finance strategy and implementation of the action plan on financing sustainable growth (o. D.) 2023). However, due to its being limited to products in the financial services industry, the regulation, although providing a necessary starting point, does not ensure transparency on the ESG activities of firms from other industries. Further voluntarily applicable standards are tackling this challenge by delivering frameworks for the disclosure of ESG-related key performance indicators (KPIs) in a regulated manner. The most commonly applied framework is the one provided by the Global Reporting Initiative (GRI), which is an independent and globally active organization that tries to tackle the issue of disclosing non-financial firm-specific data in a standardized way. So far, thousands of firms from over 100 countries have voluntarily committed themselves to respecting these standards (Global Reporting Initiative 2019).

However, without mandatory disclosure or control mechanisms such as non-financial audits, inherent information asymmetry cannot be fully counteracted by voluntary disclosure. While misleading managerial behavior with regard to a firm's balance sheets or financial statements is at least partially tackled through mandatory audits, to date no such rules exist for non-financial reporting. Under such circumstances, firms thus have the leeway to control, to a certain degree, their disclosure of ESG-related data. Under consideration of traditional signaling theory, successful lying should not be possible (Berrone et al. 2015), as all decision-makers are fully rational and can thus safeguard themselves against potentially lying transaction partners. In equilibrium, this would lead to firms having to publish all information truthfully. However, as research has shown, the decision-making of individuals is often impaired by irrational behavior and different behavioral biases, resulting in inefficient information processing. In turn, individuals might assess the trustworthiness of a signal incorrectly, which would consequently allow firms to exploit their informational advantage in order to intentionally mislead their stakeholders. This is done by exaggerating, misstating, or concealing information. As mentioned earlier, such behavior in the context of sustainability or ESG is often referred to as "greenwashing."

Greenwashing can manifest itself in practically every form of corporate communication with a firm's stakeholders: One form in which firms deceive their stakeholders is the direct form, e.g., via official reports, conference calls, conventional advertisements, or social media. Here, firms can place a particular focus on ESG-related topics and claim to have integrated such considerations into their strategic decision-making process. Stakeholders have limited possibilities of monitoring a firm's compliance with such claims. Moreover, firms can also refrain from reporting any negative ESG news or controversy which—for the sake of transparency—should usually be mentioned in such communication channels. From the external stakeholders' point of view, such behavior would be considered to be greenwashing, since information is being withheld which would otherwise be crucial to stakeholders because it directly impacts a firm's reputation. Furthermore, greenwashing can also be observed on the product level. For example, claims of environmentally friendly packaging or production are often found on products nowadays. However, without dedicated certification, such claims are often not verifiable, a situation which enables firms to mislead their customers about the alleged sustainability of a product.

Greenwashing can also occur in advertisements for financial products, e.g., a certain capital market product claiming to be particularly green or claiming to fund sustainable activities, without the products actually fulfilling all the necessary standards. One prominent example of greenwashing in a case of this kind concerns one of Germany's major players in the area of asset management. It allegedly declared various funds to be in line with the requirements for green investments according to the EU taxonomy. However, detailed investigations have recently shown that these guidelines had not been fully met (Gaur and Gaiha 2019). Finally, another aspect that may be viewed as greenwashing is the concealment of any non-ESG conformity of suppliers or other parts of a firm's value chain. This is due to the "black box" character of many supply chains, where a lack of monitoring or traceability means that firms or their products might be depicted as "green" although parts of their value chains are polluting the environment.

In short, common definitions depict the act of greenwashing as firms "sugar-coating" their respective environmental engagement. However, while these concepts and the term "green" tend to only cover the environmental dimension, the idea of greenwashing can nowadays also be applied to the social or governance dimensions of

ESG. For example, one widespread accusation is that firms are symbolically involved in political correctness, while actually refraining from any substantial corresponding engagement. Firms that change their social media accounts' profile pictures to match current movements, such as using rainbow color schemes during Pride Month, have recently come in for criticism. It was pointed out that, in most cases, the firms were not applying any guidelines for diversity within their corporate cultures. Hence, publicly acknowledging the alleged importance of political correctness but failing to actually commit to this issue can only be perceived as marketing tactics of the respective firms.

3 Detection and Measurement of Corporate Greenwashing

A crucial part of examining corporate greenwashing is the possibility of actually identifying and potentially quantifying the level of greenwashing that a firm is practicing. So far, the most common approach to spotting this form of corporate misbehavior is evaluating each firm or product on a case-by-case basis. In order to do this, various particularities are highlighted by the literature, by practitioners, and by related NGOs or other organizations. Thus, in the following, we present the approaches that are most commonly used in practice or research, and we state the benefits as well as disadvantages of each measure.

To generate a broad picture of every form that greenwashing can take, UL (formerly TerraChoice) have assembled the so-called seven sins of greenwashing. This bold expression describes seven conspicuous features that stakeholders can become aware of in order to potentially identify greenwashing on a case-by-case basis. Regardless of whether one may deem this terminology for economic issues adequate or not, the indicators presented by UL can nevertheless be viewed as a guideline for stakeholders to critically assess the information provided by firms and to uncover potential misstatements. More detailed information about the "seven sins" as well as descriptions and examples can be found in Fig. 2.

As depicted by these "seven sins," greenwashing primarily exists through firms either making misleading claims or by remaining silent about potential controversies. In a similar vein, the "ten signs of greenwashing," published by the consultancy agency Futerra, define ten different dimensions in which greenwashing might occur (see Fig. 3). First, firms could use so-called fluffy language, which might not actually consist of incorrect statements, but which lacks a clear meaning and is thus simply blurring the actual information. Furthermore, firms might release particularly sustainable products, which themselves may be "green" but which have environmental issues in some part of the firm's value chain, i.e., a "dirty" firm is producing "green" products. Third, pictures that depict a rather sustainable image could be used to advertise products, without the products actually being aligned with common standards of environmental protection. Additionally, mentioning insignificant "green" attributes of products while the overall product is "brown" can again be seen as greenwashing. A best-in-class comparison is another form of greenwashing, as claiming to be the

Fig. 2 UL's seven sins of greenwashing (own figure based on Sins of Greenwashing|UL Solutions (o. D.) 2023)

most sustainable firm within a controversial industry can mislead customers over the actual environmental performance of the firm involved. Accordingly, alleging that potentially harmful or controversial products are "green" is a further form of corporate greenwashing. Yet another form of greenwashing is the excessive use of technical words or specialized jargon which the majority of customers without the relevant educational or professional background in this specific field cannot fully understand. Further measures to mislead stakeholders include the usage of labeling on products which is designed to be close to true third-party certificates. Such labeling is intended to give customers a false sense of security by suggesting that the products are potentially certified, although they in fact lack external approvement. In addition, firms can also make other claims about a product that are simply not verifiable. Finally, the tenth sign of greenwashing according to Futerra is that of outright lies being told by firms about any relevant attribute of their products (Horiuchi et al. 2009). As can be seen, these ten aspects are closely related to UL's seven sins of greenwashing, a relation which highlights the importance and significance of all the dimensions mentioned.

Although they are rather effective, case-by-case approaches are not very efficient, because each customer would have to analyze each product or service of interest by her- or himself, without making use of any exchange of information with other stakeholders. Thus, different programs, such as the earlier greenwashing index of

Fig. 3 Futerra's ten dimensions of greenwashing (own figure based on Horiuchi et al. 2009)

Enviromedia (Voo 2010), are being developed in order to show what firms or products are associated with greenwashing. Anyone can submit greenwashing accusations to these programs, where the accusations are then looked into and published on an accumulated basis. Although the Enviromedia index was recently discontinued, other organizations have started to aggregate greenwashing accusations made against firms, such as Truth In Advertising (TINA) (2022), the Sustainable Agency (Akepa 2023), or Eco-Business (Hicks 2022). However, while undoubtedly a handy way for stakeholders to find out about any potential greenwashing engagement with a minimum of effort, a major downside of this type of ranking is the still rather subjective input. These organizations primarily rely on individual people alleging that a product, a service, or a firm is engaging in greenwashing, but without fully backing their accusations up with objective measures. Hence, such rankings are used more as a tool for depicting "perceived" greenwashing rather than using factual performance indicators. Additionally, they are usually a binary form of information because they only show whether a firm is engaging in greenwashing or not, but lack any possibility to quantify the degree of greenwashing. In this way, every form of greenwashing is treated similarly, so that, for example, imprecise claims about products lead to the same consequences as does purposely lying in claims about a product's characteristics.

To tackle these challenges when measuring the degree of greenwashing, research has started to adopt new approximations to get a better picture of the extent of greenwashing on the firm level in empirical studies. Several "ESG scores" exist that are built and offered by various data providers and are intended to indicate a firm's ESG performance. However, such an ESG score on its own is not suitable for detecting greenwashing, as it does not exhibit any information about the firm's ESG communication. Thus, one common approach in related studies relies on the ESG disclosures of firms, since it is to be expected that firms which are voluntarily publishing information about their ESG engagement are more concerned about the potential reputational impact of such a focus (Mahoney et al. 2013). Some studies have looked into the length of the ESG reports of firms, proposing that the total extent of an individual report approximates the extent of greenwashing, as it shows that increased effort is being put into communicating a potential ESG focus (Yu et al. 2020). Another measure of greenwashing compares the total funds allocated to both ESG communication and substantial ESG activities. The higher the amount spent on marketing in relation to the underlying measures, the more likely it is that the firm is engaging in greenwashing instead of truthfully advertising its actual ESG engagement (Enviromedia Greenwashing Index|Green Wiki|Fandom (o. D.) 2023). However, this measure does not take into account the time horizon of costs, which might also be crucial for examining the amount spent on certain measures. For example, some ESG-related activities might not have high initial costs, but they do increase concurring expenses over a long time span. Yet, mentioning and highlighting those activities might lead to high marketing costs in the short run, with lower respective marketing costs in the future periods. Therefore, in such a case, a firm might be depicted as engaging in greenwashing in early periods, even when only using the communication channels to advertise its actual ESG engagement.

Another recently developed method to quantify the level of corporate greenwashing is based on textual analysis of specific kinds of corporate communication, such as earnings conference calls, 10-K reports, firm homepages, or social media. By utilizing word lists that identify terms directly associated with the topic of ESG, counting such words relative to the total word count of each transcription first enables a measure to be created for the level of corporate ESG communication. In the next step, ESG communication could be defined as a function of actual ESG performance that is measured by typical scores (e.g., those provided by Refinitiv, Bloomberg, or MSCI). Considering this proposed relation between both measures, the extent of ESG communication is evaluated in relation to the ESG score by using a regression model. In other words, this approach estimates a justified level of ESG communication based on a firm's actual ESG performance. The part of ESG communication that exceeds this justified level is classified as greenwashing (Breuer and Hass 2022). While the utilization of standardized indicators does allow a quite objective measure, one major related concern is the lack of word lists on the topic of ESG topic, which limits the approach to English-language texts only.

In brief, stakeholders can choose from a broad portfolio of measures to identify potential greenwashing by firms or measure the degree to which firms engage in this practice, ranging from case-by-case-based examinations of individual characteristics across to academic measures applicable to large samples of firms. Each approach has its individual up- and downsides and should be selected specifically for each stakeholder's use case.

4 Effects of Corporate Greenwashing

When looking at corporate greenwashing, the potential effects on the respective firm and its stakeholders are a crucial aspect to be taken into account. Thus, research within this area has begun to examine the relationship between firms' engagement in greenwashing and a broad range of financial and non-financial key performance indicators.

According to current studies, customers do not appear to be as gullible as potentially ex-ante assumed by firms, meaning that stakeholders are apparently investing effort to detect any greenwashing by critically assessing information provided by and claims made by firms. This hints at the effectiveness of potential instruments for uncovering greenwashing on the product level, such as examining the "seven sins of greenwashing" individually. Moreover, it is to be expected that with increasing time horizons, the likelihood of stakeholders uncovering potential greenwashing will increase, thus reducing any benefits that greenwashing might have (Testa et al. 2018).

In a similar vein, even when greenwashing remains uncovered, research finds that the excessive amount of ESG communication used in the respective case can, in fact, lead to customer confusion, since stakeholders might not be fully able to differentiate between greenwashing and truthful advertising of the underlying attributes. Hence, customer confusion can prompt consumers to be skeptical about any ESG-related information, even if this information simply depicts truthful advertisement of substantial activities. A consequence of such confusion might then be the full exclusion of any ESG-related specifications from the customers' decision-making process, as long as verification is not fully possible (see the "sin of no proof") (Nyilasy et al. 2014). Beyond that, exaggerated ESG talk can increase stakeholders' expectations of firms' ESG performance and the green features of products. As such, greenwashing can increase the average proposed ESG focus and hence set a higher baseline for the minimal accepted level of ESG engagement (Luo et al. 2012). Combining such higher expectations with the underlying confusion about which information is trustworthy, theory suggests that increasingly skeptical stakeholders might demand, as proof, full disclosure of related information in support of a firm's claims (Milgrom and Roberts 1986).

Turning to firms' bottom lines, greenwashing can in fact reduce a firm's operating performance, which is measured as the operating return on assets. This is due to customers and other stakeholders who have uncovered incidents of greenwashing and have cut their ties to the firm or who treat it unfavorably in various ways, because they feel cheated and are hence losing trust in the firm (Walker and Wan 2012).

Greenwashing can also impact shareholders' perceptions of a firm and thus the firm's market valuation. For example, the literature provides evidence of a detrimental effect of greenwashing on firms' stock prices if the greenwashing has been discovered via external ratings: the greenwashing leads to significantly negative abnormal returns for the respective stocks (Du 2015). Further research looked into market reactions to greenwashing by only taking into account firms that are listed within dedicated "greenwashing rankings," so that cases of greenwashing are included, which might not be detected by externals of the firm. In Breuer and Hass (2022), even a positive relation between a firm's market value and greenwashing engagement is found over the period of one year. However, for longer time spans, the examination also shows that this effect turns negative and becomes more severe with increased time horizons. Consequently, assuming that investors do not exhibit lower levels of information processing than other stakeholders, it appears that investors do not react to the underlying excessive ESG communication itself, but to their expectations of the effect of such greenwashing on the overall firm performance. More specifically, while investors hence may assume a rather positive short-term effect of greenwashing, as soon as they discover its actual detrimental impact on a firm's operating performance, they react accordingly, leading to a decrease in market valuation in the long run (Breuer and Hass 2022).

To sum up: the research so far has failed to find clear evidence for any potential benefit of greenwashing, showing mostly negative effects of this kind of corporate misbehavior. Hence, according to these insights, firms should obviously refrain from making use of greenwashing. However, as both research and examples from practice show, greenwashing still seems to be a widespread phenomenon that is utilized by a large number of firms. Nevertheless, it is difficult to determine the overall degree of greenwashing in a quantitative way.

5 Determinants and Reasons for Corporate Greenwashing

Given the prevalence of greenwashing, taking a look at its drivers is of particular interest. A broad range of determinants have been identified that can motivate managers to purposely misstate their firms' ESG engagement in order to potentially mislead external stakeholders. Therefore, an analysis of the determinants of greenwashing also indicates reasons for this behavior. In general, managers will at least expect some kind of short-term benefits from greenwashing. The literature generally differentiates between four different main drivers that can be broken down into individual sub-factors influencing the level of greenwashing, as can be seen in Fig. 4.

First, various external market factors can lead managers to engage in greenwashing. Due to the high importance of stakeholders' perceptions of a firm and the respective firm's image, stakeholder preferences should shape a firm's strategy in general (Berrone et al. 2015). Hence, managers should take into account the different preferences of consumers and investors. For example, new insights from research show that investors have also started to acknowledge the importance of ESG and might even be willing to forego parts of their return to invest into stocks with a particularly high ESG performance (Riedl and Smeets 2014). Due to the corresponding costs of integrating actual substantial ESG measures, the growing demand for this topic among different kinds of stakeholders can lead firms to simply increase their communication of such a focus without truly engaging with any ESG dimension. Similarly, if competitors are perceived to be raising their ESG commitment, this can

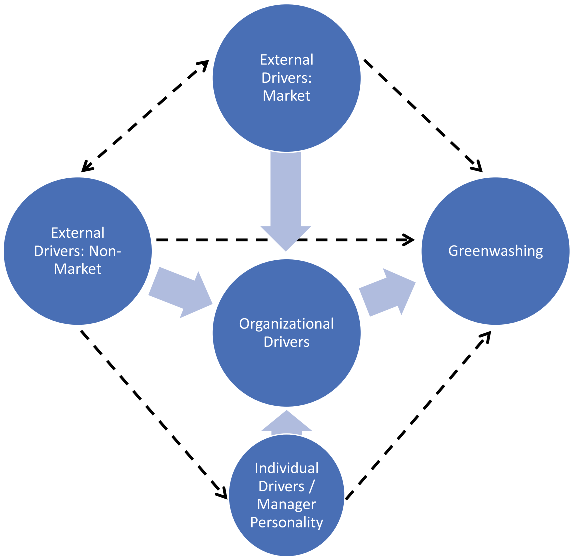

Fig. 4 Drivers of greenwashing (own figure based on Delmas and Burbano 2011)

motivate managers to act accordingly and to use greenwashing as a quick and cheap measure to match the competition.

Besides these market-related factors, institutional (non-market) forces can influence a management's decision to misstate a firm's ESG performance as another external driver. In this context, the possibility to monitor a firm's related activities is a major determining factor for the decision to utilize greenwashing: If the institutional disclosure regulation grants enough leeway to either misstate an exaggerated ESG focus or to conceal potentially harmful information, a firm's management might be more prone to take advantage of such latitude. Similarly, a lack of NGOs critically assessing related claims can increase the likelihood of greenwashing. Managers might further be more prone to engage in greenwashing in the absence of critical news about potential corporate misbehavior: If news agencies have not reported other forms of corporate misbehavior in the past, firms might perceive less of a hurdle to strategically practicing greenwashing, since, even if the greenwashing were to be unveiled, the news might not cover this topic in the future either.

Moreover, besides these external determinants, firm-specific internal drivers are also of importance. In this vein, psychological characteristics of the top management team can crucially influence strategic decision-making processes. According to upper echelons theory, a manager's experiences and personality significantly shape the behavior within a firm and hence respective firm outcomes (Hambrick 2007). Therefore, behavioral biases and individual preferences, such as overconfidence or hubris of managers, time preferences, as well as potential striving for reputational gains, are major factors for determining a firm's strategic ESG communication. They can hence also lead to increased greenwashing engagement. For example, more narcissistic and short-term-oriented managers should be expected to be more prone to engaging in greenwashing compared to any altruistic or long-term-oriented peers (Delmas and Burbano 2011; Petrenko et al. 2014).

Additionally, internal organizational forces can also increase the likelihood of greenwashing. If a firm shows a rather weak corporate governance structure, then misbehavior by the top management team might go undetected or unpunished. The necessity of disguising or overshadowing certain activities or news potentially stemming from previous controversial practices and the corresponding lack of honesty on the firm level is another factor that can motivate engaging in excessive ESG communication as some form of distraction. For example, in the case of recent firm-specific controversies, the respective management might be incentivized to rely on greenwashing to shift stakeholders' focus on those topics and away from the mentioned controversial parts. Furthermore, firms might simply lack the financial resources to actively engage in CSR-specific activities or to invest accordingly, so that relying on CSR communication alone becomes the only possibility to somehow address the increasing stakeholder demand for this topic, thus further leading to potential greenwashing.

Finally, the specific drivers of greenwashing can affect each other in a similar vein, which would in turn lead to an additional indirect (moderating) impact of each driver on greenwashing. First and foremost, all external forces as well as managers' personalities can significantly shape a firm's organizational processes, such as its firm culture, hierarchy structure, and monitoring processes, which can then in turn influence a management's decision about whether to engage in greenwashing or not. Furthermore, external market- and non-market-related forces often show strong interrelations: On the one hand, markets are an important factor for the decision-making process of institutional forces, especially considering the integration of new or the adaption of existing regulation. On the other hand, the outcomes of such institutional forces might shape the behavior of market participants.

To summarize: despite research pointing out a rather negative impact of greenwashing on financial performance, managers may have multiple motivations to nevertheless engage in greenwashing. Disguising other corporate activities, fulfilling external demand without bearing the costs of substantial ESG measures, managerial overconfidence, inefficient information processing, and wrong expectations are only the most prominent ones.

6 Guidelines for Avoiding Greenwashing

Now that we have described how greenwashing tends to turn out for a firm as well as assessing potential drivers of this practice, this subchapter depicts broad guidelines for how firms can prevent being accused for greenwashing. In doing so, we take the perspective of firms that do not have the intention of being misleading about their ESG efforts and performance. Given that stakeholders have become increasingly vigilant about the issue of greenwashing, unintentionally poor communication strategies can also lead to firms being accused of greenwashing. Within their report "Understanding and Preventing Greenwash: A Business Guide," BSR provides a comprehensive step-by-step framework which presents a checklist consisting of 14 questions to help firms to avoid inadvertently engaging in greenwashing, divided into the three categories "impact," "alignment," and "communication" (Horiuchi et al. 2009).

First, "impact" refers to the content of statements and proposes that firms should check every piece of information that they state for its relevance, its correctness, and its usefulness before they disclose it. Therefore, companies should only publish statements if they believe the content is compelling and adds value for stakeholders. Moreover, in this case, companies should ensure that they have put sufficient (financial and HR) resources into verifying the underlying facts and sources and that they therefore do not disclose misinformation. Otherwise, unfitting information, especially if it could be perceived as unreasonable given a certain firm's background, or false/unverified claims might cause consumer confusion. This confusion can in turn lead to customers refraining from buying products or services from the firm. If parts or sub-goals of the claims have already been achieved, this information should also be communicated.

Next, once a company has assured itself of the adequacy and correctness of the information, it must further ensure that other corporate activities are in line with the quintessence of these statements. In order to do this, there must be consistency across all divisions on the issue in question. It should also be checked in advance whether other products, services, or activities of the company are consistent with the respective claims and that they are neither contradictory nor ambiguous, which might otherwise lead to potential confusion and controversies. To increase the credibility of the communicated information, firms should further strive for support via third-party rankings, labels, or certification to strengthen the trust among their stakeholders.

Finally, the way in which statements are communicated is of crucial relevance as well. It is important that all information is presented clearly and understandably for the average consumers of the respective target group, without embellishing statements with potential technical terms or any form of self-glorification. This further strengthens the trustworthiness of the respective firm's communication in general, which is another major factor in this regard. Additionally, if applicable, firms should consider using data or other sources to prove the correctness of their claims (Horiuchi et al. 2009).

In short, both transparency and the ability to verify data are crucial for avoiding greenwashing. As long as stakeholders do not have any possibility to validate the environmental performance of each individual part of the supply chain, firms have the leeway to hide controverse parts. Yet, current trends—especially regarding the development of digital innovations—have at least begun to counteract such problems. In this vein, firms have started to integrate the blockchain technology to better track every section of their supply chains (Hastig and Sodhi 2019). Generally speaking, a blockchain can be described as a decentralized, growing, and expandable collection of individual datasets, which are all linked together through cryptographic hashes that combine each data block and prevent manipulation of the whole blockchain. While so far, blockchains have been primarily known for their usage in cryptocurrency networks, firms have acknowledged their usefulness in other parts of their operating procedures. In the context of supply chain traceability, a blockchain can thus create a chronological and tamper-proof database which covers all necessary information about every party in a firm's supply chain. Because of the inability to ex-post manipulate existing data packets on a blockchain, firms can ensure that no party within the supply chain fakes their respective entry. This limits the ability to engage in greenwashing through the concealing of non-complying suppliers (Global Reporting Initiative 2019). However, since technologies like these with the target of decreasing information asymmetry are only at their outset, the problem of greenwashing within a firm's supply chain will remain, overall, an ongoing issue in the near future.

7 Conclusion

Both scholars and practitioners have successfully developed specific guidelines for avoiding greenwashing. Nevertheless, there will continue to be firms that communicate the impression that they are acting more ecologically and socially responsible than they really are. However, much has changed in the sustainability discourse and in ESG reporting procedures since the 1990s. The emergence of ESG has triggered a new momentum in the transitioning of economic behavior toward environmental protection. In the same vein, the concept of sustainability has contributed to a greening of the (global) economy (Graf 2019).

That being said, there is still room for improvement. In particular, transparency regarding a firm's ESG engagement is to date still inadequate, leading to informational asymmetries between firms and their respective stakeholders. While current regulations are trying to tackle this problem, the impact of those institutional actions on this issue is limited, implying an open challenge. For example, the EU taxonomy and disclosure regulations oblige certain participants on the capital markets to publish mandatory statements regarding both their firm-specific ESG performance and the alignment of their capital market products with the respective standards of the EU taxonomy. However, as this procedure is still only restricted to firms within the EU financial services industry, the majority of global firms are still not bound to any form of mandatory ESG disclosure of (auditable) reports. Therefore, to date, firms still have the leeway to exploit such asymmetric information, which results in an ongoing problem of potential greenwashing, an issue which stakeholders must be aware of.

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Infrastructures and Transformation: Between Path Dependency and Opening-Up for Experimental Change

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Abstract Infrastructure development faces multiple challenges in the present. These are generated by digitalization, ecological orientation, transformation, and the emergence of a multipolar de-colonial world order. Under these conditions, infrastructure development faces the problem that, although designed for stability and continuity, it requires a new flexibility. To address these issues more precisely, this article first proposes a heuristic for studying infrastructures in times of transformation and tests it with two examples. In it, it is shown that the qualification of future infrastructure development lies in the characteristics of scalability, inclusivity, and updateability.

Keywords Transformation · Infrastructure · Socio-technical change · Energy transition · Structural change

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P. Letmathe et al. (eds.), *Transformation Towards Sustainability*,
https://doi.org/10.1007/978-3-031-54700-3_4

1 Infrastructures: New Challenges with Regard to Their Design

Infrastructures form the backbone of societies. Typically, specified functions such as mobility, nutrition, health, or even electricity supply are ensured in this way. Infrastructures are characterized by their normality, by their working in the background, as it were. In industrial modernity, with its expansion of positions of entitlement and thus the demands for the realization of the common good, the significance of infrastructures has taken on a completely different dimension. This is also reflected in a current definition of infrastructures, which are described as "networked plants and facilities that are geared to the provision, storage, and transformation of products for collective use (common good) and, as social inputs, determine the social, economic, and ecological conditions of life in a spatially specific manner" (Kropp and Sonnberger 2021: 189; translation the authors). Infrastructures are characterized by their stability, but at the same time, they are changed more or less imperceptibly. If, however, infrastructures are fundamentally technically rearmed and realigned, then a transformation space emerges in the process, in which it is quite obviously no longer only a matter of technical, but also of social and cultural changes. In the present, infrastructure development is receiving new attention due to developments that have brought the "vulnerability" or "criticality" of infrastructures into the spotlight.

To describe it with a short example, the flood disaster in North Rhine-Westphalia in the summer of 2021 clearly showed how dramatic the need for adaptation to climate change is, even in Central Europe. At the same time, it has highlighted the particular sensitivity of critical infrastructures (water and wastewater, transport, rescue and telecommunications, power supply, and telecommunications). The reconstruction of these infrastructures is of particular urgency. At the same time, however, this reconstruction also opens up the opportunity to create new, more flexible and adaptable infrastructures for the future and to turn away from old ones and systems. This catastrophe thus also offers an opportunity for renewal. As another example, following Russia's war in Ukraine, wholesale gas as well as electricity prices in Germany rose rapidly due to restrictions on Russian gas supplies. This affected many industrial companies as well as households and has put pressure on policymakers to find an immediate solution. One result was that Germany built terminals to use liquefied natural gas (LNG) to at least partially replace Russian gas. In addition, these terminals are planned to be adaptable and to supply liquid hydrogen in the future, which the German government calls "green readiness" (Bundesregierung 2023). However, for several reasons, retrofitting these existing terminals may be quite difficult, which is why these potential switches are best addressed in the context of their design and processes of being established (Schreiner et al. 2022).

These are only the first hints that the question of adaptability of infrastructures has to be seen as highly challenging. In any case, it cannot be a matter of reconstruction alone. The real task is to make infrastructures adaptable to future development demands at the time of their (re-)construction. This is also evident, albeit in a different way, with regard to transformation processes such as the one in the Rheinish mining area. Old infrastructures must be ex-novated, new ones built, and at the same time future development options must be anticipated and taken into account now, i.e., it has to be materially anchored in the infrastructure. This presents itself as a multi-layered problem. Infrastructures are typically a haven of stability and longevity. This is why they are typically constructed to provide services of general interest continuously and safely over a longer period of time. Moreover, infrastructures are associated with socio-technical path dependencies. The maintenance and stability of legacy infrastructures are largely due to generic principles of path dependency (David 2007) in different domains. Infrastructures are stabilized by "increasing returns" (Pierson 2000), which create incentives for policymakers, investors and planners, among others, to deepen a particular path and to make it even more costly to switch to another one. These developments are often supported by institutional designs that place advocates of a particular path in a privileged position, creating political resistance to any substantial change and making incremental change much more likely (Mahoney and Thelen 2010). Paths can also be understood as an artifact of (aggregated) behavioral patterns, such as daily routines or personal habits of using infrastructure in a certain way (Seto et al. 2016). These patterns are not reinforced by conscious rational choices, but by routines and institutionalization, which makes them difficult to change. These path dependencies can create very strong configurations that lead to technological, economic, political, and behavioral lock-ins, such as the carbon lock-in described by Seto et al. (2016), making it unlikely to switch to alternatives. Theoretically, the MLP approach describes such processes of innovation diffusion—and its difficulties. Technical developments are protected in a niche environment (e.g., subsidies) and enter the socio-technical regime when an window of opportunity emerges. The specific socio-technical regime and the overarching landscape are influencing, often blocking, the diffusion of new options. However, there might be changes by the transition of the innovative technology (Geels 2002; Geels and Schot 2007).

Research on infrastructures has experienced a renaissance in recent years (e.g., Larkin 2013; Howe et al. 2016; Pinzur 2021; Kropp 2023). While research in the 1980s focused mainly on the emergence and control of large technical systems (for many: Hughes 1993), the concept of infrastructure is now being further differentiated in very different subfields of social science research in order to investigate the specific dependencies and particular patterns of collective order formation (Barlösius 2019). Looking at infrastructures that way offers an insight in their multi-layered working unfolding not only the named function (e.g., mobility), but at the same time inscribing and stabilizing social injustice as well as developmental narratives, beside others (Larkin 2013). Through the classifications and determinations embedded in infrastructures (Bowker and Star 1999) and their independent dynamics, there are specific forms of infrastructural power performed. Bowker and Star (1999: 321) stated: "We need to recognize that all information systems are necessarily suffused with ethical and political values, modulated by local administrative procedures. These systems are active creators of categories in the world as well as simulators of existing categories." Infrastructures are not simply passive networks of artifacts, to the contrary, they are in action (Pinzur 2021). In this sense "(…) infrastructures were not only momentary subjects of contestation, but also ongoing means of exerting power through discretion over indispensable, everyday labor" (ebd.: 647; emphasis in Orig.) Notwithstanding this, the aspect of the dynamic change of infrastructures and their form typically remain in the background, even if this aspect is described by Paul Edwards with his idea of infrastructures as "posing a linked series of socio-technical problems (…)" (Edwards 2004: 209). Infrastructures are examined from the perspective of the articulation and solution of socio-technical problems. Following Edwards' considerations, the concept of socio-technical problems has been further specified (cf. Büscher et al. 2020). Important here are theoretical connections that allow to capture the diversity of processes of defining and dealing with socio-technical problems. In the abstract, socio-technical problems can be examined according to the aspects of "control despite complexity," "change despite stability," and "agency despite opacity" (Büscher et al. 2020: 13). It is these fundamental tensions that have always determined infrastructurization, and which can be examined very precisely in their form determining everyday practice from a practice-theoretical perspective (Shove and Trentmann 2019).

Currently, there are various overarching developments that challenge the maintenance and further development of infrastructures. These include the technological development of smartification (cf. Lösch and Schneider 2016), ecological integration (cf. Kropp 2023), transformation (cf. Cass et al. 2018) and, finally, the emergence of a multipolar de-colonial world order (cf. Larkin 2013). If one takes these developments together, then these changes reveal, on the one hand, an expansion of control possibilities through new socio-technical arrangements of infrastructures. On the other hand, entirely new forms of vulnerability are emerging. For example, the digitalization of infrastructures creates both new opportunities, such as the instant availability of information and data, and new risks, such as cybersecurity issues. Infrastructure development in such a present, which can be described as transformative, should continue to enable the stable provision of services for the common good, but the definition of the common good becomes more open, but even more and especially the previous conditions under which the operation and further development of infrastructures were assumed, change along with it and cannot simply continue to be assumed. This is shown, for example, by the many challenges for the design of future infrastructures in a "non-stationary age" (Chester and Allenby 2019), meaning that previous conditions of infrastructure design are no longer applicable to the status quo and beyond. For example, in civil engineering or urban planning, conventional weather data can no longer be used in the context of climate change, as weather extremes have already changed and are likely to become more severe in the future. Similarly, in the social sphere, the conditions for designing infrastructure have become more participatory and less hierarchical over time, creating space for different modes such as collaboration, negotiation, persuasion, compensation, etc. Finally, in the economic domain, massive productivity gains in the construction of infrastructure need to be gauged against the often highly increased complexity, and lifetime changes of systems and system components, affecting profitability of investments, adequately taken into account. In sum, these processes introduce new vulnerabilities, as they can slow down urgently needed steps to mitigate climate change, such as the construction of wind turbines or new transmission lines.

Therefore, it seems to be a reasonable claim to have a correspondingly adapted conceptually theoretically motivated investigation heuristic available against the background of the aforementioned development dynamics and the associated confusion of relations and ties in infrastructurization. In order to embark on this path, a greater sensitivity regarding different socio-technical forms of infrastructure development and their explanation appears relevant. To achieve this goal, two elements seem to us to be of particular importance. First, it is essential to identify the different elements that characterize such mentioned forms. For this purpose, we propose a search heuristic based on social-theoretical dimensions, but without understanding them as theory dimensions. Rather, they serve us as an exploration procedure. Second, we make a theoretical proposal that serves to disentangle the web of relevant references in each case. Therefore, for example, the observation of economy, which is of great importance for such processes of infrastructural change, does not appear on the level of the heuristic dimensions, but rather on this level of relevant factors for the formation of socio-technical ensembles. In doing so, the argumentation is enfolded in three steps. In the first step, such a heuristic is outlined, whereby we will as first sketch highlight especially five heuristical dimensions: factual dimension, social dimension, time dimension, spatial dimension, and environmental dimension. In doing so, we would like to emphasize that we do not reify these dimensions as a priori major categories but recognize here solely their heuristic value for sorting a confusing situation. The fruitfulness of such a heuristic, however, can then only become apparent in the concrete analysis, in which precisely the moments of hybridity and mutual constitution are of central importance. In addition, the innovation theory of Rammert (2010) will be used to point out that it is the individual or linked references to social fields (such as the economy, politics, civil society, art, etc.) that help to describe an innovation event and the specific valuations taking place (Sect. 2). Following this, two concise vignettes will be used to make the heuristic useful. On the one hand, the two vignettes deal with infrastructures in structural change; on the other hand, the energy transition through renewable energies and the accompanying requirements for the development of flexible infrastructures are discussed (Sect. 3). Finally, the following chapter will focus attention on the design of future infrastructure developments. Thus, the question is of how to rethink infrastructures for making them at the same time stable as well as flexible for the respective challenges. More focused: Can infrastructures, although being the epitome of societal stability through materiality, be reshaped in a way to be agile, inclusive and updateable—and, if so, how? (Sect. 4).

2 Development of a Heuristic

If one takes the dynamics of socio-technical problems and their processing as the central perspective in the maintenance and further development of infrastructures, then this is a decision in favor of a fundamentally experimental understanding of infrastructures. This is because the articulation of socio-technical problems and an innovative action triggered by them opens up scope for groping, testing, and stabilizing solutions. It is a perspective in which the ongoing balancing of technical and social innovations keeps infrastructures stable. Typically, technical and social innovations are treated as opposites. However, this is a problematic positing. This fact has recently been brought into focus, particularly through a social innovation perspective (see Howaldt et al. 2018). Based on a practice-theoretical reading of social innovations, these can be understood as "creative and purposeful changes in social practices, i.e., changes in the way we live, work, and consume, how we organize, and how we shape our political processes." (Howaldt and Schwarz 2010: 6; translation the authors). This has the advantage of actually capturing those innovations whose focus is very much on the establishment of new social practices. At the same time, however, it can equally be used to study the reconstruction of socio-technical practices, namely as the imitation of functionally specific patterns of action promising improvements and possessing technical qualities (e.g., Howaldt et al. 2018).

In the context of infrastructures, this interweaving of social and technical innovations takes on yet another significance. In fact, it can be argued that the special quality of infrastructures is precisely that they require a synchronicity of technical and social innovations. Otherwise, socio-technical problems cannot be transformed into socio-technical innovations. In order to further specify these considerations in the following, two argumentative steps will be taken. First, for the investigation heuristics of infrastructural development barriers, a sorting of relevant aspects according to the social-theoretical dimensions of factual, social, temporal, spatial, and ecological will be carried out (Sect. 2.1). Second, it is crucial not only to show such relations, but ultimately to be able to decipher the patterns of configuration. To this end, we argue on the basis of Rammert's (2010) theory of innovation, which presents a model of relations and references, that the specification of references (meaning always references to selected fields of society, such as economy, science or law) can make visible in which intricate relations infrastructure maintenance and development sometimes takes place (Sect. 2.2). Taken together, the confusing challenges of infrastructural change can be made visible in this way.

2.1 Relations of Infrastructural Change

When we speak here of relations of infrastructural change, we are referring, on the one hand, to the relations within the individual dimensions, which contain selected aspects of the socio-technical construction of infrastructures. The respective weighting of these aspects creates relations and thus makes specific qualities of infrastructures visible. On the other hand, this also refers to the relations between the dimensions, which are configured differently depending on the respective socio-technical development situations of the infrastructures studied.

Factual Dimension: Materiality, Functionality, Interconnectedness. Materiality is an anchor of stability (Latour 1991). Materiality points to a fundamental quality of sociality, even though sociality was for a long time designed precisely without the aspect of materiality (Appadurai 1986; Bennett 2010; Coole and Frost 2010). Once arrived at, however, multi-layered questions of relationality then arose. Does material agency represent itself as resistance alone? Can material agency be for itself? Pickering (1993) made this concept of material agency prominent as the "mangle of practice". Such material agency does not exist by itself, but only in its entanglement with human agency. His example of scientific experiments in particle physics traces a long historical process of mutually adapting scientific instruments and theories. A dynamic linkage of these forms of agency can be seen in the concept of "imbrication" (Leonardi 2011) or "interaction scenarios" (Schulz-Schaefer and Meister 2017), whereby prototype scenarios, in which designs of technical objects are brought into an interaction context with people, emphasize precisely the relevance of the material (cf. also: Ryghaug et al. 2018). Importantly, technology is not to be understood simply as an artifact, but rather as a product of social processes (Bijker and Law 1992) in which it is framed for specific functions. For a long time, it was assumed that technology had its own logic, which would lead to the fact that the formation of social order could also be explained by the formation of technology. Such a technological determinism has repeatedly imposed itself against the background of the insight into the overwhelming impact of technical artifacts and ensembles of the technical. At the same time, however, it falls short and is empirically and theoretically of little use. Rather, the development of technology already shows how strongly social conditions are not only inscribed as functions in technology, but also contribute to the stabilization of social conditions. This becomes particularly obvious when we look at socio-technical systems (e.g., Mayntz and Hughes 1988; Büscher et al. 2019). Here, too, it is true at first that due to the networked, complex, and large-scale technical configuration (interconnectedness), the moment of the factual appears on the front stage, but at the same time, a closer look reveals how strongly the formation of technology is directly interwoven with processes of collective order formation. This is also evident with regard to networking as another quality that is essential here. Networking refers to the character of the ensemble, which makes it clear that it is not the individual technologies, but rather their interplay in which infrastructures unfold. This applies in particular to the design of infrastructures as networked or smart infrastructures (e.g. Marcovich and Shinn 2020; Marres and Stark 2020; Lösch and Schneider 2016).

Social Dimension: Identity, Cooperation, Participation. Infrastructures have an institutional character. The functions of services of general interest relate to areas of action that are of outstanding importance for societies: Health, nutrition, mobility, and energy, as it were as basic infrastructure. Practices of everyday life take place in relation to infrastructures and influence them (Shove and Trentmann 2019). Three aspects seem to be of particular importance for a closer characterization. The aspect of identity allows us to break down the interconnected and mutually stabilized relations of actors, institutions, cultural classifications, and political economies (cf. Bernstein 2005). The concept of identity derives its importance and explosiveness from the fact that it is fundamentally positioned at the intersection of individual agency and politics (Hall 2000: 16). It is, as it were, a two-way process that establishes, on the one hand, what is considered a "we" and, on the other, positions this against a "you" (for an overview, see Wetherell 2010). The aspect of cooperation, on the other hand, emphasizes the interplay of actors in infrastructuring and thus in articulating as well as solving socio-technical problems. Infrastructuring in the present is much more dependent on cooperation than in the past; protests against infrastructure projects illustrate this: NIMBYism is the refusal of certain forms of cooperation (Schwenkenbacher 2017). At the same time, infrastructures open up new opportunities for cooperation, if one thinks of the very different digital platforms, for example (using the example of Citizen Science: Dickel and Franzen 2016). Finally, the aspect of participation refers to the legitimacy bases of projects of collective order formation (Lezaun et al. 2017). Participation plays a central role in many processes of infrastructurization (using the example of the energy transition: Chilvers et al. 2018). In the course of this, issues of knowledge, interests, and values are negotiated, and basic understandings for the collective development of infrastructures as the backbone of common good are formed. This is reflected, for example, in VDI Guideline 7001 "Communication and Public Participation in Planning and Construction of Infrastructure Projects," which identifies early participation as an essential element of successful infrastructure development.

Time Dimension: Past, Present, Future. The temporal dimension opens a triple view of past, present, and future. The dimension of the past is very present in infrastructures through the materiality of the built structure as well as the whole ensemble that is at stake here. It is the complex arrangement of various elements that as path dependency and legacy shapes and limits the space of future possibilities in the further development of infrastructures. It should not be forgotten that limitation is always necessary for the opening of experimental space. At the same time, however, in light of sustainable development, exnovation, the leaving behind of old paths, is a crucial prerequisite (cf. Kropp 2015; David and Gross 2019). However, there are a lot of examples showing, of how difficult such exnovations are. Thus, the aspect of permanence plays a decisive role. The dimension of the present is marked in particular by the aspect of urgency under which the maintenance and further development of infrastructures is negotiated. Quite different developments can build up such urgency here, be it in the form of external shocks (in the form of environmental disasters or wars), but also in the form of accidents and thus inherent development limits of infrastructures. Admittedly, the aspect of the future plays the biggest role. In the articulation and solution of socio-technical problems, visions, drafts, and scenarios play an essential role. In these, the future is visualized. With which "socio-technical visions" (Lösch et al. 2019) or "socio-technical imaginaries" (Jasanoff 2015) can and will the collective open up the future anew? Such images allow us to coordinate innovation processes of collective order despite their socio-technical complexity. Which futures are designed and which are marked as desirable? It is striking that many current practices aim at producing a multiplicity of designs, be it as scenarios in which very different futures are designed in contrasting ways in order to then pave ways into the future based on them. Or in the form of prototypes: While for a long time people were rather sparing with the formation of prototypes, i.e., the materialized design of futures, the present shows a development toward the multiplication of prototypes (Dickel 2019). With multiplicity, the space of possibilities is illuminated, but at the same time, through materiality, it is already more firmly foreshadowed than if it were just a thought, an idea (Schulz-Schaeffer and Meister 2017). This connection between cognitive and material formation is taken as a starting point in the concept of the "promise requirement cycle," according to which, in the expectation match between technological promises and social requirements, both are increasingly related to one another, materialized and stabilized (van Lente and Rip 1998).

Space Dimension: Density, Connectivity, Distance. In many cases, urban space acts as a catalyst for a system transition toward sustainability and can thus be seen as an exemplary case of spatial density. More important than the steadily growing proportion of an urban population is the role of cities as incubators and catalysts for changes in the socio-economic system (c.f. Jacobs 1970). It is primarily urban space that provides blueprints for new forms of production as well as social and cultural interaction, driving exchange between people, products, and information (Vojnovic 2014). At the same time, urban space provides "protected places" where different approaches to socio-technical change can be formulated and implemented, basically giving a space to diversity (Fincher and Iveson 2008). Incidentally, this density can also emerge in regional contexts (Späth and Rohracher 2010). Another aspect of infrastructural development can be seen with regard to connectivity. Regional developments are often intertwined with other spaces or regions of the world. And here, overlooking such interconnections qua connectivity can easily lead to false assessments with regard to the respective local socio-technical development situation. It is the teleconnections that significantly shape the spatial order, even if they are easily ignored (Seto et al. 2012). The aspect of distance has long been corresponded with the quality of the global because spatial distance meant a negligible development horizon. Exactly this circumstance is undermined by the talk of the Anthropocene, because here the earth is set level as the relevant development horizon. Already Giddens (1990) pointed out that modernity is characterized by space–time bridging, so this project seems to come to its conclusion in the present, which seems to be characterized, as it were, by an omission of distance.

Environmental Dimension: Co-Existence, Availability, Extinction. The notion of social relations of nature expresses a fundamentally relational perspective in understanding the ecological integration of society and the co-constitutive character of nature and society (current review: Hummel et al. 2023). Going further still, approaches from a post-humanist or neo-materialist perspective formulate an ontology in which non-human nature is ascribed agency (see, e.g., Haraway 2008; Latour 2017). Here, the insight into the co-existence of human and non-human living beings as well as nature as a whole resonates. This can be seen as the quasi-fundamental aspect in the environmental dimension, and deviations from it as a potentially serious problem of collectives. The decline of human collectives can often be seen in a destruction of the ecological niche on which they depended (Diamond 2005; Grober 2010). The reason for this is both complex and simple. Society cannot be thought of without the use of resources: materialization gives stability to social processes. To this end, societies establish functions that require the ongoing mobilization of resources. Infrastructures are the medium for this. Without the continuous utilization of resources, there is no provision of services. In the course of industrial modernity, the aspect of co-existence receded into the background due to the increasing and diverse functionalization of nature. The metabolism of society with nature was mechanized to the point where the limits of growth (Meadows et al. 1972) became visible. Crucial for the maintenance of infrastructures is the availability of resources necessary for this. The aspect of availability describes all those practices that raise, transform, and then purposefully use nature-environment in the form of resources for specific purposes. Renewability or non-renewability, renewable or non-renewable give here important classifications for the characterization of availability. In concepts of scarcity and criticality, moreover, the particular dependence of resources becomes thematic (e.g., MIT 2010). Finally, the aspect of extinction thematizes the extreme form of human intervention in the natural environment, in which other life is eradicated (see, e.g., Jetzkowitz 2023). In the Anthropocene, therefore, biodiversity is assigned an essential role, because the age determined by humans may be the age in which planetary boundaries become existential boundaries for the human species.

2.2 References Within Infrastructural Change

The topos of references may seem somewhat strange at first. Basically, however, the idea associated with it is not difficult to grasp. Rammert (2010) argues that, for a theory of innovation, its strong ties to an understanding of economic innovations must be severed. After all, innovations also take place in other social fields. However, these innovations take on a different character according to the structuring logic of the respective fields. Political innovations are different from innovations in the field of science or in the field of economics. The latter are characterized by market success; in the field of politics, the focus is on power and control. Therefore, innovations in this field take a different form. However, Rammert goes further. His crucial difference is the distinction between relation and reference. The category of relation addresses the question of how the quality of the new can actually be captured. To this end, he uses a differentiation formed along the three social-theoretical dimensions of factual, social and temporal, and therefore distinguishes between old and new (temporal), like and new (factual), and normal and deviant (social). The category of reference, on the other hand, focuses the reference on selected social fields in which the innovation takes place. This is because the respective fields—Rammert takes a particular look at the economy, politics, and art in his analysis, but his theory is not limited to these—shape their own structural characteristics of the production, evaluation, and selection of innovations. Thus, the field of economics is characterized by the features of profit promise and market success, the field of politics by the features of increasing power and gaining control. It becomes particularly exciting when innovations are not considered in an “exclusive” reference to a selected social field, but when the multireferential dynamics are appreciated. The nonlinearity of socio-technical change owes itself in many cases to the hardly synchronized (or even only limitedly synchronizable) interlockings between fields in the course of innovations. In this sense, this theory of innovation broadens the view of complex collective processes of structure formation, in which and through which innovations are formed, but also selected and normalized.

However theoretically speaking, this does not mean that mechanisms of diffusion by imitation would not continue to happen. However, it is the specific formation and selection conditions that are set by the field references. According to this, innovations can basically spread further and further through multiplication and imitation until they finally establish themselves in a more or less large social field. The institutionalization of new social practices plays an essential role. These practices depend on the social field (e.g., with regard to sustainable consumption: Jaeger-Erben et al. 2015). The question of the relationship between (social) innovation and transformative change has now become a core topic of social innovation research (Nicholls et al. 2015). This question is relevant because change is often blocked by established social practices (Shove and Walker 2010) and the diffusion of innovations is therefore subject to complex and fractured dynamics (cf. Shove et al. 2012). The form and dynamics of change vary not only with the degree of institutionalization (cf. Fuenfschilling and Truffer 2014) but also with the emerging tension between macro- and micro-change (or top-down versus bottom-up).

With regard to the maintenance and further development of infrastructures, these considerations come together in the sense that basic references may be clear at first. But this does not necessarily have to be the case. The next stage in the development of infrastructures can be seen precisely in the fact that they are reconfigured in their central reference. In the late twentieth century, the enthusiasm for privatization also hit infrastructure development. The initial result was that cash-strapped municipalities sold off infrastructure. Water and energy were then provided by private companies in a large number of municipalities. In the meantime, these developments have also revealed their unintended side effects. This is because the quality of service provision deteriorated in a couple of cases. In Paris, for example, the quality of the water dropped considerably and at the same time the price of the service more than doubled. The city eventually re-municipalized the water supply and also offered drinking water at a lower price than the companies. This shows that infrastructures, due to their special importance, can—or should—only be exposed to a change of references to a limited extent. But in the end, it all depends on the specific case. In the following, two selected cases will be sketchily examined in order to subject the investigation heuristics to an initial proof of concept.

3 Exemplary Cases of Infrastructural Change

Explicit transformation, which is sought through laws and measures, differs from a transformation dynamic that is always already taking place. To mark this specificity, transformation researchers speak of transition (Köhler et al. 2019). Transformation can ultimately be understood as a specific variant of innovation process. A form of networked innovation in which the framework conditions of innovation are changed at the same time. It is no coincidence that the Multi-Level Perspective (MLP) (cf. Geels 2004; Geels and Schot 2007) places a significant focus on the structural dimensions of change. It was specifically developed for the analysis of transformation processes and heuristically puts three levels—landscape, socio-technical regime, and niches—and their interconnection at the center of the analysis. Innovations are developed in niches and diffuse more or less rapidly when a favorable window of opportunity arises through situational de-stabilization at the level of socio-technical regimes.

In the following, two selected developments are reported as vignettes in order to illuminate infrastructural change in light of the heuristics and thus to make special features as well as demands on infrastructural change visible. These are the structural change in the Rhenish mining area (Sect. 3.1) and the problem of flexibilization of power grids in the course of the energy transition (Sect. 3.2). In particular, it will be asked whether and, if so, in what way forms of experimental practices can be observed in the five dimensions mentioned, which characterize the network of socio-technical problems in each case. What are the particular challenges that go hand in hand with this and can be marked as relevant?

3.1 Transformation and Structural Change

"Structural change" marks yet another form of large-scale change processes; in short, this means leaving a situation of seemingly irreversible path dependency due to an established, one-sided form of value creation and at the same time opening up new innovation opportunities (cf. Herberg et al. 2021). If we view structural change as networked innovations, we can distinguish three important dynamics that can be systematically differentiated but are at the same time interrelated. First, targeted exnovation (David and Gross 2019): How does one get out of the fixations of previous innovation activity in a planned way? Second, targeted innovation: How does one unleash suitable new settlements for innovation, i.e., which companies should and can be settled? Third, the accompanying transformation: What impulses for the transformation are made possible and what new determinations are made at the same time? This is obviously a multi-layered task in which, in addition to discursive design, the task of targeted infrastructure development in particular is of great importance. It is in the infrastructures that the new paths are defined—which then also have an effect as a self-commitment on the future development possibilities of regions. Let us look at what is happening along the various dimensions mentioned earlier:

Factual Dimension: There is a multi-layered and often not easily disentangled configuration of (technical) objects in space. This meshwork as a "stable structure without a future" stabilizes in its materiality a condition that is nevertheless supposed to be overcome precisely through transformation. With exnovation, these established ensembles of technologies and infrastructures should be rearranged. Ultimately, the previous materialization becomes more or less worthless and at the same time stands as a legacy in the way of innovations. At the same time, previous functions lose relevance or are even completely dissolved. The phase-out of lignite-fired power generation puts an end to this form of energy production. At the same time, however, it is conceivable that with the use of renewable energies, the coalfield will continue to function as an energy district, i.e., this function will be retained, but then on the basis of a different material foundation. At the same time, innovations will be spurred on. In the Rhenish mining area, there seems to be an oversupply here (cf. Böschen et al. 2021). The coalfield is thought of as an energy district, a bioeconomy district, a hydrogen district, an Innovation Valley with a variety of different material foundations (ZRR 2021). In terms of tapping into an uncertain future, this seems plausible, but with each of these options comes a different material determination. Which one seems reasonable? Which avoids too rigid a determination, like the one from which one is about to be released? At the same time, this raises the question of how to shape infrastructural conditions with particular sharpness. It is not just about a selected infrastructure, but rather about the ensemble of infrastructures. This is why the aspect of networking is particularly prominent in structural change and is perceived as a critical boundary condition for development. To mention just one aspect: the network of previous interconnections must be maintained until the phase-out is completed, but at the same time, it is necessary to build new interconnections that contain the opportunity for the targeted development of a new innovation base that is also diverse enough to avoid the former one-sidedness.

Social Dimension: Structural change situations are characterized by the fact that they take place in a ruptured manner, mobilizing hopes and fears—especially those of social decline. Identity is in danger, previous forms of collaboration are being reformatted, and participation is therefore the order of the day. Structural change represents a bundle of change processes in which the previous distribution of welfare and influence is subject to transformation. Such a rupture raises special problems of identity politics. What is reinterpreted as path dependency in the presence of structural change has in the past fueled a development in which specific local cultures have emerged, with their very own forms of identity construction. This can be observed, for example, in places characterized by mining cultures. Structural change initially entailed the establishment of a new organization: the Zukunftsagentur Rheinisches Revier (ZRR), founded as a central institution. This initially had to undergo a learning process with a view to the requirements in the social dimension. In 2020, the self-description on the homepage read: "The Agency is the strategic partner of the federal and state governments in the region. It performs the regional coordination function in order to manage structural change in the Rhenish lignite mining region together with the state, municipal and regional stakeholders." Currently, it says: "The Agency for the Rhenish Lignite Region develops mission statements, innovation strategies and action plans and supports structural change by initiating and implementing projects. The agency works closely with its partners from science, business, politics, and associations both inside and outside the region. Energy transition and climate change pose a challenge to the region. However, foreseeable changes should not be suffered here as structural breaks but should be shaped early and together by bundling all existing potentials. The agency will describe and prepare the way by which the Rhenish Lignite mining region can continue to be a modern, prosperous and innovative energy and industrial region in the twenty-first century." At least in its self-description, the three aspects of identity, collaboration, and participation are now being given greater prominence.

Time Dimension: The past plays an exposed role in the context of structural change. Structural change means leaving behind a past, and even more: a break with the past. It is multi-layered ties to the past that make it an essential aspect in structural change as a socio-technical problem of exnovation. The present in structural change is characterized by the difficult coupling of urgency and uncertainty. Finally, it is certainly not accidental that the design of futures in structural change shows considerable diversity and density. In addition, attempts are often made to valorize the structural break in the future as a positive goal to be striven for by designating regions in structural change as "model regions." These are then seen as model regions for selected innovation processes and their infrastructures. However, this raises the question of who designed this future and whether it can take on a structuring role as an inspiring model—or not.

Space Dimension: In the further development of the ensemble of infrastructures in the Rhenish coalfield, the question of the fundamental use of space plays an essential role. In opencast lignite mining, the use of space was geared to precisely its requirements. Now the task is to evaluate space differently and reorganize infrastructures accordingly. The current spatial strategy of the ZRR proposes a strategy of limited density. Density locations are to be made possible without at the same time using space unnecessarily. Settlement development, which is based on the assumption of an increasing population (ZRR 2023: 172), is to be designed according to the spatial strategy in such a way that precisely the valuable soil in the precinct is protected. This also includes a system of developed connectivity between regionally placed places with different qualities (from local points to metro areas, such as Cologne or Düsseldorf).

Environmental Dimension: The economy is essentially determined by two sectors based on natural resources and their utilization: lignite mining and agriculture. The Rhenish mining area represents the largest lignite mining area in Europe, with up to 100 million tons of lignite mined annually (2019 = 65 million tons). As of 2019, this corresponds to almost 70% of the primary energy consumption in North Rhine-Westphalia (data according to: Herberg et al. 2020: 12). Agriculture in the district is favored by good or very good soils and a diverse food industry has developed. One can simply state: It was the particular situation of availability that created the path dependency. Interestingly, however, with the soils being very fertile, there was also a distinct agricultural use of nature. This double availability has thus shaped the region in a tense way since the use of lignite. And it is no coincidence that both options, energy district and bioeconomy district, are being considered in many ways in the current transformation. Both make different demands with regard to the availability of environmental resources for the associated infrastructure developments. While the bioeconomy model entails a reassessment of regional availability, the model of the energy district de-localizes the question of availability under the guiding star of renewables. Overall, however, the focus is more on co-existence, as formulated in the spatial strategy (ZRR 2023).

Field of References: The transformation region of the Rhenish lignite mining area has been and still is characterized by monopoly structures. It is the large energy supplier RWE that essentially dominates the situation. However, the transformation of this company also illustrates the dynamics of the transformation as a whole. The transformation of RWE into an energy company for renewable energies has both begun and already gained contour. Precisely because the situation in such regions appears fixed or even blocked, transformation processes are taking place in a groping, searching manner that also allows the social order to be shifted along with it. The transformation problem to be solved is that the innovations do not immediately lead to new major path dependencies. Path dependencies are expressed in structural monopolies that give the regional economic structure a one-sided character. However, if we look at the economic and structural program (WSP 1.1; ZRR 2021) for the Rhenish mining region, it is striking how much emphasis is placed on the circumstantial effect of innovation and how little attention is paid to the corresponding development of institutional framework conditions for such innovation. This does not seem to be a coincidence. For it is precisely in moments of great uncertainty about future developments that it seems particularly attractive to use innovation programs to maintain control over future developments, at least discursively. If we consider the participation expectations of citizens, this perspective can only cover one aspect. Rather, it is to be expected that structural change will have taken place successfully when civil society has established itself as a stable reference. This is the litmus test, so to speak. Structural change represents only one, albeit exposed, form of regional transformation. At the same time, it must be surprising how much the question of structural change is negotiated in technocratic patterns. Yet the very openness of these processes should encourage people to recognize the potential they contain for the further development of democracy.

3.2 Flexibilization of Infrastructures in the Context of the Energy Transition

The energy transition toward sustainable forms of energy production, distribution, and use represents one of the major societal challenges of the present day. The scale of this challenge is determined by the shift from centralized to decentralized energy production, the diversification and multimodality of storage, and the increasing sector coupling through electrification and digitization. This can only succeed if flexibly designed distribution grids are available as a backbone. At the same time, the infrastructures are subject to socio-technical stabilization requirements from the outset and even more so in the event of a system change. The system transformation in the energy transition from a centralized to a system characterized by decentralized structural patterns brings into focus the socio-technical stabilization of technology options in niches and a diffusion dynamic based on this. Direct current technologies have a high potential for the energy transition. The fact that it has not been sufficiently exploited so far can be explained by looking at the different heuristic dimensions.

Factual Dimension: The development of infrastructures in the present can be seen as a phenomenon in which the materialization of historically grown and culturally embedded large socio-economic-technological systems are (supposed to be) subjected to a targeted change. The decisive factor for a change is, in sum, the systemic benefit, when system effects such as security of supply or system stability are achieved despite volatility, which results from the interaction of primary energy use, generation and storage park, transmission grid and flexibility of consumers nationally, taking into account imports and exports. The tension between decentralized and centralized functionalization of the energy system is demonstrated by the volatility of renewables, which produce regionally and then produce a supra-regional system problem. For the design task thus addressed, direct current (DC) technology has relevant advantages, especially supporting decentralized grid structures, minimizing grid complexity, and simplifying load flow control. However, the field of DC technologies differs strongly related to the technology maturity level (TRL) of DC technologies and thus their market readiness. Technical standards (e.g., rules and regulations for the connection of plants to the power grid) ensure a minimum level of system-compatible behavior. However, such standards are often not yet available with regard to DC technologies.

Social Dimension: The tension between centrality and decentralization is impressively reflected in all aspects of the social dimension. Although the established players, i.e., the huge companies, are playing further a decisive role, they have the re-invent their economic positioning. Moreover, it is no coincidence that forms of community play a growing role in shaping an "energy transition from below." In this context, it is precisely the interplay of identity formation, collaboration and participation that plays an essential role in shaping local energy transition situations (Holstenkamp and Radtke 2018). At the same time, there are different forms of such "citizen energy." In principle, the relevance of these organizational forms of energy production for the energy transition has been demonstrated (see Gui and MacGill 2017; Gui et al. 2017). But here, too, the question of infrastructural organization arises: the conflict between decentralized and centralized organization of the energy supply system is also reflected in variants of citizen energy production (e.g., citizen wind farms, community biomass cogeneration plants). In general, it can be shown that the interest in citizen energy cooperatives is much higher than the number of those who are already involved. Equally, it can be seen that winning over citizens is facilitated by communication, personal contacts, and the opportunity to actively participate, as well as by disclosing advantages and disadvantages. After all, the motives for getting involved vary. Citizens want to make well-informed decisions and be involved in the design of measures (Jakobs 2019).

Time Dimension: In contrast to structural change, the three aspects of time play a different role here. Although the past also plays a role in this transformation, it does so more strongly in the sense of specific constraints that, materialized as alternating current infrastructure, make it difficult to make energy networks more flexible. Therefore, a complicated design task arises in the present, because the past must be taken into account in the transition to a possibly different future. Thus, there cannot be an either-or in the design of distribution grids, but rather the question of how to keep the infrastructure change to another basic technology manageable with a phase of targeted simultaneity of both forms. At the same time, the exploration of futures also plays an essential role here. In the energy transition, it is generally striking how diverse scenario techniques have been used to create a picture of the future. Multifaceted visioneering plays an exposed role in the energy transition (Lösch et al. 2017). This may be precisely related to the fact that this production of the future is done under very strict requirements of maintaining the present.

Space Dimension: An energy transition of decentralization and flexibilization goes hand in hand with the creation of a new structure of density, connectivity, and distance. On the one hand, the aspect of distance is intensified, because different regions are developing in their own way, and on the other hand, the regional structure that was previously able to form dense structures around power plants is being broken up. The wind farm electricity of the north has to go to the south. Power plants and consumer locations have new distances. On the other hand, new local niches are emerging around renewables. How measures and formats of the energy transition are accepted and evaluated seems to depend, among other things, on the location (Hellmut and Jakobs 2019). The design of niches, and thus new density situations, acquires a particularly high relevance here. Connectivity is reflected in systemic benefits from a techno-economic perspective, e.g., in relation to transmission networks (van Leeuwen, 2018), distribution networks (Geschermann, 2017), and generation as well as storage systems (van Bracht, 2018). As a rough orientation, a benefit can be considered systemic if it is not the local balance but the national, European or global balance that is decisive for achieving a goal, e.g., costs and CO_2 reductions of the energy transition.

Environmental Dimension: The restructuring of the energy system is taking place under the conditions of a shift in environmental impact. On the one hand, renewables are expected to significantly improve the climate footprint of current energy production and consumption. On the other hand, the expansion of renewables is accompanied by other problems. For example, the expansion of renewable energies often underestimates the aspect of resource utilization. This means that availability in a new form is put to the test here. After all, the resource requirements for a corresponding form of energy transition are immense (cf. Michaels 2021), even for classic metals such as copper. Therefore, the reduction of resource consumption for copper, as offered by DC technologies, appears to be quite desirable. On the other hand, this conversion will take many decades. But questions also arise with regard to co-existence. In this respect, wind power in particular has side effects that can severely disrupt biodiversity (cf. Galparsoro et al. 2022).

Field of References: The energy transition toward a post-fossil production and consumption structure also poses a structural challenge, especially in view of the simultaneously required transformation from a centralized to a decentralized system architecture, which is marked by a shift in references. With the first steps into a breakup of the monopoly structure since the 1990s, which is in fact a highly fragile and open process, the network of actors might be shifting not only in the economic field, but also in the areas of science, civil society, and politics. Triggered by the change of cultural-institutional patterns on the landscape level (especially: Renewable Energy Act), but equally bottom-up from individual niches, the emergence and diffusion of socio-technical innovations in the context of the energy transition can be very well demonstrated (Geels et al. 2016). One important dynamic is the emergence and shaping of niche situations. Forms of community formation, such as energy cooperatives, show high potential as transformative actors in the energy transition, which was formulated as goal by German but also European legislation. However, these ambitions and their outcomes are fragile; e.g., after a rapid increase in start-ups, the 2017 reform of the Renewable Energy Sources Act (Erneuerbare Energien Gesetz, EEG 2017) in particular slowed down the spread of civic energy production. Also relevant for CEC types seems to be their degree of interconnectedness. German energy cooperatives, for example, are better networked than other citizen energy companies (Kahla et al. 2017). Obviously, in this case, too, it can be assumed that the litmus test for a successful transformation can be demonstrated when the reference is shifted to the space of civil society. Efforts to do so can already be identified in the form of energy citizenship (Hamann et al. 2023). With regard to the case discussed here, the possible use of DC technologies, this circumstance is likely to be even more significant because these technologies, except for high-voltage transmission lining, are still at a prototypical stage. So far, their use varies not only in terms of technological maturity, but also depending on the socio-technical conditions of their embedding—for example, use and implementation differ strongly depending on the country. So far, it is largely unclear what socio-economic conditions must be in place not only to increase their maturity, but also to support and accelerate their market diffusion. This is where the density of niches plays a decisive role.

4 Scalability, Inclusiveness, Updateability: Ambitions and Restrictions Within Infrastructural Change

From the point of view of transformation, obviously, new demands are placed on infrastructure development. Transformation implies a requirement for continuous re-organization, which in detail means adaptability to environmental change as well as synchronization of potentially divergent infrastructure developments in the midst of transformative change. In order to be able to do justice to these special qualities, the study of infrastructure development must be expanded to enhance its flexibility. To put it succinctly, infrastructures are needed that are agile, participative and capable of being updated. An intimidating task. How can this be achieved? How do we have to think and design infrastructures so that they can meet such demands? This can be addressed in the aspects of scalability, openness to participation and updateability.

Scalability: Typically, scalability refers to the question of diffusion by an increase in volume and/or transfer of an innovation and is thereby expressed by easily measurable indicators (e.g., Seyfang and Longhurst 2016). This form of scalability is only one, nevertheless important form. However, in many, if not most, cases of socio-technical innovations, scalability is highly related to forms and dynamics of translation and has to be analyzed and designed accordingly (Raven et al. 2011). The question of scalability as an infrastructure development challenge was evident in both vignettes. This is because this problem does not owe itself solely to the question of whether the solution found in one niche will also work in other places. Rather, behind it lies a whole set of questions that, according to the proposed heuristic, relate to the different dimensions and their interactions. Typically, the social dimension, for example, contains a wealth of preconditions that cannot be transferred from one place to another without difficulty. The questions of identity and cooperation can be answered very differently and have therefore led to different local cultures. Or also the environmental dimension: the scalability of a new infrastructure solution, if one takes sustainability as a yardstick, depends essentially on whether the designed pattern of the problem solution also maintains the availability situation despite scaling and, moreover, is not accompanied by negative teleconnections. This dimension requires a completely different knowledge base than before, which could be called a set and strategy of transformation indicators. To illustrate this limited scalability/translation of niche applications with a concrete example, one could take a look at the diversified structures of wind turbines operated by citizen energy cooperatives in Germany (Klagge and Schmole 2018). Social acceptance of these technologies is high where both environmental conditions and socio-economic factors such as economic wealth allow citizen cooperatives to successfully operate wind turbines (Ohlhorst 2018). This is the case, for example, in northwestern Germany, where certain environmental and social conditions are given at the same time. However, in areas with even higher wind potential (Mecklenburg-Vorpommern) or economic wealth (Bavaria), fewer wind turbines are operated by cooperatives (MV) or installed at all (BV) (Kahla et al. 2017). The five heuristical dimensions presented in this paper allow us to describe these different infrastructural outcomes in more detail and to investigate why a particular niche solution does not work in a different but comparable context.

Inclusivity: Social formation of inclusive infrastructures. The essential value is the binding in social practices, which allows to increase the legitimacy and functionality of socio-technical problems and their solutions. Infrastructures are expressions of the social as well as technological formation of societies. If the logic of the development of infrastructures changes, then patterns of social order in societies also change. Against this background, the question arises what effects the maintenance and further development of infrastructures have on the different user groups (be they professional users who operate the infrastructures, but also everyday users who manage their daily lives on the basis of infrastructures)? The notion of "infrastructural inversion" introduced by Bowker (Bowker and Star 1999) could also be helpful in highlighting the everyday work of maintaining infrastructures in order to enable new forms of participatory access for affected user groups as well as professionals. This means focusing more analytically and empirically on the "grind challenges" (Madhavan 2022) associated with infrastructural work in order to better understand the social conditions of infrastructural reproduction. As it seems to be essential to synchronize the development of infrastructures and the corresponding changes in social practices already in the design of infrastructures, there is a high demand for participatory accessibility. Fortunately, tools have also been proposed in the meantime, which can be applied in this context, such as the "Societal Readiness Thinking Tool" (Bernstein et al. 2022) or the concept of "Niche Readiness Levels" (Schöpper et al. 2023).

Updateability: How can updateability be built into infrastructures? To give just one example, can experimental elements be built into infrastructures—and if so, how should they be designed? In which areas could it be implemented particularly well? Wouldn't various such developments also have to be specifically interlocked, i.e., synchronized? Infrastructures that are updateable permit the prototyping of socio-technical problems and the corresponding opening of experimental spaces already in operation. If we look at this in terms of the smartification of infrastructures, then the armoring of infrastructures with new digital technologies inscribes their own temporal logic into the further development of infrastructures. In particular, this means that other dynamics of prototyping as well as ongoing updating will shape the development of infrastructures. Furthermore, smartification requires new qualities of infrastructure that allow for continuous updateability, such as compatibility, connectivity, and modularization (cf. Chester and Allenby 2019). Other examples can be found in urban planning, where infrastructure designs in some places have already addressed higher levels of uncertain weather conditions due to climate change by shifting from large, centralized, fail-safe designs (that can no longer be guaranteed) to small, decentralized, safe-to-fail designs (Kim 2018). Failure is thus calculated as a realistic option. That represents an attempt to absorb and incorporate higher levels of uncertainty, making it an adaptive type of design (Chester and Allenby 2022).

In a nutshell, taking the different lines of the argumentation unfolded here together, it is first important to emphasize that the considerations presented here owe to a perspective that, in the context of socio-technical change, specifically focuses on the permanence as well as the more or less targeted reconstruction of infrastructures. The presented offers for a heuristic refer exactly to this form of shaping reality. Which socio-technical problems of infrastructural development are articulated and solved, and what are the social and material forces at work in the process? The primary purpose of the proposed heuristic is to identify such forces and thus facilitate an analysis of the mostly hybrid situations. In this context, the aforementioned three design claims of future infrastructure development (scalability, inclusivity, updateability) can be understood as guiding values that link the socio-technical analysis of infrastructure developments with the question of a possible better design. This is why that they aim at enabling an agile development of infrastructures, but on the other hand, it poses new challenges for cooperation between very different knowledge actors: developers, architects, engineers, and construction industry, just to name a few. In this sense, one could and should investigate patterns of prototyping and updating of infrastructures, focusing on issues of stability and instability of such processes. Moreover, one can examine how the representatives of participating knowledge cultures work together to solve socio-technical problems—and what challenges need to be overcome in the process.

Acknowledgements Funding: This work was funded by the German Ministry for Education and Research in the Research Campus “Flexible Electric Networks” with the project “DC-Socio-Economics.”

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Dynamic-Nonlinear Socio-technical Change: Transformation as a Sociological Theory Problem and a Possible Solution

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Abstract There are calls for transformation in all places, but the starting point for a sociology of transformation is anything but simple. A sociology of transformation must be thought and designed in the triad of transformation research, transformative research, and research transformation. This means the provision of knowledge on how transformations take place, social science research that uses this knowledge to intervene in social and societal processes in a targeted way, and reflection on how sociology itself changes as a discipline due to such action and socio-political expectations. Against this background, the article starts from the assumption that a sociological perspective (combining the relational approaches of network and field theory) specifically tailored to the current transformation conditions and challenges (exemplified in a case study) can make a significant contribution to understanding as well as shaping transformation processes based on a joint reflection of possibilities.

Keywords Socio-technical change · Sociology of transformation · Network research · Field theory · Transformative research

1 Introduction

The question of transformation has a striking tension. On the one hand, there are calls for transformation in all places: transformation of the energy system, transformation of urban ways of life, transformation of capitalism and many transformations more. The calls are not only loud and audible, they are also put forward with good arguments. For example, the way of life of Western industrialised societies and their imitators has a considerable problem in respect to sustainability. And in the Anthropocene, limits to the availability of resources not only become inescapably

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P. Letmathe et al. (eds.), *Transformation Towards Sustainability*,
https://doi.org/10.1007/978-3-031-54700-3_5

visible, but at the same time, questions of justice between the various groups of people become urgent in a completely new way. On the other hand—and in a peculiarly opposite relationship to this—the willingness as well as the ability to change seem to be decreasing rather than increasing (visible in the rise of polarised political debates, overarching bureaucracies, and limits to individual adaptability). The demand for fundamental change meets a pronounced resistance to change. The established paths seem to be anything but well-trodden, but rather exhibit a persistence that is sometimes difficult to understand. It is these structural path dependencies against the backdrop of both urgent and far-reaching needs for change that give rise to a sociology of transformation.

But the starting point for a sociology of transformation is anything but simple, for several reasons. Firstly, the task of identifying structural path dependencies is theoretically very demanding. With which "lens" can these be made visible without at the same time fixing existing conditions or exaggerating change dynamics? Secondly, there are considerable problems of interpretation. The prominently articulated diagnoses of Blühdorn (2013), in which democracy is interpreted as a simulation to "whitewash" unsustainable societal natural relations and internal coordination, vividly illustrate the extent to which prior assumptions in modelling[1] determine the interpretive perspective. Thirdly, a fundamental problem of sociology, namely that its exponents are always contemporaries of the formation they are trying to observe from a distance, is considerably exacerbated. Critical sociology has so far been able to operate with plausible overarching normative assumptions (while controversial in between approaches). Not so a sociology of transformation, which, although critical, cannot have the same certainty of scale. Fourthly and finally, a particular challenge of a sociology of transformation is that transformation is based on the recognition of a structural difference which, from an epistemological point of view, can in principle only be recognised in retrospect. At the same time, for practical considerations of the political shaping of transformation, there is a strong interest in gaining insight into current transformations, if possible through participation, in order to gain shaping knowledge.

In addition to these four reasons, however, a sociology of transformation must also challenge the currently predominant self-image of sociology as a science free of value judgments. Max Weber's famous postulate in this regard, made more than a hundred years ago, continues to have indeed an unbroken effect today. Accordingly, the task of sociology is to provide as accurate a picture as possible of contemporary society, without, however, recommending what can be changed. For, from a sociological point of view, every change means the creation of winners on the one hand, but also the creation of losers on the other. In other words, no social change, let alone a transformation of society, will only produce winners. There will always be groups or social milieus that are disadvantaged by a change. Accordingly, a sociologist would be taking sides if he or she were to make frank recommendations for change. So much

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[1] Model or modelling is used in the article in a broad sense, applicable to scientific constructions based on assumptions and deriving dynamic results.

for the background of the unbroken predominance of value judgement in our discipline that is of interest here. It is, of course, a major hurdle for sociology to open up in the direction of transformative research. But it was also Max Weber who spoke of the "eternal youthfulness" of sociology. By this, he meant that sociology should always have contemporary society as its main focus, so that it must constantly question its concepts, theories and methods as to whether they still allow a penetration of social reality, which has been changing dynamically since the beginning of modernity and is even accelerating in the process of change (Rosa 2017). Accordingly, Max Weber assumed that sociology must change according to its object of study in order not to lose relevance. In accordance with this "eternal youthfulness" precept, it is therefore not sacrilegious to also question Weber's postulate of freedom from value judgement as to whether it is still "youthful" enough, i.e. still suitable for contemporary society and sociology's self-understanding.

These different challenges and the problem of dealing with them can be illustrated very well by looking at the discussion on public sociology. In his emblematic essay *For Public Sociology*, Burawoy (2004) distinguished four forms or ways of working in professional sociology. These were grouped according to the two dimensions of audience (academic/extra-academic audience) and the type of knowledge (instrumental/reflexive knowledge). Accordingly, professional (academic/instrumental), political (extra-academic/instrumental), critical (academic/reflexive) and public sociology (extra-academic/reflexive) emerged. A first assumption is to position sociology of transformation in the light of this typification precisely as a call for targeted coupling between these types. A second, more far-reaching assumption is that this typology may need to be expanded. To name just two reasons for this: First, entirely new types of data are being added, with a new sociological territory of the predictive ("Digital Sociology", Marres 2017; "Computational Social Science", Lazer et al. 2009 and Conte et al. 2012) emerging, e.g. the expansive use of data from simulations. Second, with real-world laboratories and living labs, entirely new sites for the production of knowledge and innovation are being established in the borderland between science and society, which reconfigure social and knowledge orders (Schäpke et al. 2017; Lemm and Häußling 2021; Böschen et al. 2021a, b). Such developments cannot be ignored by a sociology of transformation, but must rather be used as an occasion to reorient sociology itself.

The main task is understanding about structuring processes of collective order in transformative change—for which a sociological theory must be offered. At the same time, however, the pressure on the social sciences is growing not only to better understand the structures and dynamics of transformation, but even more to produce successful steering knowledge. As if the situation was not already complicated enough, we are also observing transformations in science itself, especially through the "digitalisation of research", which expands the ways of knowing of the present, but at the same time undermines the foundations of knowledge. Therefore, sociology of transformation must be thought and designed in the triad of transformation research, transformative research and research transformation. This means the provision of design knowledge on how transformations take place, social science research that uses this knowledge to intervene in social and societal processes in a targeted way, and reflection on how sociology itself changes as a discipline due to such action and socio-political expectations.

Against this background, this article starts from the assumption that a sociological perspective specifically tailored to the current transformation conditions and challenges can make a significant contribution to understanding as well as shaping transformation processes. Learning in transformation processes is demanding. It requires a reflective culture of trial and error. In a non-dynamic-feedback reality, one would speak of error culture. The point, however, is that in the inevitably nonlinear feedback processes of transformation, what used to be called error is inevitably part of the process of moving through the problem and solution space; in other words, it becomes just as much a constitutive component of the ongoing transformation as what has traditionally been called the implementation of the solution approach.[2] In other words, the impasses that one takes in a transformation project are just as instructive as the solution paths, since both enlighten one about the character and scope of transformative change. Taken together, sociology as a science of reflection can make a significant contribution here by helping to think through the cultural-institutional preconditions and at the same time making them transparent. What experimental spaces can be opened up at the institutional level that does not immediately fail due to systemic constraints or individual benefit calculations? This need for reflective re-positioning and striving to encompass the multiple perspectives available in transformation processes is a key constitutional fact of sociology as a science, but it is also especially demanding in a setting, where the drive to change is paramount. Therefore, a sociology of transformation might fulfil a special role, as a navigator through reflective and critical experimentation for transformation.

This article therefore sets itself a threefold task. Firstly, with the help of the Aachen Model of Transformation research (see this collection), we justify why the multi-level perspective (MLP; Geels 2004, 2022; Köhler et al. 2019), in particular, which is widely used in transformation research, is insufficient with regard to understanding processes of structure formation, despite all its undisputed strengths, and why a specific sociological theoretical perspective is therefore needed (Chap. 2). The thesis of this article is that such a specific theoretical perspective can be gained by combining field theory on the one hand and network research on the other. This is because their respective strengths and weaknesses in the analysis of structural formation and change are reciprocal to each other and can therefore not only be balanced out by a clever combination, but also led to a productive enhancement (Chap. 3).

[2] In the case of nonlinear feedback phenomena, much more complex constellations of effects must be applied than simple cause-effect chains. For this type of phenomena, several sources and heterogeneous forms of effects (cf. also Arendt 1954) must be taken into account in the sense of interactions. This leads to the fact that one and the same measure can have very different or even diametrically opposed effects per constellation. In other words, one intervention can lead to success and another time the same intervention can end in failure. If one becomes aware of this, it becomes obvious that in a nonlinear feedback reality there can basically be no (substantial) errors and certainly no such thing as a one-best-way. Or to put it more cautiously: in such a reality, it makes little sense to try to draw up a catalogue of possible errors for all cases or to write a guidebook with template-like solution paths.

The fact that these theoretical-conceptual considerations provide added value for the understanding of transformative processes, especially those that take place in a dynamic-feedback manner, will be demonstrated by means of a concrete development process for the sustainable design of textile chains. The interlocking of different social forces and forms as well as levels of structure formation can be made visible here very well by means of the complementary field network research shown. What is more, it is precisely developmental disruptions, obstacles, framework conditions and blind spots that can be made transparent in this way and clarified for transformation actors as decision-making constraints (Chap. 4). A sociology of transformation understood in this way would then help to establish a new level of learning ability in these processes, since a reflected culture of trial and error and correction in these explorative situations, as outlined above, is inevitable. It is not about avoiding log jams, but about making visible the pitfalls and obstacles that need to be taken into account. In the concluding summary, not only are the most important findings compiled once again, but also an outlook on further tasks for a sociology of transformation understood in this way is given (Chap. 5).

2 Aachen Model of Transformation and the Sociology of Transformation

The Aachen Model of Transformation is based on the distinction between three dimensions, whereby the necessary and unavoidable interactions between them are to be taken into account above all. These three dimensions are, firstly, research on transformation processes, which can be subsumed under the term transformation research. The second dimension is characterised by attempts to bring about, accelerate or otherwise support social change with the participation of science. Here, the term transformative research is relevant. Finally, however, a third level must also be considered, which is triggered with the changes of research itself through societal changes or through its active role in them. Here we would then speak of research transformation. In this model, there is a dynamic stabilisation between these levels if science is to be successfully embedded in social transformation processes.

Each of these dimensions is already represented by a more or less extensive literature, but their connections have not yet been clearly elaborated. While transformation research often works with encompassing analytical frameworks on a large scale (such as the multi-level perspective approaches elaborated by Geels and others), works from the field of transformative research (real experiments, niche experiments and real labs) often argue at the level of small-scale cases with limited scope. The impact of the two forms of development on the researching disciplines themselves is often discussed, in turn, in quite different contexts. At this point, we should also refer to the extensive discussion of these questions in the transdisciplinarity debate, which pursues a similar line of inquiry when it is concerned with how knowledge can be developed jointly from different positions in order to then also be reflected back into the respective specific fields of knowledge (Lawrence et al. 2022). Here, too, a reflective and procedural mode is favoured (Lorenz 2022), but in contrast to the model proposed here, the specific role of a discipline is not examined more closely here, nor are the interactions between the sociological research and practice dimensions specifically named here.

From a sociological point of view, it makes sense here not to focus on these levels (which are already independent fields of research), but to deal much more explicitly with the relations between them. This entails a twofold assumption. Firstly, the main conceptual-theoretical challenge for a sociology of transformation is the simultaneous, more or less unsynchronised change taking place in various dimensions of social coordination. Secondly, this challenge is exacerbated by the fact that change in the various dimensions must not be analysed as independent of one another, but rather must be taken seriously in their dependence on the interrelated constitution of the preconditions for change. The three analytical dimensions refer to spaces of change that can generate mutual stabilisation, but also possible destabilisation in complex processes of interaction. Making these interactions describable as a reciprocal structuring process is the explicit aim of this contribution (see Fig. 1).

- The coupling of transformation research and transformative research pursues, on the one hand, the effects of transformational research on ongoing transformation processes (i.e. questions about the possibilities of influencing large-scale transformations through real experiments and real laboratories and the then necessary integration of these approaches into the models of transformation research) and, on the other hand, the application of experiments to the results or predictions from transformation research (e.g. in the identification of "windows of opportunity" to which one can connect).
- The interaction between transformative research and research transformation can be observed very well through the need for new competencies among researchers and new focal points in the disciplines or the creation of new disciplines and roles

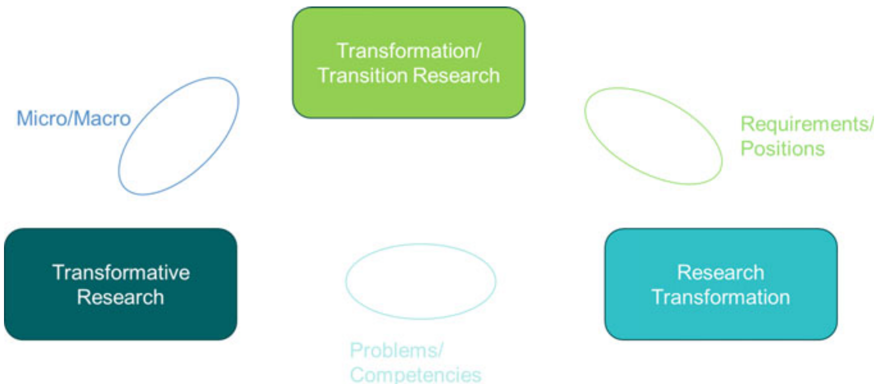

Fig. 1 Aachen model of transformation

and additionally also in the relevance of these changes for the implementation of transformative research projects. What problems do researchers encounter in these processes and how can these be translated back into new qualification or evaluation structures within the scientific disciplines?
- Finally, the interrelationship between research transformation and transformation research manifests itself on the one hand in the demands placed on science by the transformation (such as increasing politicisation) and on the other hand in the fact that new methods and approaches for understanding and explaining transformation processes can be generated.

This complex picture of the structural dynamics involved then also shows that the framework of the multi-level perspective is not sufficient to adequately capture these dynamics. MLP attempts to make socio-technical transitions, such as the change from sailing to steam navigation or the low-carbon transition, describable in a framework consisting of three distinct levels. At the niche level, new possible solutions (such as new bottom-up sharing concepts for mobility in urban quarters) might take place. On the regime level, established actors control the status quo of a developed dominant socio-technical field (such as the status quo of urban transport), and on the landscape-level societal trends (such as in particular the societal norm of sustainable transport concepts related to the example used here for illustrative purposes by MLP), public perception and events determine the emergence of windows of opportunity that can destabilise existing regimes. The framework allows for clear categorisations, but tends to get in the way of an analysis of the possible complex interactions between levels, as well as within levels, and tends to reify these levels (see also Schmitt et al. 2023).

In particular, the intervention and reflection perspective of transformative research and the repercussions of the transformative process on the research itself are not sufficiently taken into account there and observed in their retroactive effects on transformation processes. On the one hand, these complex nestings in transformations open up a special opportunity for observing social change in real time. On the other hand, this nesting poses a particular theory problem. So what is the theory problem? Transformation means that the cultural-institutional structure that makes up a society, as well as in which research is embedded, moves along with it. Moreover, such research cannot remove itself from events as distanced research. Rather, it has always been a form of engaged research. In this sense, transformation sociology in Burawoy's typology (2004: 11) would necessarily always be public sociology. Beyond this, however, the question arises: How do the four forms connect with the considerations of the Aachen transformation model? What consequences, then, does this particular constellation entail? How can the relevant interdependencies not only be made theoretically accessible, but also be reflexively caught up in the shaping action that sociology as transformation sociology inevitably becomes? Intervening research requires a theory that makes the respective relations and the dependencies within them visible. Theoretical tools are therefore needed to analyse these complex interactions in contemporary transformation processes and at the same time to assist in the positioning work of a sociology of transformation, especially between professional and public sociology. It is therefore less a matter of taking up a fixed positioning on transformation processes as a sociology than of pointing out the possibility of switching between them in a controlled way in order to do justice to changing demands and criteria. Theoretical tools from field theory and network research, which make structural dynamics representable as changes in positioning without scales, can support these reflexive positioning of self and others.

3 Theoretical Framing: Field and Network Theory

The theoretical-conceptual problem of interest here consists primarily in the question of how the mutual relation and interactive stabilisation between the three aforementioned dynamics can be conceived and in a way that does not lead to the introduction of sociology as a neutral observer or to the reification of individual structural features of societies as indispensable. This poses a general theoretical-conceptual problem, which cannot be answered here. Our intention here is much more modest. In the present article, we propose a strategy for joint reflection. This strategy consists of making the potential of two relationally oriented sociological theories fruitful with and for each other: field theory and network research. Field theory and network research are both capable of mapping and explaining complex structural dynamics between different social spheres. What is more, it is to be assumed that, due to their respective special focuses, they can be linked in a complementary manner in order to capture the different facets and dynamics of transformations in a sociologically meaningful sense (cf. also Schmitt 2019). The aim is to explicitly search for the forms within which the two research perspectives can mutually support and complement each other. The aim is to make potentials for the observation of complex embedding and disembedding processes comprehensible by focusing on relational structures and their changes.

3.1 Field Theory

Transformations typically take place in such a way that established structures and (collective) actors lose influence and new (collective) actors in turn gain influence. In this way, new relations emerge between actors, but also between actors and structures. Field theories offer one way of illuminating such developments. From such a perspective, transformation spaces become places in which transformation fields unfold and processes of structural change can be observed. And in this sense, a plethora of analyses have been carried out on issues of transformation in which field theories have been fruitfully employed. In this way, changes in the scientific field were carried out, for example, with regard to the organisation of the university (e.g. Baier and Schmitz 2012), the specific features of fields of investigation while hybrid interaction spaces are taking place (cf. e.g. Herberg et al. 2021) or the emergence of "techno-scientific fields" (cf. Raimbault and Joly 2021). Or studies that took regional densification as an opportunity to examine specific path dependencies and opportunity structures in the linking of different domains of action, for example in the context of questions of knowledge exchange or education (Herberg 2018), or with a view to problems of regional structural change (Böschen et al. 2021a, b).

This relevance of field theories for the study of forms of path dependency as well as processes of fundamental change owes much to specific theoretical attentions as well as addressed theoretical tensions that are taken up and dealt with in such theories. This is why, that these theories, in whatever form they are formulated (cf. Böschen 2016), take up precisely the tension between actors and structures and thereby emphasise the importance of structures as well as actors and their specific alignments and related changes. Nevertheless, there are different variants that set the accents differently with regard to the stability and emergence of structures and which need to be brought into the discussion (Raimbault and Joly 2021). On the one end of the spectrum, there is the modelling of fields in the way Bourdieu (1992) did, who spoke of objective structures and thus gave fields the character of immutability. At the other end of the spectrum are theories that view the dynamic reconstruction of fields as an inherent moment and have reconstructed them as strategic fields of action (Fligstein and McAdam 2012). Although at first glance these two perspectives seem to be mutually exclusive, if one makes appropriate adjustments, accentuations and expansions, interesting innovations arise for transformation research. After all, questions of transformation owe much to the tense combination of stability and change. The relevant question is how this simultaneity can be meaningfully dealt with in a theory without accentuating one or the other side of the coin too strongly.

In the sociological discussion of the last decade, field theories have experienced a renaissance (cf. Bourdieu 1992, 1998a, b; Fligstein and McAdam 2012). Fields resemble spaces of play. They can be understood as "historically constituted spaces with their specific institutions and their own functional laws" (Bourdieu 1992: 111; translation the authors). Fields constitute positions and thus preshape the practical meaning of the actors operating in them, but their reproduction is not independent of how the actors relate to these positionings. Fields are areas defined by specific rules of the game, in which the rules frame the actions of the individuals, but do not necessarily determine every move. Field theories are attractive because they not only allow us to bridge the gap between macro- and micro-views, but also take a look at the dynamic formation of social order (Böschen 2016).

Field theories shed light on the relation between structure and actor. Pierre Bourdieu in particular addressed this problem in his field theory. In social practices, structures manifest themselves and are reworked at the same time. Actors realise structures that are set for them as guidelines for interpretation and action, but at the same time, actors are not fixed to these structures, but move within them, including individual adaptations. However, Bourdieu's field theory emphasises structures in particular (Müller 2014). In contrast, Neil Fligstein and Doug McAdam's field theory accentuates the relationship between actors (Fligstein and McAdam 2012). They conceptualise their field theory as a theory of strategic fields of action. Here, opponents compete against proponents and try to reduce their influence and expand their own.

Strategic action thereby determines the respective traits of the actors. Through the formation of lines of conflict between opponents and proponents, established structures are simultaneously transformed or new ones are formed in order to deal with the emerging conflicts. In his work, which focuses in particular on the analysis of habitus and the distribution of power, Bourdieu has more or less assumed the power of fields as a framework. However, this is not necessary for theory. Therefore, the emergence of such field structures, which is addressed by the theory of Fligstein and McAdam, can be brought into line with Bourdieu's theory. Then, as it were, the processes of liquefaction and crystallisation of structures can be examined as field-specific processes of structure formation.

Such forms of structure formation can be examined in particular in terms of their materialisation, for example in the formation of infrastructures. This is because materiality stabilises social practices (Shove et al. 2012). However, there is no determination of patterns of action. In his field-theoretical reflections, Kurt Lewin referred to the things in a field that triggers something in actors as "objects with a prompting character" (Lewin 1963). This meant objects or persons in an individual's field that cause the individual to move towards or away from them. In general, such elements can be described as prompting moments in fields. These are signs in the perceptual field of actors that can trigger a movement (interpretation, action). What is decisive here is the potential to trigger an activity, not the unambiguous consequence of the presence of a prompting moment. The context does not function in an objective sense. The signs are interpreted by actors and then proceeded with a more or less routine response. So one cannot assume a causal effect on the perception and action of actors. Only in very rare cases do prompting moments develop a compelling effect in such a way that the perceptual and action requests they contain are followed without circumstance.

Now, for a sociology of transformation, questions of structuring are of particular importance. The tension between structured structure and structuring structure comes into play here in a special way. In previous approaches to field theory, the aspect of structuring has been treated very differently. Pierre Bourdieu fixes structure, as it were, through the conceptual condensation of centres of rule as autonomous and heteronomous poles of a field. In Bourdieu's view, these embody the specific intrinsic and extrinsic rules of social sub-areas. In doing so, he basically falls short of the possibilities of his theory. For what would be an argument against not starting from stable constructs of autonomous and heteronomous poles, but rather examining precisely their formation as poles, each for itself, but also in their constellation to each other? In contrast to this, Fligstein and McAdam addresses the dynamic formation of structures through the emergence of strategic fields of action. Here, however, the aspect of the preconditions of structure formation through preceding structures is underexposed. If one takes the suggestions from both theoretical traditions of field theories, then an insightful conceptual-theoretical framework opens up for examining processes of structuring (cf. Böschen 2016).

In a sociology of transformation, it is important to be able to pose questions of multi-layered de- and re-structuring more precisely. Taking the approach of Bourdieu as the central frame, the theoretical problem can be described as follows. If one declares stability and change to be a central theoretical problem of a sociology of transformation, then it makes sense to raise two questions that relativise the static nature of field relations within Bourdieu's previous conceptualisation. Typically, according to Bourdieu, a field is formed from an autonomous and a heteronomous pole, each of which appears as a static-fixed quantity. On the one hand, one can ask whether these poles are not themselves continuously configured and reconfigured. On the other hand, it must be assumed, especially in the case of transformations, that it is not only the references between two poles that shape the transformation process, but also the multiplicity of several autonomous and heteronomous poles as well as their specific mutual relations.

Taking the first point, it is a question of not understanding autonomous and heteronomous poles as static variables, but rather of analysing them as variables being continuously "under construction". The stability of such poles may be very high, so that their change seems rather unlikely. However, this should not obscure the continuous re-structuring that is taking place and which sometimes also occurs below the usual depth of analysis. These micro-shifts in the tectonics need to be captured. In a first approach, poles can be understood as centres of regulation essentially formed by discursive, institutional and pragmatic schemes and rules. The more actors follow these and the more they are materialised (for example through infrastructures), the more stable such centres of regulation are.

Taking the second one, it is not only such centres of regulation that matter, but always in a certain context. Bourdieu has defined this through a bipolar structure of autonomous and heteronomous poles. In contrast and as an extension to this, it seems more revealing to proceed less from such a bipolar structure and more from a multi-polar structure. This forms a matrix, as it were, whose change can be studied as a longue durée (Böschen 2017). As mentioned above, transformation processes can be read precisely as changes in the bi- or multi-polar field structure. Thus, especially in regional structural change processes, which mean an ex-novation from a path dependency, the importance of science as a future innovation driver is often emphasised. However, this brings the field of science—and thus its structural patterns—more into focus. Such a reconfiguration of the transformation field is highly demanding, which is why it is not surprising how quickly such situations are blocked. With a field-theoretical perspective, the moments of opportunity for the emergence of structures could be identified more easily.

Finally, such modelling transforms the problem of "Coleman's bathtub", which describes the difficult mediation of micro- and macro-processes as a theory problem. For in-field theories, this tension can be studied as actor-centred structuring. However, this path has not been chosen so far because corresponding theoretical-methodological connecting points were missing. Yet network research offers precisely the theoretical and methodological approach that leads further here.

3.2 Network Research

Social science network research not only offers a conceptual toolkit for describing relations between social phenomena (e.g. between scientific communities) and the positions of network actors but also has an extremely comprehensive range of methods for analysing precisely these relations and positions (see Stegbauer and Häußling 2010). This range of methods enables the analysis of individual positions in the networks (for example, by means of different centrality or equivalence measures), as well as analyses and, above all, visualisations of the entire shape of a network (density, diameter, centralisation, modularity, etc.) (see Wassermann and Faust 1994 and Newman 2018 for the scope of possibilities).

Thus, a special feature of network research can be seen in the fact that it can look at both micro- and macro-phenomena of the social network researchers speak here of freedom of scale (especially important in White 1992 and 2008). For the question we are interested in here, we see the possibility of using network research to make shifts in the field of science, triggered by the dynamisation between transformation research, transformative research and science transformations, visible. In this way, new positions such as the real laboratory expert or the expert for science communication can be identified, as well as so-called gatekeeper, broker and hub positions, which, due to their respective special structural position in the network, assume positions that are distinctly powerful and determine the discourse. What is central here is that it generally starts from observable relationships and also distinguishes different levels of aggregation, such as multiplex relationships (which integrate indeterminate forms of relationships) or clearly defined types of relationships (with White "types of tie", White 2008, p. 36ff). Here again, it is the freedom of scale that needs to be pointed out, as they occupy an important position in network concepts.

Furthermore, it is possible to explore the range of effects of certain findings or developments in one of the three phenomenon areas—transformation research, transformative research and research transformation—as well as the repercussions triggered there, as spill-over effects between different networks that are connected by transportable identities (Padgett and Powell 2012), e.g. persons who are a trade partner in a business network and a supporter in a political network. The concepts from network research allow us here to make transitions, mediation and brokerage between these areas comprehensible, as well as to make the divisions into different communities with different approaches and questions visible. Reaches are then generated through connections and mediations.

Also from a macro-perspective, individual scientific disciplines (here sociology), scientific concepts and instruments can be analysed positionally, making shifting relevance or role changes visible. Here it becomes possible to also see institutional arrangements or network clusters as units that themselves also form networks, e.g. a stronger collaboration structure between public administration and sociological research.

Finally, we expect network research to provide an answer to the general question of whether the new developments in the field of science indicated by the triad can give rise to new network structures and control regimes, which not least stand for new political and/or economic influences on scientific activity. In particular, examining these effects, between delimitable areas of the social, is a strength of the network perspective, as it can clarify how the bridges or brokers are positioned and how an overarching network with multiple levels shapes itself (Lazega and Snijders 2015).

3.3 How the Two Perspectives Complement Each Other

Both perspectives adopt a fundamentally relational perspective (cf. Häußling 2010) in that they always assume that it is only by being embedded in a structuring context that recognisable relevant social units (such as actors) can be formed and their scope for action and strategies identified. However, this structuring context arises in different ways and can therefore also be used in complementary ways. While field theory assumes objective relationships that arise from the distribution of different capacities (in Bourdieu's case, capitals) between actors or groups of actors, network theory approaches assume observable relationships (interactions, repeated interactions, communicative references, etc.) that happen more between defined units and do not derive their position from their relative endowments. Both views have great analytical potentials and are not mutually exclusive.

While objective relations allow us to observe which positions, resources and capacities accumulate, which of these capacities are particularly influential and how the weightings between groups of actors shift. Changes become apparent when new capitals become important or different groups meet in new fields. Field theory brings some concepts here that make these re-organisations in and between fields clear. The concept of hysteresis, for example, highlights the phenomenon that actors cling to their traditional capabilities even when field structures change, thus blocking transformation processes. The concept of types of capital also makes clear how actors can translate their endowments when new fields are constituted and how new positions result from this. The translation possibilities offer connections for analysing where autonomous and heteronomous poles are to be located that structure the emerging field and how transdisciplinarity can be read as a successful balance between field forces of different fields. With the help of field theory, transformation can be understood as a struggle for resources and thus positions, strategies can be identified and thus structuring processes can be analysed.

In contrast, the more directly observable types of relationships that social network analysis assumes offer better access to opportunity structures, such as brokerage positions (which can explicitly mediate between different areas) or structural holes (where solutions fail due to a lack of exchange) (cf. Burt 2007). Positions are determined here by the access paths possible to them and thus one can see where condensed areas form, to what extent these are closed to the outside and whether new positions also emerge through new possibilities of contact. The observation of entire network constellations then also enables assessments of the entire opportunity structure, of resilience if nodes fall away and of general dynamics, such as information flows or closure tendencies.

The two perspectives are often juxtaposed as if to decide whether observable or objective relations are more important or original.[3] Here, the suggestion will be made that it might make more sense to combine their strengths in order to observe and analyse a transformation process that is taking place simultaneously in research, society and new sub-fields. Mutual (de-)stabilisations of structural dynamics are expressed particularly clearly when one looks at both objective relationships (as imbalances in the balance of power) and observable relationships (as opportunity structures). Here, the complementarities between the approaches can also be made strong, which help to make three problems central to a sociology of transformation workable. Firstly, the problem of scaling structural dynamics, which opens up as a gap between transformation research (with its focus on "great transformations") and transformative research (with its orientation towards niche experiments). Here, field and network theories offer scale-free concepts that make it possible to capture the expansion of structural dynamics methodologically (cf. Padgett and Powell 2012, Fligstein 2021 and Schmitt et al. 2023). Secondly, the problematic of the methodological mix of engagement and distance calls for new research designs that explicitly address positioning and shifting relations or even use them exploratively. Finally, the two perspectives also complement each other in a third dimension, which then deals more specifically with the reconfiguration of positional relations, taking seriously that this reconfiguration can refer to quite different relations.

4 Mutual (De)stabilisation of Structural Dynamics—The Case of BIOTEXFUTURE

Using the transformative research project BIOTEXFUTURE (running since 2019 and till 2025) as an example (based on the experiences so far), we want to show the mutually influencing structural dynamics in the sociological triangle of transformation and illustrate that none of the dynamics in the pillars can be considered in isolation because they interact in specific ways, which can inhibit or support the transformations.

BIOTEXFUTURE[4] is an innovation space funded by the BMBF whose overarching goal is the extensive transformation of the textile industry from a petroleum-based to a bio-based industry. This is clearly a major socio-technical transformation, as a whole range of actors and infrastructures have to change together. For example,

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[3] Bourdieu (2005) himself is not least responsible for this with his sharply formulated distancing of his approach from network research.

[4] BIOTEXFUTURE was acquired by the Chair of Sociology of Technology and Organisation (STO, Chair holder: Roger Häußling) and the Institute of Textile Technology (Head: Thomas Gries) at RWTH Aachen University in 2019. The funding volume of this innovation space amounts to 30 million €, with which a number of consortia for the generation of socio-technical innovations in the textile sector can be funded.

petroleum-based plastics and additives account for well over 70% of the total production volume in the textile industry as a whole, and textiles made from these basic materials are the best researched and large-scale machine parks are geared to them. At the same time, consumers are accustomed to certain standards in terms of quality, functionality and price and orient themselves to them. How this can succeed is undoubtedly the subject of transformation research (in line with the approach of the MLP), which can observe many niches (start-ups developing new materials and designers trying out these materials), would also observe clear trends in the landscape and would stop at the entrenched and established processes of the textile value chain on an industrial basis. Since such an approach is evolutionary in nature, it says little about the possibilities for action and processes of reflection at the various levels that play a significant role in determining feedback and change.

The model innovation space itself evokes exciting connotations. In the bioeconomy innovation spaces, certain fields of the bioeconomy (in addition to textiles, also nutrition, maritime systems and urban spaces) are to be advanced through a targeted linkage of different innovations. To this end, they each set up an independent governance structure that determines this orientation and implements it through the selection of innovation offerings. The expectation is then that, from a transformational point of view, the different innovations will work together (i.e. together generate greater reach and impact), as this is supported in the innovation space by organised collaboration on the one hand, and there is a strategic orientation guiding such collaboration on the other. Two other features of the innovation space concept are particularly important here. On the one hand, the innovation projects are explicitly about industry-science collaborations, i.e. formats in which companies develop an innovation together with universities or research institutions, resulting in solutions that are technically and economically convincing. On the other hand, the aim is for the innovation spaces to have an external impact, so that they draw the attention of the public and politicians to the problems and possible solutions in their respective fields and thus strengthen their social relevance. Taking these features together, the construct of innovation space is already a format that directly addresses the interactions between transformation research, transformative research and research transformation by trying to change the way transformation is generated in evolutionary processes and by trying to bring about a partially "planned transition" with, however, considerable freedom in generated protected spaces (often referred to as niches in the MLP). In BIOTEXFUTURE, as mentioned at the beginning, the focus is on the transformation of the textile industry with a basic orientation towards innovations that help to avoid the use of newly produced petroleum-based plastics and additives. In this context, it is important to cover the complex and long value chain of textiles and also to map it in innovation projects, bringing together entrepreneurial ideas and scientific findings. In BIOTEXFUTURE, this is achieved through an intensive consultation process during project development, regular exchange formats, mandatory demonstrator development and transformative accompanying social science research in the TransitionLab. Insights from transformation research have thus been taken into account in the construction of the innovation space by explicitly using elements of transformative research to transform research and industry alike. The idea behind this is to have a positive impact on social transformation through research transformation in technology development. Additionally, the social sciences will learn through involvement and have to also transform their approach by creating accompanying research projects, that are able to fulfil multiple roles, studying transformation in progress, as well as supporting the success of transformation and enabling learning across boundaries.

The TransitionLab[5] in BIOTEXFUTURE sees itself as such a transformative research in that it not only observes the work in the development projects of the innovation space, but can also bring insights from social science research into them in an advisory capacity and as expertise at an early stage, thus establishing a social perspective within technology development. From a network research perspective, the positioning of experiments from transformative research with regard to the results of transformation research is particularly interesting here. Here, it is a matter of the innovation space itself being understood as a real laboratory, for example by establishing concrete relationships that support recognised synergies or by seeking semantic connections to overarching societal trends in order to bring solutions that have been found into conversation and thus disseminate them. This then already traces an interaction between transformation research and transformative research, which should be taken seriously in today's social constellation. For this purpose, the TransitionLab is also interdisciplinary, since insights from marketing, innovation research, network analysis, transformative research and transformation research must be used to achieve the most holistic view possible of the social embedding of textile innovations. However, these different insights need to be brought together and also translated for the level of technical constructions. By involving the social sciences in the construction and networking of the innovations, insights from transformation research can be directly incorporated into the design of the experiments and networks. At the same time, however, a feedback effect on science and research questions can also be observed. Thus, experimental research designs now lend themselves to be central rather than the evaluation of historical sources, and at the same time, the reactivity of science in society is now an issue and one cannot return to a simple observer position that makes non-interference the yardstick of scientificity. Instead, the issue now is to learn systematically from interference. BIOTEXFUTURE therefore tries out and practices different forms of collaboration with technically oriented development projects and stakeholders. In the process, a number of hurdles emerge in practice that must first be worked on. For example, the time and resources required for such transdisciplinary collaboration are quite high and often come into conflict with the classic planning of technical development projects. At the same time, it becomes clear that it is not the pillars themselves that are crucial for a sociology of transformation, but the interrelationships between them. Scientific advice, process organisation and science communication become elementary components of the transformation process itself, since technical innovations, e.g. the use of polymers derived from algae, are already influenced in their development by

[5] The TransitionLab is led by the Chair of Sociology of Technology and Organisation (STO) at RWTH Aachen University (Marco Schmitt).

findings from social science studies, then exploratory feedback is organised for the prototypes and finally industrial embedding is included for scaling. Here it becomes clear how mutual processes of change at different levels (research practice, forms of exchange, involvement of different actors) can generate scope for transformation. However, this also changes the position of the researcher in the change process under investigation. He or she then switches between advisor, process designer, critical observer and change agent, without being clearly committed to one of these roles. Here one is part of the "structures in motion" that one wants to investigate and shape. Here one can also see from the example that the reconfiguration of positions is by no means to be understood as a pure design process, but arises from and with the structural dynamics themselves. Positional changes are initiated, get rolling and lead to changed constellations without being able to predetermine them. The case of the TransitionLab points also to specific pitfalls those positional switchings could entail. For instance, when the social sciences should be involved in early prototyping, this creates additional work for the technical innovation projects and these additional resources were sometimes not seen as something helpful for the innovation, but as a drag on already limited resources. This may lead to mistrust and holding back on collaboration.

In this context, examples from the field of the German "Mobilitätswende" are also interesting, for example, where a successful bicycle decision not only generates imitators, but also helps to build supraregional support structures that facilitate and make it possible to facilitate the conditions for such a bicycle decision in other cities as well (cf. Schmitt et al. 2023). These multiplying relational possibilities then allow for niche accumulation (as a relationality to gain reach) that produces large-scale uniform changes. Positioning in and creating network structures then allows for a higher chance of success of the desired transformative change here.

A science that is actively involved in shaping the transformation requires specific methods and concepts to be able to do this at all. Not only do individual scientific disciplines (such as sociology) have to abandon their research paradigm, which is largely oriented towards observation and description, and enter into a more intensive entanglement with their object of study (because they are now not only a part of the object of study, society, but also change this object by means of their research, quite specifically, during the constellations of observation). They also face the challenge of developing new methods, for example, in order to meet the requirements of the necessary transdisciplinarity: Scientists and diverse non-scientific stakeholders enter into an open-ended discourse on an equal footing, which alone forms the basis of legitimacy for the negotiated concrete transformation.

In a closer look at the relation between research transformation and transformation research, it is particularly significant how an increase in the number of transformation processes within and transformation demands on society diagnosed by the latter has implications for the self-understanding of the sciences themselves. We diagnose the present as a time of increased transformational demands on society: ecological crisis, pandemic, return of war, to name only the most important transformations to which society has to find viable answers at present. This inevitably leads to increased socio-political pressure on the sciences to treat the implied research questions as priorities, for example, over questions of basic research in any discipline. At the same time, there is also a demand on the sciences to give up their freedom of value judgement in favour of a committed direct participation in the transformation as well as in favour of a normative positioning in shaping it.

We assume that a concrete socio-ecological transformation towards more sustainability can only succeed if a mutually beneficial dynamic arrangement is found for all three dimensions, i.e. for transformation research, transformative research and research transformation. At present, it can be observed that, for example, knowledge about social transformations that have already taken place is only incorporated into transformative research in a very selective manner, if at all; this is therefore an untapped potential that could be better utilised in transformation projects. This is because such knowledge clarifies possible pitfalls, interdependencies between measures or circumstances that were not anticipated in advance, typical understandings of the roles of stakeholders, the design potentials but also the design limits of each measure, the legitimacy problems of participation procedures, the different speeds at which measures are implemented, and the not always compatible inherent logics of the (scientific) disciplines, economic, official, civil society and political actors. On the other hand, in the individual scientific disciplines, persistent tendencies can be observed that stand in the way of an active transformation of their own understanding of science. An example of this is sociology, which has always resisted departing from a value-neutral position, as explained in Sect. 1 with reference to Max Weber. So if a discipline like sociology is to have an active valuational role in transformation projects in the future, what does this mean in terms of research practice?

Of course, this is not to say that sociology has to side with a social grouping and henceforth assert its interests (against those of other social groupings)—for instance, in the sense of Karl Marx's characterisation of science as a superstructure phenomenon that—in other words—only benefits the rulers in society. The value judgement dispute in our discipline has flared up again and again because it can at best only function as an ideal type, i.e. as a vanishing point of sociological research that can never be caught up with itself. For as a sociologist, one's research is itself part of the society one wants to study. Even as researchers, for example, we cannot deny our socialisation; values, prejudices, ideas and needs of our respective social milieu migrate more or less subconsciously into the research. At the same time, in times of digitalisation, scientific research is also becoming unbounded: Open Access allows barrier-free access to scientific publications by anyone and everyone. So we cannot rule out the possibility that people we interview in our daily research activities via survey have not taken note of one or two social science findings, possibly translated once again by an expert in science communication into generally understandable language.

In other words, especially in a highly networked, accelerated and delimited society such as ours, it is not at all possible to withdraw into a purely descriptive crow's-nest position; rather, we sociologists have to admit that description and evaluation stand in a complex, hardly fully reflective and thus resolvable interrelation to each other.

Knowing this and in the horizon of pressing questions of the time, in which sociological expertise is needed more urgently than ever (to shape the social pillar of sustainability), sociology needs a viable way to accompany the transformation process in a distanced and committed way. But how exactly?

A heuristically helpful answer to this question is provided by Mol's (1999) "ontological politics". It is not, of course, politics in the conventional sense. Rather, it is the politics of multiple enactments: for Mol, the quantity and variety of de facto enacted practices—and thus of practices established in a society—is a political question. She assumes that there are many, but by no means arbitrary, enactments of a specific phenomenon—such as the provision of textiles. Accordingly, it is significant which of the possible enactments are actually chosen. This is because it shapes the phenomenon in question in its continuous execution. For Mol, part of the enactment is not least her own research. That is, whether she wants to or not, her research interferes. This interfering and "taking sides" leads to the question of how social science research relates to the normative implications it generates. Mol proposes to participate in the reconfiguration of norms established in practices, without, however, having to determine in advance which concrete norms she is referring to. This distinguishes her approach from other normative approaches that introduced normative postulates as premises and used this prior normative framework to examine their research objects in an evaluative way. In other words, preferences as to which norms should be followed only emerge in the course of research in the sense of Mol. Or to use her terminology: The norms are formed in the enactments in which she intervenes with her research. It is precisely this kind of dynamic and normative positioning as a researcher that preserves the necessary agility to balance the different needs and concerns of the stakeholders in the ongoing process of knowledge discovery.

As can be seen from the example of BIOTEXFUTURE, such dynamic stabilisation is a process that requires and necessitates structural adjustments in research, transdisciplinary cooperation and the resulting learning processes. Making this describable for different cases and also drawing generalising conclusions should be the central task of a sociology of transformation, because a reflection and analysis of the entanglement of changes in different spheres through emergent elements of self-organisation, which can be triggered equally by power relations and by opportunity structures, show how research, society and newly emerging strategic fields meaningfully intertwine or dysfunctionally block each other in a transformation movement. None of the dynamics can be understood in isolation in this sense, as the effects between them are of central importance.

5 Summary and Outlook

As described, sociology of transformation is interested in questions concerning the interdependence between research, society and strategic fields that arise between them. In doing so, it is important to take a look at the multifaceted interactions that result from the entanglement of change requirements in society and research and how these are reflected in emergent constellations. A very decisive background is the fact that shaping transformation is seen as a societal requirement (problem of expectation and implementation). Politics and civil society partly expect science to participate directly in shaping societal transformation processes. At the same time, the role of science is described in this as a provider of expertise to enable evidence-based policy. Nevertheless, the evidence is framed differently in each case against the background of different convictions and strategies of the actors. And for science, the demanding challenge of not being able to non-intervene arises. This creates multiple sources of failure and peculiar side effects. In short: social transformation inescapably grips the observer (problem of position and reflection). Hence, distance is a difficult position to maintain, which manifests itself in the need to adapt methods, instruments and perspectives. A program of a sociology of transformation must combine critical perspective and distance as well as describe the question of design beyond social technology. For this, both field and network theoretical approaches make offers that are interested in structural dynamics in their course and at the same time provide methodological instruments to trace phenomena such as the gaining of reach or the changes of positions and thus also constellations and to present them in a comprehensible way.

At the same time, sociological activity inevitably approaches “engineering”, as described, in transformative research projects. It is necessary to create new formats of participation, to accompany the processes in a moderating and intervening way, and finally to make decisions on upcoming questions of direction regarding socio-technical transformation, knowing full well that this will create advantages and disadvantages which are unequally distributed among people. Initially, it seems to be an advantage that social science expertise is now being integrated into transformation processes at a much earlier stage, which is the intention of science policy. The previously prevalent method of involving sociology only in the so-called implementation phase of an innovation in order to create acceptance, or of living a shadowy existence alongside engineering-dominated disciplines in the sense of a rather influence-less accompanying research, is obviously no longer tenable in terms of science policy either. Instead of acceptance, the focus is now on participation and transdisciplinary research settings in which the perspectives of as many stakeholders as possible, especially civil society stakeholders, are included in the early phases of an innovation. It is well known from social science innovation research that fundamental decisions are often made in the early phases of innovations that can hardly be revised, improved or expanded. It is therefore of considerable importance to include sociological expertise in this phase and to raise sociology to the level of engineering. At the same time, even the most prudent transformation sociologists cannot anticipate all the consequences of their intervention in the design processes and their feedback with further interventions as well as with the contexts in which the respective transformation is embedded. Only with a time lag, which can be considerable, does it become clear what the consequences of an intervention are, i.e. what it actually is. Accordingly, this kind of sociological transformation must be accompanied by continuous monitoring and reflection of actions and experiences, as well as of the associated consequences,

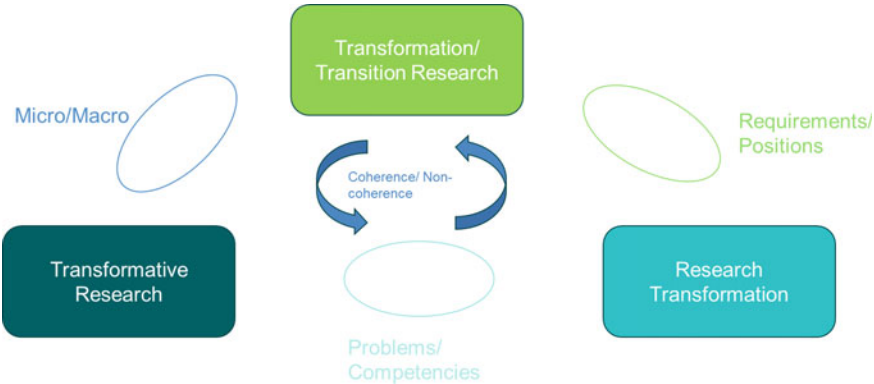

Fig. 2 Transformation dimensions and the positioning of transformation sociology

which should enable the possibility of changes of direction of varying scope to remain in the transformation process (Fig. 2).

In the middle of the triangle of research transformation, transformative research and transformational research, we see a critically reflective theory of scientific transformation that takes a look at the development in and between all three fields from a necessary distance. A widespread trend in the entire scientific landscape towards transformative formats harbours the danger of a loss of freedom for research itself; for example, if basic research without addressing the topic of sustainability hardly has any funding opportunities, a hitherto valid fundamental understanding of science will be affected. It may well be that with the science hype of the transformative, a paradigm shift in the sense of Kuhn is taking place in the direction of a so-called postnormal science (Farrell 2008). If this is the case, it is just as important to capture this as the reverse case, in which the previous science paradigm engages with the transformative in a way that is then, however, still unclear. Such a critically reasoning theory would not least have to engage in ideology critique, which is not least ignited by the concept of transformation itself. Transformation is more than "normal" change, that is certain, but the word suggests that it is also not so radical as to amount to a revolution. Are there, we sociologists must ask self-critically, any examples in the history of society in which a fundamental transformation (now towards a more sustainable society), in which all forms of economic activity, communication and interaction with nature are supposed to change, has taken place without extensive discontinuities, frictions and conflicts? In other words, doesn't a sociology of transformation have to become active in transforming the term transformation itself and keep options open here that we cannot honestly foresee in this way in nonlinear feedback reality entanglements? If one agrees with this, then the term transformation is no more than an empty word that could be retrospectively filled with the dictum of eyewash (greenwashing), a dangerous project (which, in other words, triggers more change than intended, such as revolution), or also a successful new design of society and science. In order to constructively participate in the latter filling the empty word, however, first and foremost, a critically reasoning theory of (scientific) transformation is needed. Relational approaches with their focus on positioning, scale-free descriptions and measuring instruments for structural dynamics offer a good starting position for this. In particular, a clever combination of field and network theory (as discussed here) offers the possibility of generating a sociologically substantial theory of transformation under the premise of active scientific, political, civil society and industrial participation. We plead for a sociology of transformation that should focus on the dynamics of transformations through a relational view and engage socially based on structured formats and flexible proximity and distance relations to enable a point of view that is focused on the interrelated zones of transformations and research.

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Labor Market Aspects of Transformation: The Case of Different R-Concepts of the Circular Economy

Almut Balleer, Wiebke Hagedorn, Berfin Bayram, Kathrin Greiff, and Alexander Gramlich

Abstract Sustainability transformation is a multi-dimensional and comprehensive approach covering various aspects, environmental, economic, and social, and transformation itself. To give direction to sustainability action, sustainable development goals (SDGs) play an essential role. Even though SDGs are comprehensive and give orientation for sustainability actions, they neither cover the solutions to be implemented nor quantify the transformation. In this regard, circular economy (CE) is a useful approach when it comes to finding possible solutions. Within the context of CE, life cycle thinking plays an essential role, and tools, such as environmental life cycle assessment (LCA), life cycle costing (LCC), and social LCA (sLCA), are widely used. Another important aspect that should be considered within CE is the labor market effects. The labor market will strongly be shaped by CE and the implementation of CE depends on labor market conditions. Yet, means to meaningfully measure the labor market needs and impact of CE are still missing. This chapter takes a closer look into how labor market assessment and life cycle thinking can be combined in order to implement sustainable industrial transformation.

Keywords Sustainable transformation · Circular economy · Labor market · Life cycle assessment

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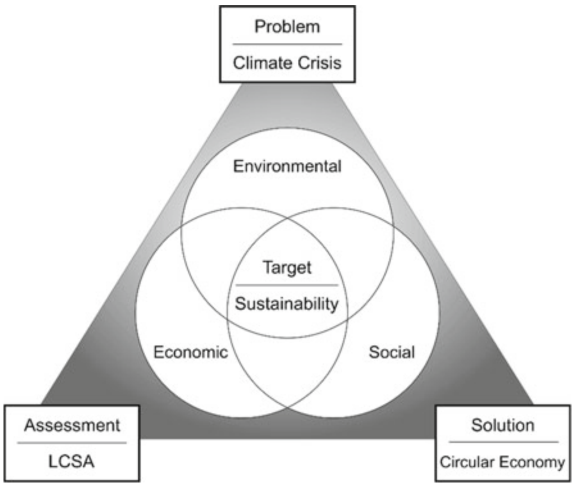
P. Letmathe et al. (eds.), *Transformation Towards Sustainability*,
https://doi.org/10.1007/978-3-031-54700-3_6

1 Introduction

The climate crisis develops at an accelerating speed and demands urgent action. It comprises the crossing of planetary boundaries such as climate change, loss in biodiversity and many other dimensions, which have a mutual influence. The climate targets are integral part of the sustainability development goals (SDGs), which define the requirements for the target state—a decent and safe living of all beings and future generations, see Fig. 1. Therefore, the SDGs represent the triple bottom line, which means considering the ecologic, economic, and social dimension alike. To achieve this ideal, solution approaches are necessary, which suggest how to adapt the world according to the goals. One prominent and promising solution approach is the CE. It aims at product-centric concepts to increase resource efficiency and sustainability by narrowing, slowing and closing material flows (Bocken et al. 2016). The so-called R-concepts are possible ways to redesign value chains and the provision of goods and services. Some key mechanisms here are the prevention, reduction, recycling, and reuse of waste streams. The approach has been addressed in multiple policy frameworks on the international level. One example is the commitment of the European Union to the CE, by addressing it as a central strategy in the European Green Deal and following Circular Economy Action Plan (European Commission 2020). One specific example of a policy on national level in line with this action plan is the tax reduction for reparation in Sweden. Another progress was the introduction of the anti-waste and circular economy law in 2020 in France. Here, a deposit system focusing on reparation and criminalization of the planned obsolescence is part of the development (Svensson-Hoglund et al. 2021).

The SDGs are the target and CE is a promising way to achieve these goals. CE activities have a strong and direct contribution to some SDGs, but overall CE interfaces with all SDGs. For instance, the CE centrally targets the SDG 12: responsible

Fig. 1 Interconnection of fundamental frameworks



consumption and production, the definition of which contains the efficient use of resources (United Nations 2015). It relates not only to the environmental but also to the economic and social dimensions of the SDGs. Regarding the economic dimension, the link is more obvious, as it is recognized that CE activities contribute to value creation. In this sense, there is a common understanding of how CE practices contribute to the SDGs with an economic dimension, such as SDG 8 (decent work and economic growth). In contrast, the understanding and recognition of the link between CE and the social dimension of the SDGs (e.g., SDG1: no poverty) is not yet as clear and strongly established, although social dimension, such as the well-being of individuals, is as much a part of the goal of CE similar to the economic and environmental dimensions (Padilla-Rivera et al. 2021). The CE is therefore tightly linked to the notion of sustainability transformation, i.e., sustainable development especially when applied on the industrial, national, or even global level. Sustainability transformation is defined by Markard et al. (2012: 956) as "…long-term, multi-dimensional, and fundamental transformation processes through which established socio-technical systems shift to more sustainable alternatives." The sustainability transformation concept requires a dynamic approach to capture the changes as it is a complex model. Even though there has been a growing attention on sustainability transformation research, a well-defined and comprehensive methodology is still lacking. So far, an established methodology is the life cycle sustainability assessment (LCSA), compromising LCA, sLCA, and LCC. However, in practice sustainability assessments are often reduced to one dimension, and very few studies cover all three dimensions (Visentin et al. 2020). The most widely applied and recognized sustainability dimension is the environmental LCA.

The far-reaching changes of implementing the CE also include labor market effects such as the creation, substitution, loss, and redefinition of jobs. The degree of these labor market effects will depend on the degree of industrial transformation and will likely vary across sectors. For example, economic activities to realize product life extension are labor-intensive and might result in an increased demand for labor input (Schroeder et al. 2019). Material-intensive sectors might reduce their labor demand, however. Scaling up the effects, e.g., to the sectoral level, will be important for the net quantitative effect. Existing employment projections for Europe are positive, estimating an increase in jobs of about 700 k. These optimistic projections build on the increased need for recycling industries and repairing services (Cambridge Econometrics, Trinomics, and ICF 2018). Also, the four most material-intensive sectors, which account for 90% of the global material use, require only 15% of the global workforce (Laubinger et al. 2020) which might reduce the aggregate adverse effects. The labor market determines other aspects over and above the quantity of labor input and the net employment effects of industrial transformation. These include the type of labor input as well as wages paid. As wages are related to labor productivity, efficiency gains from implementing the CE will determine wages paid to workers during and after the transformation. If efficiency gains are large enough, they may potentially even counteract the fact that falling labor demand reduces wages, all other things equal. The change in the type of labor input is reflected in the change in demand for skills and different tasks. These aspects are crucial to determine which jobs are resilient to the industrial change accompanying the CE. The implementation of the CE and its effect on the labor market therefore connects to the SDG 8 which promotes sustainable growth, prosperity, and decent work for all. Labor market effects are therefore part of social transformation.

The labor market is also important to make the implementation of CE possible in the first place. In fact, it is unclear whether the shift in labor demand related to the rise of new sustainable industries is met by a sufficient supply of labor. In light of scarcity of labor, it is important to understand not only the quantity but also the specific skills needed for the industrial transformation. Looking forward, details about the change in the demand for skills and tasks will inform policymakers about how to build up qualification for existing occupations and educate new workers in the best possible way to ensure not only job but also production stability and enhance productivity. The connection between the labor market and the CE is therefore also linked to the SDG 4 (quality education), SDG 8.4 (Improve Resource Efficiency in Consumption and Production) and SDG 12 (Larsen et al. 2022).

Against this background, the aim of the chapter is to outline a strategy to better assess the different dimensions of labor market transformation connected to an implementation of the CE with the aim to increase resource efficiency and reduce environmental impact. Emphasis is placed on connecting the CE and the assessment of the labor market transition through life cycle sustainability assessment (LCSA), specifically in the data collection phase. This is similar in spirit and will overlap to a certain degree with research on social LCA. Different to sLCA, the focus will be on detailed quantitative labor market effects of the production process itself and not specific indicators of working conditions when producing both inputs and outputs. The aim here is to understand the underlying industrial transformation, i.e., the change of the production process itself, in more detail and the connected qualification of labor that is needed for this. The measurement will relate closely to corresponding existing measures of labor market effects at different aggregation levels and will therefore allow scaling up of the effects from the product to the sectoral level. The level of detail uncovers the specific skills needed to make the implementation of CE possible. Taken together, our approach not only equips policymakers to jointly assess both environmental and social sustainability bringing in a new perspective but also addresses aspects of how to implement sustainable economic transition.

This chapter outlines a potential strategy and discusses a potential implementation based on a case study of applying CE to steel design. It provides a concept for assessing labor market effects, which will be explored in future research. Next to changes in the production and corresponding political incentives, the CE also crucially relies on consumption behavior. This is particularly important with respect to collection, recycling, repairing, which requires substantive collaborative action to support the success of the various CE strategies. Consumption and work are ultimately related, and therefore, labor market inclusion and competitive wages will determine consumption choices. This chapter does not discuss these aspects of sustainable consumption further.

The chapter is structured as follows. We start by outlining industrial transformation generally from two disciplinary perspectives: First the labor market perspective

(Sect. 2), and second, the perspective of the CE (Sect. 3). Section 4 then compiles the respective gaps in the disciplines and develops a strategy to jointly assess the environmental and labor market aspects of the CE. Section 5 then illustrates how to proceed within the life cycle inventory (LCI) stage of an LCA using the case study and thus describes the chance to simultaneously elaborate effects on the labor market. Section 5 also elaborates on how to apply our strategy to all R-concepts of the CE more generally, which is followed by the conclusion in Sect. 6.

2 Transformation from a Labor Market Perspective

We start by describing the link between industrial transformation and labor market outcomes excluding the question of sustainability transformation. Economics mostly refers to industrial transformation as "structural transformation" which is defined as the reallocation of economic activity across the major economic sectors agriculture, manufacturing, and services (see e.g., Herrendorf et al. 2014). Reallocation of economic activity refers to a shift in production volumes and values across sectors which can be linked to different causes. The most prominent cause is technological change and the related increase in productivity in one sector relative to another. A change in relative productivity can be linked to a change in relative prices which leads consumers to substitute products and intensifies the sectoral shift. In addition, changes in preferences may affect aggregate demand for different products which also leads to economic reallocation (see e.g., Acemoglu 2009).

Economic policy can spur industrial transformation by supporting the framework and conditions which determine the conditions of production or spur technological development. Economic policy can also affect relative prices of products, thereby directing economic, ecological, and social development and influencing the direction of structural change (e.g., through directing technical change as in Acemoglu 2002). This idea is central when assessing the scope of economic policy to fight climate change (see e.g., Acemoglu et al. 2012).

The concept of industrial transformation does not only apply to changes across major sectors. In fact, it may be used at the disaggregated economic level as well and is, hence, applicable within narrowly defined industries or even at the product level. Two perspectives can be taken with respect to the aggregate and individual effects of industrial transformation. First, one can investigate how aggregate transformation, for technological progress, affects single industries, firms, products, or individuals. This is interesting to see on average, but when there are substantial heterogeneous effects of transformation (see e.g., Hornstein et al. 2005). This means that industrial transformation affects different groups differently, for example, high-skilled workers benefit from technological progress, while low-skilled workers suffer. Second, one can investigate how individual transformation in firms and industries aggregates to shape the overall economic transformation that we observe. The relationship between "granular" effects and aggregate outcomes has been investigated substantially and depends, among other things, on (the change in) the underlying economic structure.

This structure is determined by the distribution and, hence, importance, of individuals firms for aggregate outcomes and by the interlinkages between different firms and industries through supply chains. The central result here is that changes in part of the economy, e.g., in an industry or subsector, can generate important aggregate changes, and therefore, understanding individual developments may deliver important insights for the economy as a whole (see e.g., Gabaix 2011, Carvalho and Gabaix 2013 or Horvath 2000).

A reallocation of economic activity is, naturally, related to a reallocation of production inputs and resources in the economy. Production inputs encompass intermediate inputs (such as raw materials or processed preliminary products), capital and labor, broadly defined. Hence, industrial transformation crucially changes the demand for these inputs across regions, industries, and economy wide. With respect to labor demand and, hence labor input, industrial transformation therefore has substantial implications for crucial parts of social transformation.

The central elements of labor market outcomes are employment and wages which constitute a central component of economic prosperity. There exists a traditionally pessimistic view that technological progress generally and especially when related to an increased use of capital (machinery) will make labor a redundant production factor (nicely discussed in Acemoglu and Restrepo 2018). The corresponding reduction in labor demand will then lead to a fall in both employment and wages. Structural changes such as the industrialization, the information, and communication technology (ICT) revolution or the recent automation have all led to more rather than less employment and higher rather than lower wages on average (see e.g., Herrendorf et al. 2014).

A view on the heterogeneity of labor market effects is appropriate, however. Clearly, all previously mentioned developments have made some labor input redundant and have decreased some employment and some wages, respectively. At the same time, some parts of the workforce may strongly benefit from industrial transformation when complementary to capital (machinery). An overall positive labor market development may therefore be accompanied by an increase in labor market inequality between different groups in the economy (see e.g., Herrendorf et al. 2014) being defined as the wage differential between these groups. Structural change may hence adversely affect inclusion with respect to the labor market.

Different aspects of heterogeneity have been important when assessing past developments during phases of industrial transformation. First, the largest part of the existing research and growth and inequality considers competencies of workers such as educational attainment, occupation, or skills more generally. Second, demographic characteristics of workers such as age or gender may be of interest. Different sectors and industries have a different employment structure in terms of competencies and demographics and sectoral shifts, therefore, substantially change the demand, employment, and wages of these different groups of workers.

One prominent aspect of inequality at the end of the twentieth century is the increase in the skill-wage gap, defined as the differential of wages between high and low-skilled workers that has been observed across developed countries, but particularly so in the USA. Skill here usually refers to educational attainment, where low skill is predominantly measured as up to high-school education and high skill refers to some college education or higher. The increase in this gap can be related to many aspects that have changed over time, but is, most importantly, explained by the concurrent advances in information and communication technology (ICT). ICT has enhanced productivity of a large range of capital equipment (machinery, computers), in the service sector. This so-called capital-embodied technical change can explain the increase in the wage gap if one type of labor input (skilled labor) is complementary to capital, while another type of labor input (low-skilled labor) is substitutable with capital in production. The economic literature refers to this phenomenon as "capital-skill complementarity" (see Herrendorf et al. 2014 or Hornstein et al. 2005 for more detail).

The discussion on the skill-wage gap reveals the importance of the underlying production process for the labor market effects of transformation. Here, the production process (the production function) itself does not change, but instead, one of the production inputs (capital) becomes more productive which affects the quantity and price of all other inputs (labor), and differently. Some labor will be replaced by capital, a process which recently has been generally referred to as automation. An example like ICT and the increased use of computers is the rising implementation of robots, in manufacturing. Here, some labor input is also replaced (substituted) by capital input (see e.g., Dauth et al. 2021), while some labor input is complementary.

The focus has shifted from the exclusive measure of skill (education) to also measuring labor input in terms of occupations or tasks. Occupations usually refer to the occupational area (field such as biologist, social scientist, etc.) which is sometimes also related to industry or sector, and occupational type (Managers, professionals, technicians, sales, etc.) which informs about the position in the hierarchy. Occupations are usually classified, e.g., as KldB in Germany or using the ISCO standard internationally.[1] In addition, occupations are often linked to and measured together with tasks. According to Autor (2013), "a task is a unit of work activity that produces output. A skill is a worker's stock of capabilities for performing various tasks." Hence, occupations and tasks are related to skill. Tasks measure the actual activity on the job such as selling, teaching, repairing, etc. (see Rohrbach-Schmidt 2009). Tasks often also measure complexity and are grouped into routine versus non-routine, but also manual versus complex or cognitive versus non-cognitive. These aspects of tasks are sometimes, but not generally measured together with the occupation. Measuring tasks together with occupations follows the definitions used in the databases of the BIBB/IAB, or DOT and O*NET (see Autor 2013 for a good overview).[2]

The production process can be thought of as a series of different tasks as depicted in Fig. 2. The economy starts from a production process as shown in panel A. Some tasks are more labor-intensive, some more capital-intensive. Automation then means that

[1] See https://statistik.arbeitsagentur.de/DE/Navigation/Grundlagen/Klassifikationen/Klassifikation-der-Berufe/Klassifikation-der-Berufe-Nav.html.

[2] BIBB/IAB (https://metadaten.bibb.de/de/group/dataset/23), source: Federal Institute for Vocational Education and Training Germany (Bundesinstitut für Berufsbildung) and Institute of Employment Research (Institut für Arbeitsmarkt und Berufsforschung); DOT and O*NET (https://www.onetonline.org/), source: U.S. Dictionary of Occupational Titles from the U.S. Department of Labor.

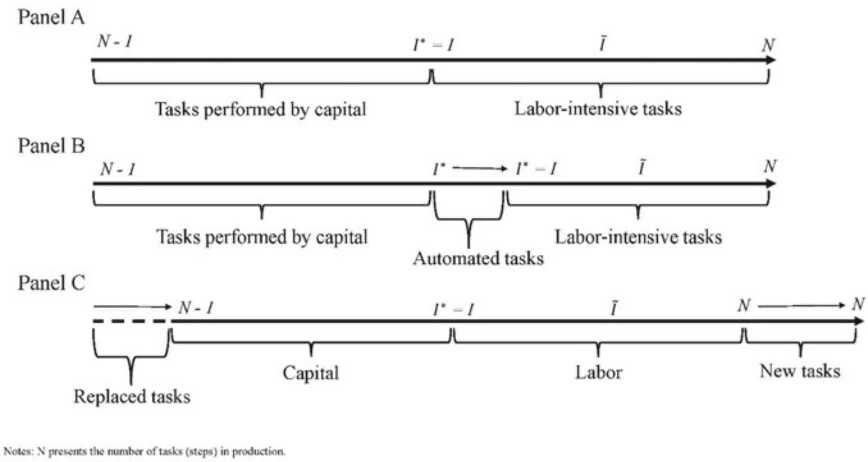


Fig. 2 Production process as a sequence of tasks (according to Acemoglu and Restrepo 2018)

some of the tasks previously performed by labor are now automated, i.e., performed by machines (see panel B). Empirical research shows that replaced tasks are often manual and routine tasks, while cognitive, non-routine, or complex tasks are less often automated (see e.g., Dauth et al. 2021). This intensifies the wage inequality between occupations that perform different tasks. Since non-routine and complex tasks are often performed by occupations which also require relatively high skill, automation also increases the skill-wage gap described above.

In addition to changes within production processes, transformation may induce the production process itself to change. Technological progress, related to automation, for example, may render some production steps obsolete altogether, but may also generate new production steps (tasks). This is illustrated in panel C of Fig. 2. If we relate tasks to occupations, this means that some occupations become obsolete, some occupations change the structure and type of their tasks and new occupations appear. Dauth et al. (2021) show substitution within and across occupations for robotization in German manufacturing, Acemoglu and Restrepo (2018) document the growth in new occupations between 1980 and 2015 in the USA.

A favorable labor market development during structural change therefore relies on both a sufficient increase in productivity to generate larger or more valuable output which leads to an increase labor demand for all remaining tasks generally and the sufficient appearance of new tasks relative to abundant. For existing employees, structural change can therefore generate employment stability and/or wage increases if their tasks are complementary to the process driving transformation or if they are able to learn on the job to change the composition of the tasks answering the change in demand for labor input. Fitzenberger et al. (2020) show that persons who perform cognitive tasks experience more stable employment between 1990 and 2005 and are, hence, more "resilient" to change. Skills and education, which are often a prerequisite for jobs with cognitive tasks, have therefore shielded workers from adverse effects in the past.

Labor market outcomes are not only the result of changes in labor demand but also labor supply. Educational attainment has substantially increased over time (see e.g., Autor 2014). Labor supply as a whole has increased in numbers but will decrease in the future due to demographic developments. Moreover, hours worked per worker have substantially decreased over time (see Boppart and Krusell 2020). Labor shortage especially of skilled workers has increased in importance and restrains production (see e.g., Balleer et al. 2022). If labor supply of skilled workers or workers being able to perform certain tasks does not meet changes in the respective labor demand due to industrial transformation, inequality between skilled and unskilled and between workers with different tasks will intensify. Labor market policy can attempt to stir labor supply by encouraging education or supporting on the job training in times of structural change.

3 Transformation from the Perspective of the Circular Economy

As already mentioned above, the question of how industrial transformation goes along with a sustainable transformation is very much in the political focus all over the globe. The CE is seen as one relevant solution approach, which is introduced in the following (Domenech and Bahn-Walkowiak 2019). This section addresses the definition and strategies of CE, how to translate it to the product level, and how to ensure that induced change is in line with the overall strive toward a sustainable development. The labor market perspective is not included in this section.

The sustainable use of resources requires a holistic, systemic approach that combines economic, environmental, and social aspects. Therefore, the CE combines multiple approaches, which are often addressed separately. The concept integrates various doctrines and perspectives. It looks at the entire societal metabolism and combines it with a life cycle approach at the product level. The transition to a CE is intended to enable the efficient and circular use of natural resources to keep resource consumption within planetary limits. What is required is a holistic system change such as structural change in consumption patterns and rethinking and creating production chains. In addition to dematerialization (savings and reduction of both material and energy consumption), strategies for rematerialization (reuse, remanufacturing and recycling) are also required, leading to a CE.

In short, it can be said that in a CE, raw materials and materials should be kept in use—in the economic cycle—and waste, including emissions, should be avoided (Ellen MacArthur Foundation 2012; Kirchherr et al. 2017). The aim is to maintain the value added in raw materials, materials, and products for society and to avoid further expenditures and negative impacts (BAFU 2021; Ellen MacArthur Foundation 2012; Kirchherr et al. 2017). This leads to the narrowing, slowing down, and closing of material flows and cycles and thus reduces the extraction of raw materials from the environment (Bocken et al. 2016).

The approach became increasingly popular in the last decade founding on various concepts and long research in the field of resource efficiency (Reike et al. 2018). It is seen as a promising solution and is addressed in various political frameworks. However, the dynamic development in an international and interdisciplinary scientific environment led to a diversity of definitions. The definitions often comprise various focus such as material flows, environmental impact, business models, consumption patterns, or products. Kirchherr et al. (2017) published the most comprehensive review including 114 definitions in their analysis. It included the sustainability dimension according to the triple bottom line—economic, environmental, social—as one criterion as well as time, the consideration of business models, R-concepts, and the waste hierarchy. The authors found that none of the definitions included the required aspects in a holistic manner and suggested the following definition:

> A circular economy describes an economic system that is based on business models which replace the 'end-of-life' concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes, thus operating at the micro level (products, companies, consumers), meso level (eco-industrial parks) and macro level (city, region, nation and beyond), with the aim to accomplish sustainable development, which implies creating environmental quality, economic prosperity and social equity, to the benefit of current and future generations. (Kirchherr et al. 2017: 225)

However, the definition of the CE is of general nature. To implement the CE in practice, it requires a specification for the micro level as the materials in the anthropogenic system are used for and bound up in products. Such specifications are named R-concepts. They describe possibilities for maintaining the value of materials, so-called Value Retention Options and are based on the life cycle of products. Again, there are various translations of the CE definition into so-called R-concepts. In literature, there are approaches that span 3 to 10 different strategies (Reike et al. 2018). A common approach with a high differentiation is that of Potting et al. (2017) which is shown in Fig. 3. It includes 10 R-concepts that are ordered according to the degree of circularity. The latter reflects the idea of the waste hierarchy. The degree of circularity is less an indicator than an estimation and expectation regarding value retention and reversibility. The higher the degree of circularity of the implemented R-concept, the higher the expected contribution to a circular product or economic system. In principle, the application of a plurality of strategies to a product system is possible, but the implementation occurs sequentially in time.

The R-concepts depicted can be divided into three groups according to the above-mentioned effects—narrowing, slowing, and closing material cycles. Refuse, rethink, and reduce are R-concepts that start in the product development process. Redesigning the product or even the way it is used, for example, by changing business models, can achieve a reduction in resource requirements for a product system. The development of new product service systems and/or the establishment of new consumption patterns is one possibility (refuse). The intensification of product use is another (rethink).

An R-concept that primarily targets product design is "reduce." This can mean, for example, changing product design by applying lightweighting principles (Hagedorn

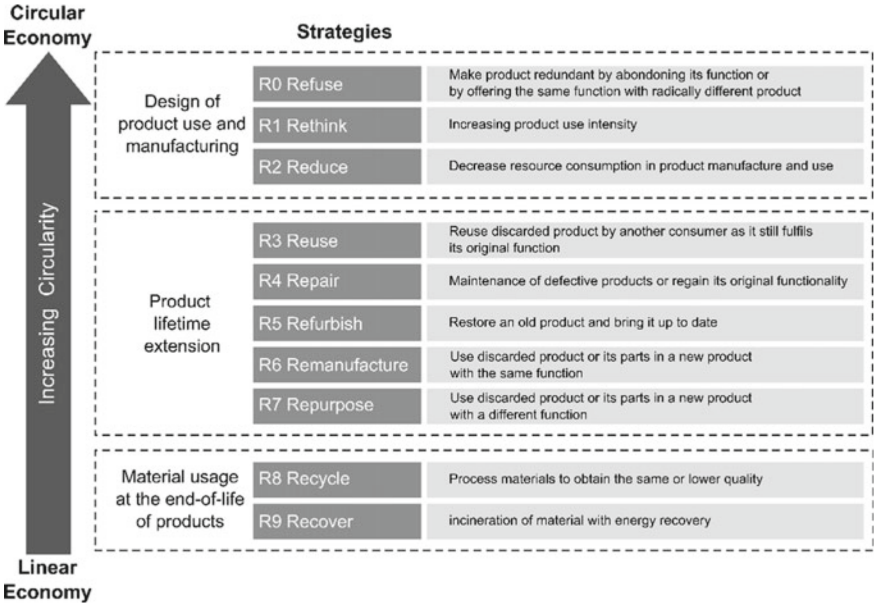


Fig. 3 Translation of the circular economy onto product level (according to Potting et al. 2017)

et al. 2022). In some cases, it also comes down to over-functioning products. An example is the payload of some steel beams, which are not always necessary to that extent. This in turn enables the reduction of material use (Brütting et al. 2019). The reduction of resource demand can also be achieved by optimizing the manufacturing process and improving the production yields.

The R-concepts reuse, repair, refurbish, remanufacture, and repurpose, on the other hand, act on an existing product. The aim is to increase the service life and provision of the functionality of a product or its components. In this way, the materials remain in use and in anthropogenic storage for longer, the product lifetime is extended, and the flow of materials through the system is slowed down. The need for resources for new products decreases because existing products and their functionality are available. An example here is multiple use by different people if the product still provides a service (Reuse). This corresponds to the second-hand market at flea markets or internet-based platforms. If the product is defective, it could be repaired. Another option is the general overhaul of a product (Refurbish). This involves, e.g., disassembly, cleaning, and repairing processes. If a product does not provide any service and can no longer be repaired or refurbished, the product or components can be used in another product with the same function (Remanufacture) or a different function (Repurpose).

The R-concepts recycle and recover are the options classified with the lowest degree of circularity. Both strategies focus exclusively on the materials that are bound up in the product. Therefore, these strategies should be used as the last option to make use of products. When recycling valuable materials such as metals, plastics, glass or paper, various processes are necessary to create valuable secondary material as an output. Ideally, the material flows back into the manufacturing of products as an input and substitutes primary material. It must be considered that qualities or material properties change as there are limits to the recycling processes. Thermochemical recycling (recover) is the material or energy recovery of material flows for which there is no other possible use.

The CE is presented as being environmentally superior compared to the linear economy. And applying circular strategies to a product system has the potential to increase the material efficiency and at the same time significantly reduce the environmental impact. It even needs a combination of so far-undertaken energy efficiency measures and material efficiency measures related to the CE to meet climate targets (Hertwich et al. 2019). But the improved environmental performance is not a sure-fire success: The implementation of circular strategies can lead to a shortened production process which is also shown by the presented case study (see Sect. 5 and Hagedorn et al. (2022)). It can require an adaptation or even a different process which has changed input and output parameters resulting in a changed environmental impact. It can also require additional processes such as transportation, disassembly, cleaning, preparation, and replacement of components. Additionally, the material efficiency does not per se correlate with the environmental impact. Therefore, it is fundamental to investigate the adapted product system and compare it to the status quo to prevent effects such as backfiring.

Most studies show the multitude and diversity of indicators for evaluating CE (Elia et al. 2017; Kristensen and Mosgaard 2020; Parchomenko et al. 2019). However, the range of indicators is heterogeneous and does not cover all strategies equally. Thus, most indicators are assigned to the closing and slowing down of material flows. Narrowing is hardly covered. Most indicators focus on the outer cascades which mean recovery and recycling, which are an example for closing, see also Table 1. The indicators result often from balancing material flows, mostly excluding the material quality (Hagedorn et al. 2020). In terms of recycling, especially, the qualitative differences resulting from impurities and contaminations show the difference between product systems. It is based on the imperfect sorting and mixing of different material grades. It inhibits the absolute decoupling from primary material demand which offsets losses and inefficiencies.

Considering the aim of the CE to be a holistic systemic approach striving for sustainable development, there is an imbalance of assessment approaches. This is shown even by focusing on the environmental dimension only. A multitude of indicators are found in literature to assess the environmental impact. It is valid if mass-based indicators are assigned to the environmental dimension (Jerome et al. 2021). But the environmental impact includes various categories which do not correlate. Focusing on the resources only can lead to so-called burden-shifting (Hauschild et al. 2018). Furthermore, the scope should be considered. There are a multitude of simple indicators with a narrow focus in opposite to assessment methods including upstream and downstream processes to a varying degree (Elia et al. 2017; Jerome et al. 2021). The inclusion of indicators is valuable to assess changes in the process chain on a very

Table 1 Possible labor market effects due to different R strategies

CE strategies	R-concepts	Possible labor market effects	Data collection possibilities
Narrowing	Refuse	Change in consumption patterns and behavior leads to a comprehensive change in what products are needed to the point that no more products are needed → elimination of production processes but also change to new service-systems e.g., change in mobility (no own car) leads also to a change in shopping behavior for example to more delivery services	Data on labor market characteristics of workforce before implementation of strategy (doable) Data on labor market characteristics of future services (try and infer from existing services) Data on future consumption patterns (speculative)
Narrowing	Rethink	Increasing product use → sharing economy → Number of products reduced, but rental service is needed	Data on labor market characteristics of workforce before implementation of strategy (doable) Data on labor market characteristics of future rental services (try and infer from existing services)
Narrowing	Reduce	Reduction of needed material and energy for same service/function, can be achieved with less material or different material → Elimination of specific production processes and thus of related jobs, occupations and tasks	Data on employment, hours worked, demographics, skills, occupations, and tasks before implementation of strategy (doable)
Slowing	Reuse Repair Refurbish Remanufacture Repurpose	Product level (R3, R4, R5) no new products are needed, number of products is reduced. But services are needed and thus skills for disassembly, cleaning and repairing Remanufacture and Repurpose Product parts are used in production process of same or different products → no new material is needed → different production processes and thus different skills are needed	Data on employment, hours worked, demographics, skills, occupations, and tasks before implementation of strategy (doable); measuring scale of output is important (forward-looking)

(continued)

Table 1 (continued)

CE strategies	R-concepts	Possible labor market effects	Data collection possibilities
Closing	Recycle	Depending on the application of recycling, material for different processing steps are needed and thus different skills, e.g., collection, sorting, raw material production	Data on labor market characteristics of workforce before implementation of strategy (doable) Data on labor market characteristics of future production steps (try and infer from existing production, doable)
Closing	Recover	In future we will need to use also more recovering processes like gasification and pyrolysis to close carbon cycles → new skills are needed for this	For existing production steps, collect labor market characteristics from comparable industries Assessment for completely new processes should relate to existing characteristics (speculative)

detailed level (Jerome et al. 2021). However, these are not sufficient for ecological assessment (Hagedorn et al. 2020; Helander et al. 2019). Therefore, more comprehensive methods such as the environmental LCA should be used to investigate the overall change in environmental impact (Elia et al. 2017). Particularly for CE assessment, quantification of environmental impact is important, and LCA is a very useful tool as a support for environmentally sound decision-making.

The methodology of LCA is defined in the ISO standards 14040 and ISO 14044 (EN ISO 2020a, b). The methodological principles strive for a holistic approach and the so-called life cycle thinking, a systematic consideration of all life cycle phases from raw material extraction to material disposal. The selection of impact categories such as climate change, acidification potential, or ecotoxicity is of high importance. Considering all relevant impact categories prevents the so-called burden-shifting (Hauschild et al. 2018). The iterative process of conducting an LCA is structured in the (1) definition of goal and scope, (2) the preparation of a life cycle inventory (LCI), (3) the impact assessment, and the (4) interpretation. The goal and scope include the choice of modeling approach (consequential, attributional) and the precise definition of product system and define the functional unit, which is the foundation for the comparison. The LCI is often the most comprehensive stage of an LCA. Here, the processes of the defined product system are modeled including all relevant input and output flows such as energy and materials. This leads to a detailed description of value chains. The impact assessment comprises the linkage of the LCI to impact factors of various categories such as global warming potential, acidification, freshwater use, and toxicity. Those impact categories are midpoint indicators, which can be combined in endpoint indicators, which summarize categories on a higher level such as the ecosystem, human health, and resource availability. Lastly, the results are interpreted with respect to the initial goal of the study. An LCA enables to compare product systems providing the same good or service. Therefore, the results are relative within a good or service category.

Existing LCA-based studies cover a wide range of products and CE concepts such as recycling, product life extension, and reuse (Harris et al. 2021). Particularly for CE, different methodological approaches and allocation procedures need to be considered and discussed to appropriately model circular interventions such as recycling (Nicholson et al. 2009). A separate research focus here is the linking of the different levels of consideration. Challenges are data availability and compatibility as well as system complexity.

The CE approach is systemic and brings far-reaching changes that contribute to sustainable transformation. The focus of CE is on the flows of raw materials that are taken from the ecosphere through extraction as an anthropogenic intervention. The goal is to meet the needs of people through the production and use of raw materials in the form of products in the anthroposphere. The focus of analyzing circular interventions lies so far on the economic and environmental dimensions. However, assessments most often exclude the social dimension, even though CE is a holistic and systemic approach (Hagedorn et al. 2020; Harris et al. 2021). Analyses show that only 13% of publications explicitly refer to holistic sustainability (Corona et al. 2019). Against this backdrop, there is extensive discussion on how and whether CE as well as metrics address holistic sustainability (Kirchherr et al. 2017).

4 A Strategy to Assess Labor Market Aspects in the Circular Economy

Section 2 exhibits how industrial transformation has impacted the labor market and how this is closely linked to the transformation of production processes. Section 3 defines and describes the solution approach CE and why LCA is useful for assessing its effect. Implementing R-concepts is therefore expected to affect labor market outcomes and through this, one critical part of social transformation. The connection of the labor market perspective with the assessment of different dimensions of sustainability provokes questions that have yet been unanswered and that we elaborate on in this section.

4.1 The Research Gap from a CE and a Labor Market Perspective

From the disciplinary perspective of the economics of the labor market, labor market outcomes have been measured in many dimensions which provide detailed insights into many aspects of the SDGs. This encompasses measuring the quantity of labor input, but also its quality and detailed information about occupations, jobs, and tasks. These are important to assess the heterogeneous impact of industrial transformation on the labor market (inclusion), but also to assess the quality of work (prosperity). As Sect. 2 outlines, existing research on the labor market effects of industrial transformation has relied on available data on the quantity and detailed characteristics of the labor market and is therefore, by definition, performed ex-post. This renders the evaluation of concurrent or future phenomena such as digitization or the transformation of the energy system difficult and speculative. In order to design forward-looking labor market policy that accompanies industrial transformation well, it is important to connect the assessment of labor market effects more closely to the production process. Understanding future changes in production processes will enable us to understand future changes in labor demand, possibly as detailed as at the occupation or task level. This would enable policymakers to assess potential scarcity on the labor market with respect to quantity of labor or specific skills and allows to design and target labor market policy while or even before industrial transformation takes place. The strategies of the CE evaluate current production processes and lay out actual and potential changes in the production process by means of the LCSA. Connecting traditional disciplinary labor market assessment more closely with an LCSA approach might therefore provide promising insights for policy decisions.

A first set of studies that quantify the labor market effect of the implementation of CE strategies gives an outlook on possible scenarios on the quantitative employment effects. Here, projections are based on the adverse effects of vanishing industries, e.g., material-intensive industries, and the beneficial effects of (re)appearing industries, such as repairing, recycling, etc., that are potentially labor-intensive (Cambridge Econometrics et al. 2018; Laubinger et al. 2020). These projections therefore focus on the industrial or sectoral level and do not consider (detailed) changes in the production structure. The CE is highly product-centric, however. R-concepts may be applied differently to different products both across, but also within industry or sector which may generate highly heterogeneous effects. This is especially important when scaling up (aggregating) the effects of the CE to the industry, sectoral or national level.

The assessment of the environmental aspects of CE strategies based on a LCA is also product-centric (case-by-case). It then follows that evaluating these strategies along the full triple bottom line would also be performed at the product level. The environmental LCA can be expanded to cover also the social and economic sustainability dimension based on the life cycle costing analysis (LCC) or the social life cycle assessment (sLCA). LCA, LCC, and sLCA are correspondingly all performed at the same level and follow the general 4-step procedure outlined in the previous section. Broadly speaking, all approaches can in principle be defined on the same product system but refer to different aspects with respect to the goal and scope (step 1) as well as the interpretation (step 4) of the analysis. This then also means that different data is collected (inventoried, step 2) and the measurement of the triple bottom line needs to employ different indicators, i.e., impact categories (step 3).

The awareness of LCC increased in the 1970s, when it was realized that purchasing decisions should not only be based on initial acquisition costs but operational and maintenance costs should be additionally considered. This was also found in Europe in the mid-1970s, through the increased attention on the share of follow-up costs within total cost in the building and construction industry (Hoogmartens et al. 2014). It can be differentiated between three types of LCC. The *Conventional* LCC (cLCC) is usually from the perspective of one market actor, such as manufacturer or consumer, and only direct costs and revenues that are relevant to the performer of the LCC are considered. The system boundary of cLCC covers only internal costs which occur within the economic system where sometimes the use and end-of-life costs are even neglected. Environmental LCC (eLCC) assesses all internal costs and environmentally relevant externals that occur during the whole life cycle of a product. It is suggested to perform eLCC aligned with LCA. Societal LCC (sLCC) includes all internal and external costs within the life cycle of a product that is covered by anyone in society. sLCC covers eLCC and further external costs, such as positive or negative consequences for society, considering current and future impacts (Hunkeler et al. 2008).

The development of the sLCA is more recent and aims at quantifying and qualifying the social impact of products and services along their entire product life cycle. It differentiates between stakeholders such as workers, local communities, society, consumers, and value chain actors (UNEP 2020). Like the LCI that measures the input and output flows related to environmental impact, sLCA assesses the social impact of a product system. Within sLCA, various impact categories covering six stakeholder groups (worker, local community, value chain actors, consumer, society and children) are available. For instance, some impact categories with respect to workers are child labor, fair salary, health and safety. There is a wide range of impact categories covering various aspects such as local employment, cultural heritage, corruption and fair competition and salary (Benoît-Norris et al. 2011, UNEP 2021). The sLCA is based on indicators that measure the degree of the different impact categories named above both qualitatively and quantitatively (e.g., in the PSILCA database, see Maister et al. (2020)). Most often the impact is measured at the input level of production, i.e., with respect to material or intermediate products. Here, standards in (industries of) origin countries are often behind the impact assessment. Less often, an assessment of standards has been applied to the production modes or output and, hence, production in developed economies more generally. Tokede and Traverso (2020) review the application of sLCA to a number of cases and outline shortcomings and future paths of extending and improving the sLCA.

In sLCA, the data collection and its quantification are challenging as the data collection process itself is time-intensive and the quantification of the data in sLCA is seen to be a subjective process (Onat et al. 2017). With the increased awareness on sLCA, some databases have been developed to quantify the social impacts with the aim of reducing the consumed time on the data collection and creating a base for a transparent impact assessment. The Product Social Impact Life Cycle Assessment Database (PSILCA) and the Social Hotspot Database (SHDB) are the two main databases that are currently used in sLCA. SHDB is based on a worker hours model, in which annual wage payments and wage rates by country and sector are used. In the PSILCA database, which has the basic activity variable as worker hours, comprehensive data on industry and country level considering four different stakeholder groups, workers, value chain actors, local community, and society are included. Even though there is a growing attention to improve the data quality in sLCA through databases, the current databases are criticized as they do not demonstrate regional or local particularities (Huertas-Valdivia et al. 2020). Moreover, the indicators behind the sLCA are useful to measure social conditions generally and the impact categories named above in particular. Due to the nature of an indicator, one can primarily assess a change within an impact category, but it is hard to compare the performance of a product or service category across impact categories.

Due to its assessment based on indicators and its aim to cover social aspects broadly, the sLCA does not allow a very detailed labor market assessment. It can only quantify labor market outcomes to a limited degree, focuses mostly on labor market aspects related to the production of inputs, but less the production process that is affected by the CE itself, and it cannot inform about details and various characteristics of labor market input which are needed to design meaningful and targeted labor market policies. The clear advantage of an sLCA is the close link of social assessment to the LCA, LCC, and other components of the LCSA via the life cycle thinking approach to the product system. The strategy we propose combines the life cycle thinking approach with labor market assessment. It therefore overlaps with sLCA in some respects but should mainly be seen as a complementary assessment to sLCA. In this study, we focus on the connection of LCA and labor market assessment. The connection to other components of the LCSA is straightforward, however, but left to future studies. Moreover, different to sLCA, our strategy does not only yield an assessment of the labor market aspects of CE but also provides a detailed view into the challenges of implementation and scaling up the CE.

4.2 A Strategy to Assess Quantitative and Detailed Labor Market Effects Within an LCA

What would the connection of a labor market assessment with an LCA mean precisely? Let us start with the product level. Moving along the aforementioned stages of the LCA, performing a labor market assessment together with an environmental assessment has the following implications:

(1) Goal and Scope: The environmental LCA defines the product system and the goal and scope with respect to the environmental impact that should be assessed. This is illustrated by the inner column of Fig. 4 as the product-centric R-concepts of the CE are applied to goods. A labor market assessment would extend the goal and scope of the analysis (step 1) to also consider the labor market impact. Labor market assessment can be seen as a relevant part of the sociosphere. This step is conceptually similar to extending the scope of the LCA to also include sLCA. The variables and outcomes defined are different to sLCA, however Generally, the definition of the product system, its functional unit, reference flows, as well as the back- and foreground system are not changed through this extension. The stage and, in this case, the application is unchanged. Within the first stage, the impact category framework must be chosen. Next to the environmental impact category, further labor-related variables and outcomes must be defined and included. These encompass the number of workers and hours worked and the related occupations, skills and tasks of these workers during these hours.

(2) Life Cycle Inventory: This stage includes data collection. For the environmental LCA, this is often based on close cooperation with industry partners. To define the production process and receive primary data, visits to the production site are common. The input and output flows in relation to the functional unit and reference flow are quantified. To evaluate labor market effects in a detailed way,

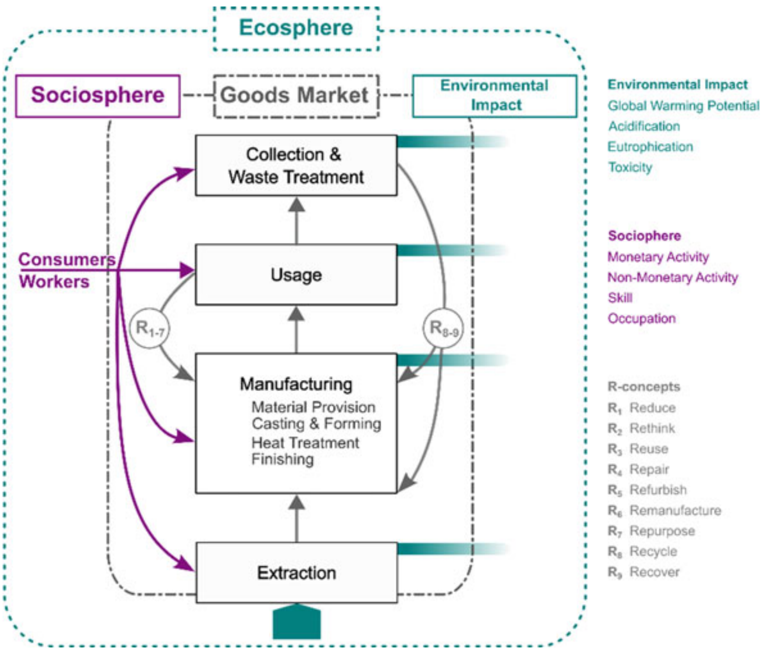


Fig. 4 Multi-level perspective on a generic process flow and examples for environmental impacts and sociophere (own graphic)

it would be possible to simultaneously collect data regarding the labor input at each production step of the environmental LCA. This is reflected by the green (environmentally relevant) and purple (socially relevant) arrows in Fig. 4, where labor market effects cover a particular part of the sociosphere. In many applications of sLCA, the production steps are referred to only when considering the energy and material input and, e.g., the working conditions in the production of energy and material inputs. Here, measurement would not relate to the inputs at all, but instead focus on the detailed labor market aspects of the actual production processes. More concretely, at each production step, one would collect the number of employees involved, the number of work hours in combination with the occupations of these employees (following the KldB or ISCO classification), their skill measured in their educational attainment (completed and not completed degrees of education), their age and gender (not of primary importance), and, if possible, their hourly wage. One would moreover measure the tasks performed at each production step according to the definition in the BIBB/IAB, DOT O*NET and/or STAMP. It is useful to also collect information about the machinery operated in each production step if the information is accessible. This informs us about automation of processes rather than their omission. The above describes a data collection strategy for new LCAs that aims at a joint assessment of environmental and labor market impact. For existing analyses, one would need to collect information about labor input measured in the same way as outlined above linked to different production steps. This requires building an inventory similar to the existing inventories for environmental or social LCAs.

(3) Impact Assessment: This stage integrates the input and output flows of single processes with impact categories. The impact assessment of the environmental LCA is performed parallel to the assessment of labor market effects. Environmental LCA and labor market assessment do not interact. The assessment of labor market effects is based on straightforward aggregation of the quantitative measures of employment, hours worked, occupations, and wages. The combination of occupations, skills, and tasks is also aggregated, but weighted with their respective importance. For example, if certain tasks are more central to a production process than others, they obtain a higher weight in the aggregation. Relating labor input to output allows assessing labor productivity and linking this to measured wages.

(4) Interpretation: This stage of LCA remains unchanged in principle. The data are analyzed and the difference between various product systems is shown. Key here is the change in the production process, i.e., whether each step of the process is kept, changed, or abandoned when implementing the proposed CE strategy. For example, it would allow us to compare conventional and circular product systems. In general, multi-dimensional interpretation is difficult. For example, with respect to the environmental performance, a conventional product might be superior in terms of global warming potential, but inferior in terms of human toxicity compared to a circular product. Increasing complexity in the assessment then poses a conflict of interest with respect to the objectives of the analysis.

A multi-dimensional interpretation can either report the interpretation based on each dimension parallel to each other or come up with some measure to prioritize or aggregate different impact assessments. Adding the labor market aspects would in principle not increase the dimensionality of the interpretation. Instead, it would inform about the labor market consequences of each possible interpretation. The change in the quantity of employment informs us about job stability and resilience. The change in the quantity and combination of occupation, skills, and tasks informs us about changes in labor demand. Relating these changes in demand to existing labor supply provides a measure of scarcity (or abundance) of labor needed for the transition. Increased multi-dimensionality would be present if labor market consequences and environmental consequences were to be traded off in some way. This is not yet taken into account in this strategy, however.

Moving beyond the product level, the goal and scope of the analysis could include more aggregate labor market effects at the industry, sectoral, or even national level. As our labor market assessment is quantitative and reflects commonly used aspects of labor supply and demand in the literature, aggregation to higher levels follows the same procedure as aggregation at different production steps (see step 3). The aggregation will consider that different products, industries, and sectors should be weighted according to their size, e.g., measured by their employment shares, value added or similar. While labor demand can be easily aggregated, it is important to note that a change in labor market demand will not necessarily equal the change in employment. Some labor market outcomes such as wages or scarcity cannot be easily scaled up by simple aggregation but are results of the interplay of labor demand and labor supply on the labor market. For example, the supply of labor including different dimensions of skill as well as the demand for skill-related tasks in the same and other industries as well as the size of different industries are relevant and will affect wages. Extending the scope of the analysis would leave the data collection at the product level (step 2) of the analyses unaffected. In addition, one would need to collect information on labor demand and supply as well as size of the production within the product class, the industry the product belongs to, within the sector, etc. For employment and hours worked, this data could be collected from administrative labor market statistics at the disaggregate product level (such as statistics from the Destatis or IAB for Germany). For more detailed information at the more aggregate industry level, one could use the BIBB/IAB database that collects occupations and tasks at broad industries. The impact assessment (step 3) would then need to include an aggregation from the granular (individual or product) to the more aggregate level. This will then allow us to assess aggregate labor market effects as well and allow insights into the general importance and heterogeneity of the labor market effects. The impact assessment would then also include a concept of evaluating the interplay of supply and demand for labor market outcomes such as wages, e.g., by means of an economic labor market model. Thinking aggregation further, industries or sectors are part of complex organizational systems and are embedded in value chains. Similar to the existing projections of the labor market effects of CE, it is possible to take into account how changes in production patterns might also affect upstream and downstream production (using input–output linkages). Consequently, they will also affect labor market outcomes in up- and downstream industries. The higher the level of aggregation, the closer the analysis to measuring the total impact (cost on) the sociosphere of implementing CE strategies.

Moving from the perspective of a particular product to the industry, sector or national level also raises the question of assessing the effects of the implementation of (comparable) CE strategies on other products within the same or in a different industry. This means the joint assessment and potential interplay of the labor market effects of CE strategies with respect to more than one product category. Following the strategy above, this includes data collection across a range of related products. Alternatively, it would be valuable to incorporate labor market assessment on already existing LCSA generally, or environmental LCAs specifically, with respect to CE strategies. This would mean to change the life cycle inventory (step 2) substantially by moving from data collection to filling in missing labor market data on existing finalized LCAs. We do not address this approach further in this chapter.

One central characteristic of the CE is the involvement of the consumer. The consumption perspective is especially crucial when it comes to the so-called rebound effects, which often hinder the full environmental potential of sustainable solution approaches. In fact, consumers and workers are the same persons interacting with firms in the CE in two dimensions: on the goods market and labor market. This is reflected in Fig. 4. Consumption behavior and labor market income are crucially linked. Adding this interlinked perspective here could provide information of how labor market aspects of the CE are linked to the demand for its products. Moreover, consumers do not only buy the goods to which the R-concepts are applied. The implementation of the CE also requires non-monetary activity by consumers or collaborative action. This includes the manual sorting of waste in households, the partial involvement in the collection process, the reuse market, sharing products, as well as repairing. Even when the reparation process is taking place in a commercial way, the consumer is involved in the process by actively moving the goods, which require reparation. Put differently, questioning, and shaping consumption patterns, and transferring them to business models can already reduce the required input for production (Buhl et al. 2017). The same applies to the design of product and service systems. The interaction between the CE and collaborative action is yet unclear. An assessment of some or all of these consumption effects means further broadening the goal and scope of any combined LCA-labor market analysis to take these into account. We do not address these aspects here further.

5 Application of Our Strategy to R-Concepts of the Circular Economy: Case Study and Discussion

After outlining the general strategy to perform an environmental LCA together with a labor market assessment when striving toward a CE, we now discuss the application of our strategy to the R-concepts of the CE. We start by considering a case in which the R-concept "reduce" was applied in steel. The case study refers to the assessment at the product level. The focus is set on a research question regarding material development, which leads to changes within the entire production process. Within the multi-level perspective of Fig. 4, this refers to the manufacturing step within the product system design. We then discuss how to apply labor market assessment to the R-concepts of the CE more generally.

5.1 *Case Study: Steel Design for Better Environmental Performance*

The material of products is of high importance as it dictates the product's environmental profile directly and indirectly. For steel, the chemical composition and processing determine the material characteristics required depending on the product application. Therefore, the material development process is crucial and is increasingly often related to questions of sustainability. When assessing the environmental performance of material development, it is important to consider not only the change in composition but also the resulting changes on the process level, product design, product performance, and its end-of-life. Within a case study, the environmental performance of a forged product (U-bolt) in the automotive industry made from the new air-hardening ductile forging (AHD) steel was investigated by applying an environmental LCA (Hagedorn et al. 2022). The focus was set on the relation between the material development, the implications for the manufacturing process and product design.

The AHD results from a research project with the aim to develop an alloy which can be processed with a short heat treatment of a precipitation-hardened ferritic-perlitic (PHFP) steel but reaches the material characteristics of a Quench and Tempered (Q + T) steel (Gramlich et al. 2020a, b; Gramlich and Bleck 2021). The AHD combines both as it achieves a complete martensitic microstructure directly after air-cooling from the forging heat. This way, the energy-intensive heat treatment becomes unnecessary.

The new chemical composition resulted from thermodynamic equilibrium calculations and was cast on laboratory scale. Then, the material characteristics were analyzed for different components from the U-bolt weighing 2 kg to planet carriers of a planetary gear weighing 250 kg. Whereas the strength and ductility of the AHD reach similar levels as the commonly used Q + T steels, it has a higher fatigue strength. It was increased by 129% and more than doubled the component lifetime.

However, as the lifetime exceeds the lifetime of the truck in which the component is installed, the functionality is of no use. Instead, it enables us to apply lightweight design principles and to reduce the thickness of the product. A total weight reduction of 50 wt% is possible. This goes along with the CE strategy of narrowing as the material input to provide the service of a U-bolt can be halved.

The case study comprised the analysis of the production of a U-bolt from a cradle-to-gate perspective. The U-bolt was modeled based on the standard quench and tempering steels 42CrMo4 and 33MnCrB5-2 as well as the AHD. The environmental LCA was carried out on the material, process, and product levels.

As described in Sect. 3, the LCI is one of the four process steps of an LCA. The process of conducting an LCI is linked to extensive data collection. First, the appropriate modeling approach, consequential or attributional, must be chosen as it influences the requirements for data (European Commission and Joint Research Centre 2010). In this case, the attributional approach was chosen as the production process of the U-bolt in the technosphere was modeled as observed in practice. The product system is observed with regard to changes on the process level, ignoring potential effects on an organizational or even sectoral scale and on background systems.

The LCI begins with identifying any processes which physically treat the product under investigation. This results in a technical process flow, which is completed by all input and output flows (European Commission and Joint Research Centre 2010). The process flow of the U-bolt from a cradle-to-gate perspective is shown in Fig. 5. The processes are assigned to four groups: The material provision comprises the smelting process as well as secondary metallurgy which adds mostly alloying elements to reach the predefined chemical composition. The casting and forming follow and start with casting, which is the first forming process after opening the furnace, in which liquid steel starts to solidify and is poured into shape and batches. Blooming and rolling are further processes to shape the steel and reduce the size and, in this case, especially thickness. Whereas blooming contains multiple hammering processes, the steel component is led through a continuously narrowing opening to reduce the size in rolling processes. After that, the required thickness of the steel bar is forged so that the straight line is bent into a U-shape. Afterward, the heat treatment is required which means the austenitization (high temperature, short period of time), quenching (low temperature, short period of time), and tempering (high temperature, long period of time). The process leads to changes in the material characteristics such as toughness and hardness. Some finishing processes follow such as shot blasting to remove the scale layer. Before the product is coated in order to achieve surface and corrosion protection, the product is cleaned. Finally, the product is checked within quality control.

For the LCI as the basis to conduct an LCA, all input and output flows are gathered. This means especially resources such as material, energy, air, and water as well as product outcomes, emissions, and waste streams. The input flows are of physical nature and are taken directly or indirectly from the ecosphere. These data are commonly gathered in close cooperation with industrial partners. They can result from process- and machinery-specific on-site measurements. Automatic machinery commonly has control modules, which allow to read out process data. Alternatively,

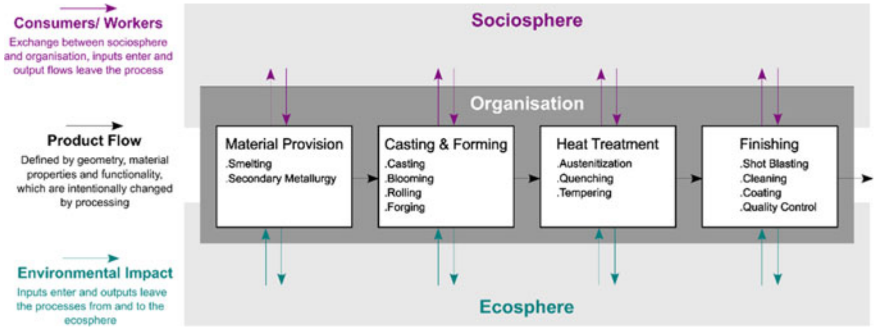


Fig. 5 Technical process flow of the production of U-bolts (own graphic)

the data can be derived from company-wide procurement and sales data. Combined with information regarding batch sizes and time-specific production volumes, it is possible to calculate the required input and output flows.

The process of data collection is complex and time-consuming. The data is often available, but the structure of data collection is uncommon for operational procedures in business. For instance, procurement and sales data are often measured in monetary units or quantity rather than weight (Hagedorn et al. 2020). The required information is often distributed in a decentralized manner across different positions in companies which initiates unfamiliar communication and work paths in the process of data collection. If data is unavailable or to validate them, literature research plays a vital role in the stage of LCI.

Then, the LCI is connected to environmental impact categories. Commonly databases are used, which provide a variety of industrial processes and impact assessment frameworks. These LCA databases are mostly implemented in LCA software for modeling and final calculation. In theory, it would be possible to calculate LCAs manually. However, since production processes are often complex systems, using software for calculations is the status quo.

Finally, the results are interpreted. Various established impact categories are analyzed. As the LCA is a comparative methodology, the results of the covered product systems are compared. This helps to derive which processes of the product systems are relevant for the overall environmental performance and form so-called hotspots. Further, it indicates which product system is environmentally beneficial. As the LCA is an iterative process, insights from each stage of an LCA might lead to the revision of other stages; e.g., when finding that the heat treatment is an ecological hotspot in the production of a U-bolt and it is known that the data provided are subject to high insecurities, it could be reasonable to carry out further investigations on the heat treatment.

Considering the aforementioned stages of the LCA including the perspective of labor market at the product level has the following implications:

(1) Goal and Scope: Regarding the case study, the overall aim of the LCA-based investigation was to quantify the change of alloy about its environmental impact.

As outlined above, the first step of the investigation should now be extended in order to include labor market aspects. In particular, this means to include the quantity of labor input used (employment and hours worked) as well as to include information about the occupations, skills and tasks and basic demographics (age and gender). Generally, the definition of the product system, the stage and, in this case, the application remain unchanged.

(2) Life Cycle Inventory: Data collection in this case was performed in cooperation with industry partners. The assessment of labor market aspects would now require extending the data collection at different steps of the production process documented in Fig. 5 with respect to labor market outcomes. This means collecting the number of employees and their respective working hours at each step. This also requires collecting basic demographic information, occupations and skills of these workers measured according to the classifications and definitions outlined in Sect. 3. Moreover, the industry partner would be asked to provide information about the tasks at each production step following the classification and definitions outlined in Sect. 3. It would be beneficial to also collect machinery used in each step. If possible, wage information would be informative. Regarding the case study, it should be possible to collect the additional data regarding the required human resources differentiated by machinery and the production steps in Fig. 5. To scale labor input at the level of the production step and, to compare the respective importance of production steps at the product level, further production-related performance indicators such as time, batch, or throughput could be helpful in addition to numbers of employees and hours.

(3) Impact Assessment: In this stage, labor market outcomes are assessed parallel to the environmental impact. Based on the change in the quantity of employment and hours worked, the impact may be positive or negative. In the case of producing a U-bolt, the material input can be reduced, and the heat treatment becomes unnecessary. This means that some production steps vanish (compare Fig. 2). Remaining employment will inform us about occupations and tasks that vanish against those that are resilient to the implementation of the R-concept reduce. The change in wages will inform us about productivity changes and whether remaining workers participate in this respect.

(4) Interpretation: The interpretation of the environmental LCA remains unchanged and is complemented by the labor market assessment. This could also be done for various interpretations, potentially. Adverse employment effects will call for supportive labor market policies that help to re-integrate the displaced labor in other firms or industries. For this, it is useful to know where now obsolete skills are needed. Likewise, vanishing occupations and tasks may be targeted with specific education toward (closely related) occupations and tasks that have been shown to be resilient.

The case study can highlight changes in the production process in relation to the impact on the required labor and environmental dimension. However, there might be further effects, which can be seen on a company or market level. The U-Bolt is a product with a very high production volume representing only one of the product segments. As the production is highly automatic, it is likely to have a very low labor share and will induce possibly small quantitative effects. It will, however, inform about automation potential in the application of the reduce R-concept strategy (compare Fig. 2). Further, the implementation of lightweight design reduces the material input. On a larger scale, these material savings might also affect the production capacity altogether and, hence, the quantity of labor demanded regardless of a change in tasks potentially. This will most likely induce negative labor market effects quantitatively. Such effects are not evaluated within an LCA but rather by scaling up LCA results from product to company to market level. This is especially relevant when it comes to monitoring the available and occupied capacity of the labor market in relation to policymaking.

5.2 Discussion of Labor Market Assessment for R-concepts

The case study provides some early insights about assessing labor market effects within an LCA. The case study relates to the R-concept Reduce. Table 1 addresses potential effects of other R-concepts in comparison. Reduce reflects a narrowing of production meaning a decreased amount of required material and energy for the provision of a good or service. This R-concept emphasizes potentially adverse labor market effects related to jobs, occupations and tasks that vanish due to automation or redundancies. This relates closely to previous phases of how industrial transformation has affected the labor market as is outlined in Sect. 2 and depicted in Fig. 2.

Different R-concepts will have varying labor market effects, e.g., in the case of reduce, the demand for labor is likely to decrease in quantity and remains unchanged in quality. In the case of refurbish, new processes will likely require labor with a different quality and quantity. The labor market assessment of the other R-concepts is more involved. Like reduce, some strategies slow and/or narrow production, e.g., through producing fewer products (Repurpose). Here, it is important to measure the scale of production (output) together with automated or obsolete production steps as this will also scale labor demand. In this case, labor market policy should focus on the re-integration of the obsolete occupations in other parts of the economy.

Especially interesting are R-concepts which involve key changes in the production process as processes change fundamentally (recycle), or new production steps appear, e.g., quality proof or rental services (rethink, recycle, recover). Here, it is important to describe the changed and new production steps as detailed as possible in terms of labor market characteristics. With respect to changed and new production steps, it may be useful to compare these as close as possible to existing occupations and jobs (e.g., through the link between occupations and tasks at the industry level described above). This is potentially easier in case of changed than new steps, since new processes can be better described relative to the old ones. In the case of these R-concepts, labor market policy can provide substantial support through re-education programs.

The R-concept recover involves the introduction of new production processes. A successful labor market assessment relies on detailed descriptions of these processes, like an LCA of the existing ones. If this is possible, forward-looking assessment is possible as well along the outline above. Sometimes, as in the case of the Refuse, this also involves considering future consumption. Scaling production in this way is outside our assessment strategy here. If credible estimates exist from other sources, this would easily be incorporated into our assessment as well.

6 Conclusion

Sustainability transformation is a multi-dimensional and complex task but fundamental to achieve progress toward the climate targets that are time limited. The SDGs define the requirements for such transformation and approaches such as the CE provide solutions, which can be implemented on product level. The R-concepts of the CE define varying possibilities to redesign the provision of goods and services as they should increase the material efficiency by narrowing, slowing, and closing material flows. That way, change according to the CE is expected to reduce the environmental impact of product systems. As the CE changes production processes, it will strongly affect labor demand. Yet, means to meaningfully measure the quantitative labor market impact of CE are still missing, especially at a detail that would allow meaningful conclusions about labor market policy. Quantitative labor market assessment allows scaling up effects from the product to the industry, sectoral or national level. It also allows to judge whether the implementation of CE could be restrained by the (un)availability of an appropriately trained workforce. This chapter elaborates a possible strategy to evaluate R-concepts of the CE with respect to their environmental impact, while at the same time, monitoring labor market outcomes.

R-concepts of the CE have been assessed with respect to their environmental impact based on LCAs (Hagedorn et al. 2022). So far there is no approach for measuring potential labor market effects. Not even in the most holistic approaches such as LCSA. With this study, using the introduced LCA case study as an example, it was shown how an integration would be possible. Also, it illustrates the requirements for evaluating certain occupations, skills, and tasks. This can help to inform labor market policy to design targeted re-education or re-integration programs.

The developed strategy involves an adaptation of the four steps of the LCA to include, measure, and interpret (the changes in) the quantity and characteristics of labor input at various production steps. This case study shows that this is generally implementable, for relatively straightforward R-concepts such as reduce in which production steps become obsolete or automated. The chapter also discusses that R-concepts involve substantial changes in existing production steps, while also potentially creating new production steps, thereby shaping the demand for labor in the direction of certain occupations and tasks. Since some R-concepts describe future changes in production processes, linking these closely to labor market outcomes does not only allow to assess social consequences during or even before industrial transformation takes place but may also allow to design forward-looking labor market policies that can alleviate adverse effects or support beneficial labor market effects, making transformation more sustainable from a general point of view.

The focus of this work was set on the data collection process of LCA and labor market effects as it was seen to be easily integrated. Further research should focus on developing specific impact category framework reflecting the diverse characteristics (qualitative and quantitative) of labor markets. Also, the integration of such framework with the existing LCSA, namely LCA, LCC, sLCA, should be investigated as the aim is a holistic assessment framework.

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Corporate Social Responsibility—Conscious Investing and Green Transformation

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Abstract In the first part of this chapter, we introduce the reader to the concept of corporate social responsibility. We outline different underlying motivations of CSR for a firm. Furthermore, we elaborate on different channels through which CSR is linked to the maximization of firm value. Specifically, we examine the impact of CSR on firm valuation through future cash flows and the required expected rates of returns. In the second part, we introduce the EU taxonomy as a possible solution towards the problem of evaluating firms' CSR performance. The EU taxonomy is aimed to channel investments towards sustainable opportunities by ensuring transparency about firms' environmental performance. We also explain its practical relevance, limitations, and future developments. Overall, we emphasize the role of unified efforts in green transformation.

Keywords Conscious investing · Corporate social responsibility · EU taxonomy · Green transformation · Sustainability

1 Introduction

The term "shareholder value maximization" became prominent in the 1980s (Rappaport 1986). The paradigm that all firm activities should be focused on generating value for the firm's investors—in other words increase firm value—has however been dominant in businesses and financial markets much longer. It can be traced back to the capitalist motive of capital accumulation (Marques 2020). Over the last decades, many have made out the capitalist motive of firm wealth maximization as the gravedigger of the natural environment and thus the basis of our wealth and life on earth. In the popular discourse, capitalism is widely blamed as the root cause

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P. Letmathe et al. (eds.), *Transformation Towards Sustainability*,
https://doi.org/10.1007/978-3-031-54700-3_7

for natural destruction (The Guardian n.d.; Forbes n.d.; Global Social Challenges n.d.). Especially young people blame capitalism for climate change. A poll among Britons aged 16 to 34 finds that 75 percent agree with the statement that "Climate change is caused by big corporations that pollute the atmosphere [...]. Therefore, capitalism is the problem not the solution." (Institute of Economic Affairs n.d.). Sociologists have coined the term "treadmill of production" to describe how the capitalist desire for growth and capital accumulation destroys the natural environment without succeeding in improving individuals' well-being (Schnaiberg 1984; Schnaiberg and Gould 1994). Overall, there is an overwhelmingly negative sentiment that the capitalist motive of firm value wealth maximization is to blame for environmental destruction.

This gradually declining opinion towards firms has led to the evolvement of "corporate social responsibility" (CSR), which can be described as the practice of introducing environmental and social factors to corporate decision making. The development of this concept thus was not proactive, but a reaction towards society questioning the legitimacy of large corporations (Brown 2008; Lee and Carroll 2011). Over the last decades, CSR has made its way to the top of research agendas and is widely considered an absolute necessity of doing business by many practitioners (Lindgreen et al. 2009). This trend has led to a seeming erosion of the paradigm of firm value maximization. Section 2 of this chapter takes a closer look at common definitions of CSR.

Much hope for a successful transformation towards a sustainable economy rests on firms acknowledging this concept. One example of societies counting on such engagement by firms is given by the transformation towards a sustainable energy production. Based on the EU Member State National Energy and Climate Plans (NECPs), the EU Commission estimates that achieving the current EU 2030 climate and energy goals alone requires annual investments in energy production and consumption to increase by a total of €350 billion during the current decade. This effort also requires large amounts of investments by firms. Moreover, climate change is not the only environmental sustainability issue where firms' commitment is required. Water pollution, biodiversity loss, and plastic pollution are only few of the other issues which require action at substantial cost.

This raises the question as to which forces could induce firms and their managers as the main decision-makers in day-to-day business to spend the enormous amounts required or, more generally, consider environmental and social sustainability in their decision making. A first solution would be simply by establishing legal rules to which firms and their managers have to obey. However, there are limits for fulfilling goals by simple force, as decision-makers may try to evade legal requirements. A second possibility is that firm managers' preferences inherently drive them to achieve sustainable goals. Though this might be the case, there may also be managers that are mainly interested in personal (positive) monetary consequences. One way for managers to increase personal welfare may be to raise firm value, which often serves as the basis for managerial compensation. We thus detail how CSR relates to firm value by impacting its two determinants: (expected) firm cash flows and the minimum expected average rate of return which investors require to provide funds to the firm.

In such a situation where CSR also implies higher firm value, there would be no real conflict of interest between sustainability goals and firm value maximization apparently easing the way to a green transformation of the economy. Section 3.1 points out negative consequences of CSR on firm value, which are due to managers selfishly spending firm resources, and Sect. 3.2 explains the positive effects of CSR, which are a consequence of stakeholders behaving more favorably towards the firm.

One especially relevant stakeholder group in this context are investors. Non-monetary gratifications also affect how investors value financial assets and thus firms. It has long been observed that firms are valued at a lower price if their business model contradicts social norms. The increased emphasis on sustainability among investors consequently leads to sustainability being a determinant of financial instruments' prices. Section 4 details the channels behind investor preferences for social and environmental engagement demanding lower returns from firms, i.e., firms having a lower cost of capital. These rely on so-called CSR-conscious investors, i.e., investors forfeiting profits in exchange for the so-called moral dividend sustainable firms provide, polluting firms being avoided by this investor type, and lower riskiness of sustainable firms due to, for example, a reduced threat of lawsuits or consumer boycotts.

Even though all of these channels discussed in Sect. 4 provide convincing incentives for managers to engage in CSR, an issue that has yet not been addressed is that of whether these incentives bring anything new to the table. Given that CSR already affects firm value due to its impact on cash flows, which is a result of other stakeholders', e.g., customers', reactions, we address the question of the added benefit of investors considering CSR in Sect. 5. We explain that, firstly, firms can alter their business model to focus on, e.g., non-CSR-conscious customers and thus largely avoid the consequences of consumer boycotts by CSR-conscious customers. Due to diversification consideration, firms cannot focus on only a minor group of investors without cost. Secondly, stock market investors are typically better informed about the operations of the firm than other stakeholders are. Thirdly, investors are widely considered to be the most relevant stakeholders by managers. And finally, managers are more likely to adjust their behavior when pressured by multiple rather than by only one single stakeholder group.

However, for investors to be able to consider firms' CSR effectively, they need access to information on this issue. Section 6 points out that there is a lack of reliable information on CSR. Section 7 goes on to introduce the reader to the EU taxonomy on sustainable activities, which intends to remedy this problem. In this section, we also explain the lawmaker's concept behind the EU taxonomy, its application in practice and point to future developments as well as limitations of the EU taxonomy. Given the effect that CSR-conscious investing can have on businesses and the economy as a whole, the EU taxonomy will constitute a cornerstone of the green transformation of the EU economy.

Overall, this chapter outlines why and how CSR and CSR-conscious investing can contribute to a green transformation of modern societies by reconciling the goals of firm value maximization and environmental sustainability. Central to this harmonization is that sustainability is increasingly perceived as a value of outstanding relevance. This shift in perception puts pressure on firm managers to meet stakeholders' expectations regarding firms' sustainability. Failing to satisfy such demands increasingly has monetary consequences for firms and for managers. The increasing awareness towards environmental issues thus not only has led to the emergence of CSR, but it also provides managers with incentives to include sustainability issues in their decision-making processes. This chapter points out that the overwhelmingly negative perception of capitalism and the motive of firm value maximization as the "gravedigger of the natural environment" is misleading. In fact, firm value maximization (mostly) has to satisfy the social norms prevalent within societies. For long, stakeholders, such as customers, have not placed enough emphasis on sustainability to ensure that it is considered in corporate boardrooms.

We acknowledge however in the concluding Sect. 8 that these concepts have limitations and that other actions are needed to achieve a transformation towards an ecologically sustainable society. Despite this chapter focusing on the role of firms and investors, other societal actors are also of major relevance for these efforts, as they will also bear a substantial burden of the transformative process.

2 What is Corporate Social Responsibility?

According to ISO 26000, social responsibility is the "responsibility of an organization for the impacts of its decisions and activities on society and the environment, through transparent and ethical behavior that: contributes to sustainable development, including the health, and the welfare of society, takes into account the expectations of stakeholders, is in compliance with applicable law and consistent with international norms of behavior, and is integrated throughout the organization and practiced in its relationships." Beyond that, numerous definitions of corporate social responsibility (CSR) have emerged from the scientific literature. However, the common theme among all definitions is a reference to ethics, sustainability, and stakeholders. Moreover, it seems widely acknowledged that CSR only refers to actions that go beyond firms' legal requirements (Carroll 1991; Barnea and Rubin 2010).

The World Bank, for example, defines corporate social responsibility as the "commitment of businesses to behave ethically and to contribute to sustainable economic development by working with all relevant stakeholders to improve their lives in ways that are good for business, the sustainable development agenda, and society at large." Carroll's (1991) view on CSR encompasses the widest array of aspects, where he defines CSR as a business behavior that is economical, environment-friendly, legal, and socially supportive. According to Salzmann (2013), economic and legal aspects of CSR in Carroll's (1991) definition are associated with extrinsic preferences while ethical and philanthropic aspects are related to intrinsic aspects.

Benabou and Tirole (2010) distinguish between three categories of CSR based on the motivation underlying the CSR activities. The first category is "strategic CSR" which is aimed at securing a competitive advantage, advertising, or promoting a favorable image. This category is motivated by the axiom "doing well by doing good." Moreover, the rationale behind this category is that the profits earned by the firm will primarily benefit the shareholders as well as other stakeholders. This view indicates that CSR represents a win–win outcome for shareholders and stakeholders, as doing good for other stakeholders can indirectly increase firm value (Benabou and Tirole 2010; Deng et al. 2013).

The second category is "not-for-profit CSR," which is also labeled "delegated philanthropy" (Benabou and Tirole 2010) or "altruistic CSR" (Liang and Renneboog 2020). This category emerges from societal or stakeholder demand and expectations towards the firm. It is characterized by shareholders being willing to forgo profits in favor of the overall social well-being (Liang and Renneboog 2020; Bagnoli and Watts 2003).

The third category of CSR considers the agency situation between shareholders and managers. This type of CSR emerges when firms' managers want to invest in philanthropic activities regardless of other stakeholders' benefits. The underlying managerial motivation can range from reputational gains to personal pet projects. Such initiatives are not aligned with firm value wealth maximization and are thus referred to as doing good with other people's money (Benabou and Tirole 2010).

While CSR belonging to the first category is by definition in the interest of shareholders, CSR from the second category is not. CSR belonging to the third category only is in the interest of managers. In the next sections, we will elaborate in detail how CSR can be detrimental or advantageous for shareholders. From the perspective of corporate finance, the dominant concern of shareholders is that of increasing firm value. Firm value depends on the firm's (i) future cash flows and its (ii) cost of capital. Higher (expected) future cash flows correspond to higher firm value, as the firm will use its future cash flows to repay investors for their initial investment outlay. The higher the payments that investors obtain for the initial investment outlay, the more highly they will value the firm. A firm's cost of capital is the minimum expected rate of return that investors require in order to provide funds to the firm. Investors evaluate the payoffs they receive from the firm against its cost of capital. A higher cost of capital thus means that investors will value the firm at a lower price. Assuming a simple situation, where a firm delivers a perpetual and constant expected cash flow, firm value is given by

$$\text{Firm Value} = \frac{\text{Expected Cash Flow p.a.}}{\text{Cost of Capital}}.$$

The next sections elaborate in detail on how CSR can affect future cash flows and the cost of capital. Section 3.1 explains how CSR affects future cash flows. We first point out the negative consequences of CSR on firms' cash flows, which are due to managers selfishly spending firm resources. The positive effects of CSR—elaborated in Sect. 3.2—are due to stakeholders behaving more favorably to the firm. We will explain that this behavior affects cash flows in the case of product and factor market participants of the firm, namely employees, customers, and suppliers, as well as when considering governments and the public at large. Only when investors react more favorably to the firm, CSR has an effect on the firm's cost of capital.

3 The Effects of CSR on Future Cash Flows

3.1 Negative Effects of CSR on Firm Value Due to Managerial Opportunism

In line with the third category of CSR according to Benabou and Tirole (2010), CSR viewed as a "private provision of public goods" may negatively affect a firm's performance if it represents private benefits for the managers in terms of reputation, job security or other tangible and intangible benefits. Empirical evidence indeed shows that managers over-engage in CSR for private benefits (Krüger 2015; McWilliams et al. 2006; Cheng et al. 2013), to seek personal gains like job security by avoiding close monitoring (Carroll 1991), to enhance their reputation as good citizens (Barnea and Rubin 2010; Surroca and Tribó 2008), to hide earnings management (Prior et al. 2008; Chih et al. 2008; Muttakin et al. 2015) and to mask the adverse impacts of their decisions (McCarthy et al. 2017). Eventually, the violation of managers' agency role by investing in CSR will lead to inefficiency of investments and hence deterioration of shareholders' wealth (Masulis and Reza 2015).

3.2 Positive Effects of CSR on Firm Value Due to Stakeholder Reactions

The positive effects of CSR on cash flows refer to the first category of CSR according to Benabou and Tirole (2010) and manifest in terms of developing intangible assets like human capital and the reputation which ultimately results in enhanced competitiveness of the firm (Jiao 2010). The literature also predominantly confirms this perspective that CSR promotes the financial performance of firms. For instance, a meta-analysis by Margolis et al. (2007) documents that approximately half of the existing empirical studies confirm a positive effect of CSR on financial performance. Friede et al. (2015) even find that more than 90% of the empirical studies confirm this relationship. Similarly, other studies associate CSR with better financial performance and ultimately with higher firm value (Jo and Harjoto 2012; Al-Tuwaijri et al. 2004; Burnett and Hansen 2008; Erhemjamts et al. 2013; Rodgers et al. 2013). These studies measure financial performance in terms of accounting-based proxies (e.g., return on equity or return on assets) as well as market-based proxies (e.g., market-to-book ratio or long-term stock returns).

Various other researchers have also investigated the impact of different components of CSR on firm value. For instance, Guenster et al. (2011) conclude that firms' environmental performance is positively related to their value while other researchers provide evidence for a positive effect of social performance on firm value (Jiao 2010;

Orlitzky et al. 2003). These mechanisms also have implications for firms' CSR performance itself, as firm value considerations motivate managers to behave socially and environmentally responsible (Heinkel et al. 2001; Ghoul et al. 2011).

The next two sections detail how CSR can increase firm cash flows by changing how either employees, suppliers, and customers or governments and the public at large behave towards the firm.

3.2.1 Employees, Suppliers, and Customers

CSR improves the perception of customers, suppliers, and employees about the firm (Campbell et al. 1999). Thus, CSR leads firstly to increased sales volumes due to customers being willing to pay higher prices for sustainable products (Lins et al. 2017) and lower risks of consumer boycotts (Waddock and Graves 1997). Secondly, CSR reduces the risks of strikes since employees behave more loyally towards the firm. It also leads to higher employee motivation and satisfaction (Edmans 2012), thus increasing productivity. Thirdly, suppliers offer more favorable conditions to firms with a better CSR performance (Dai et al. 2021).

By enhancing the image that these participants of the firm's product and factor markets have about the firm, CSR contributes to increasing the firm's cash flow and thus positively affects firm value. Moreover, high-CSR firms are also more innovative when it comes to developing new business models, products, and services thus securing the basis for future cash flows (Nidumolu et al. 2015; Famiyeh 2017). For example, Porter and Linde (1995) argue that "green" firms are not only more proactive in adopting strategies which involve finding innovative solutions to harmful waste and pollution challenges, but also with regard to other matters.

3.2.2 Governments and Public at Large

Governments are interested in firms' CSR, as such business practices meet governmental policy objectives. This works by not only achieving environmental goals but also human development goals. Similarly, since CSR involves the interaction of a broad variety of stakeholders, it is used to regulate the roles and relations among all stakeholders including civil society, businesses, and governments (Steurer 2010).

The general public being the direct recipient of CSR activities can pressurize firms in terms of private politics, through protests and lawsuits. In some cases, activists even go as far as buying enough shares of a firm to initiate a proxy vote (Eesley and Lenox 2006). Along these lines, previous studies conclude that CSR can lower penalties for existing regulatory violations while it also decreases the likelihood of new legal cases (Hong and Liskovich 2015; Barnett et al. 2018). This underlying risk associated with environmental violations can seriously affect firm's cash flow and ultimately its value. British Petroleum's (BP) Deepwater Horizon oil spill of 2010 is a good example of how firms' cash flows can be adversely affected due to the ever-active role of governments and the general public. The incident has costed

BP an amount of 63.4 billion dollars, to cover the clean-up costs and legal fees till September 2018.

Beyond reducing potential clean-up costs or legal fees, certain aspects of CSR are likely to become more relevant as they reduce a firm's Pigouvian tax burden. Governments are currently seriously considering to intensify the use of Pigouvian taxes which are based on environmental taxation to internalize the negative environmental externalities. Even though Pigouvian taxation is often criticized for its political infeasibility, Germany has recently implemented carbon price reforms. The pressure for such meaningful legislation is partly attributed to the young public, represented by *Fridays for Future* and partly due to the EU Effort Sharing Regulation (Edenhofer et al. 2021).

4 How Does CSR Reduce the Cost of Capital?

Classical finance views an investment's riskiness as the only determinant of the minimum expected rate of return that investors demand from that investment besides the riskless interest rate for lending (Markowitz 1952). The logic behind this view is simple: Generally, risk-averse investors demand higher expected returns as a compensation for risk. However, behavioral finance has demonstrated that investors do not solely consider monetary aspects in their financial decision making but that also other features of an investment affect the cost of capital. Importantly, investors also take into account to what extent investment projects comply with their moral norms. Examples of this are so-called sin stocks. Firms that make profits from, for example, weapons manufacturing, tobacco, or sex-related services, are deemed immoral by many investors and thus investors are only willing to invest in these firms, if they offer on average a higher return as a compensation (Hong and Kacperczyk 2009; Bolton and Kacperczyk 2020). Since sustainability has become an important aspect of moral norms, this mechanism thus reduces the cost of equity capital (Ghoul et al. 2011) and debt capital (Goss and Roberts 2011; Attig et al. 2013) of firm firms which behave socially responsible.

Moreover, Dhaliwal et al. (2011) finds that when firms start CSR-related disclosures, they enjoy a reduction in the cost of equity in the subsequent years. This effect works by reducing the information asymmetry regarding CSR and hence attracting CSR-dedicated institutional investors. Several other studies also conclude that strict disclosure standards regarding CSR are useful in reducing informational asymmetry and ultimately the cost of capital for the firm (Hail and Leuz 2006; Chen et al. 2009). In this section, we explain at least four distinct channels through which CSR reduces firms' cost of capital in more detail. Common to them is the argument that investors consider CSR as a moral obligation and that this belief determines investors' behavior towards the firm.

(i) **Moral Dividend: Moral Behavior of Firms Compensates for Lower Returns**

Financial markets have a "discriminatory taste" for CSR, which is not explained by the traditional risk and return relationship (Derwall 2007). Bollen (2007) finds that cash inflow volatility of funds with a focus on firms, which behave socially responsible, is lower than that of their "conventional" counterparts. Although these funds yield relatively lower returns, the investors' inclination to such funds may be attributed to investors' non-financial utility. As already mentioned, this component is often labeled as a "moral (or social) dividend." Liang and Renneboog (2020) define moral dividend as "the return given up in exchange for an increase in utility driven by the knowledge that one invests ethically."

(ii) **Enlarging the Investor Base: Investors Screen Out Amoral Firms**

CSR also results in a lower cost of capital, since more investors are willing to supply a sustainable firm with funds. Heinkel et al. (2001) show that negative or exclusionary screening by investors leads to fewer investors—or a smaller investor base—for firms with low levels of CSR. If there is an undersupply of funds to the firm, the cost of capital to acquire sufficient funds will naturally increase. In simple words, more investments in high CSR-performing firms increase the supply of capital for these firms and hence decrease the corresponding cost of capital while divesting out of low CSR-performing firms decreases the supply of capital and hence increases the cost of capital for these firms. However, this effect depends on the relative size of socially responsible investment opportunities as compared to alternative opportunities available in the capital market (Haigh and Hazelton 2004; Statman 2000).

3. **Stabilizing the Investor Base: CSR-Conscious Investors Are More Loyal in Times of Crisis**

Bollen (2007) and Renneboog et al. (2011) find that CSR-conscious investors do not withdraw their funds even in the case of low returns. Hence, high-CSR firms are more secure that their investors will not leave the firm during times of crisis.

However, CSR-conscious investors are repaid for their loyalty in times of crisis. For instance, during the 2008–2009 financial crisis, companies with a high CSR performance achieved four to seven percentage points higher shareholder returns than companies with low CSR performance, as measured by the intensity of CSR. This works via higher cash flows in the form of higher sales growth and gross profit margins and a decreased cost of capital, as these high CSR firms can more easily raise capital in financial crises (Friede et al. 2015).

(iv) **Risk Reduction**

CSR can influence the cost of capital via reducing firm risk (Chava 2014). Firm risk is associated with the idea that low-CSR firms are considered riskier by investors. Waddock and Graves (1997) point out that firms with low CSR are relatively more exposed to lawsuits. As a compensation for this higher risk, investors demand higher rates of return from low-CSR firms (Ghoul et al. 2011; Chava 2014). Similarly, Attig et al. (2013) show that higher CSR engagement leads to better credit ratings and ultimately lower financing cost.

5 What is the Additional Value of Investors Considering CSR?

As highlighted by our previous sections, the reactions of numerous stakeholders to a firm's CSR activities are relevant for firm value. This leads to the question as to whether investor reactions, specifically demanding a lower cost of capital, provide any incentives for managers to engage in CSR that go beyond the incentives provided by the reactions of those stakeholders that affect the firm's cash flow. These additional incentives could be questioned against the backdrop of managers already considering CSR due to its impact on firm cash flows and thus firm value. In this section, we address this issue and explain as to why CSR-conscious investing offers a meaningful incentive for managers to engage in CSR. In doing so, we highlight the role of CSR-conscious investing for promoting the transformation of economies towards more sustainability.

5.1 No Extreme Clientele Effect

The effects of investors screening out firms and of customers screening out firms are distinct due to diversification considerations. In the case of investors and customers alike, not all actors will equally consider CSR as important. Regarding customers, firms can specifically target non-CSR-conscious customers and thus escape the consequence of being screened out by groups of customers to some extent. The behavior of the non-CSR-conscious customers towards the firm does not change by the firm being screened out by other customers. The same does not hold for investors. In their case, screening out low-CSR firms by some investors also changes the behavior of non-CSR-conscious investors towards the firm.

Specifically, when CSR-conscious investors divest from low-CSR firms, the remaining non-CSR-conscious investors forego their potential of diversification when they decide to hold on to low-CSR firms and thus demand a higher cost of capital. This mechanism is outlined in a theoretical model by Heinkel et al. (2001), who assume two types of investors: "green" investors who value CSR and "neutral" investors who are not concerned about any ethical inclination towards CSR. All investors have the opportunity to invest in two kinds of firms. "CSR-oriented" firms fulfill the requirements of a green investor while the other firms do not consider CSR and therefore are not considered by green investors unless a firm is reformed and starts considering CSR. After green investors have excluded such firms, the risk-sharing pattern changes for the existing few neutral investors who hold (all) the stocks of non-CSR firms. As a consequence, these neutral investors expect a higher rate of return to compensate them for their lack of diversification. The higher expected rates of return due to this lack of risk-sharing lead to a decline in share prices of non-CSR firms as compared to their green counterparts.

5.2 Better Informed Actors

5.2.1 More "Adequate" Reaction

The stakeholders of firms differ regarding the extent of information they have with respect to firm sustainability. For example, customers of an average consumer goods firm do not have the resources or capabilities to assess the sustainability of the firm. They have to rely on the little information they obtain from the press and are easily deceived by advertisements. A sizable part of the shares of most firms is held by large institutional investors (Duggal and Millar 1999; Elyasiani and Jia 2010) who assess firms thoroughly (Daniel et al. 1997; Baker et al. 2010). These investors thus have much better information on the firm's sustainability and can punish firms for behaviors that would not be noticed by customers. In this regard, institutional investors have an upper hand when it comes to influencing a firm's policy and screening out polluting firms.

5.2.2 Quicker Reaction

Investors are the most salient stakeholders based on situations when they exhibit high levels of power, legitimacy, and urgency. Out of Mitchell's et al. (1997) three-factor framework for stakeholder's salience: power, legitimacy, and urgency, urgency is found to be the best predictor of shareholders' salience (Agle et al. 1999). Urgency in this context refers to investors' potential to create time-sensitive pressure on firms, for example in the form of deadlines or reflects an investor's determination or assertiveness and "willingness to apply resources"(Gifford 2010). Investors are therefore expected to inspire a relatively quicker reaction towards new information as compared to other stakeholders.

Du et al. (2017) as well as Cordeiro and Tewari (2015) demonstrate that stock prices take no longer than a few days to adjust to CSR-related news. The authors argue that investors react to CSR, because they expect it to influence the firm's cash flows in the ways pointed out above (due to employees', customers', suppliers', regulators', public reactions).

5.3 Salience of Investor Interests

Gifford (2010) deploys Mitchell et al. (1997) framework of power, legitimacy, and urgency in order to establish the salience of shareholders in contrast to other stakeholders. Mitchell et al. (1997) state that shareholders' "power" is embedded in their ability to use their governance-related privileges, "legitimacy" is provided by the legal institutions and society in general, and "urgency" lies in the shareholders' capacity to establish deadlines for their demands. In this vein, managers generally consider the interests of investors relatively stronger than those of other stakeholders of the firm. This could be due to the fact that managers are legally obliged to act in the best interest of investors in most legal systems and only recently laws that allow managers to also consider the interest of other stakeholders have gained more and more ground (Alexander et al. 1997).

5.4 Multiplicative Effects

Rowley (1997) points out that managers respond to the interaction of multiple stakeholders rather than to each stakeholder individually. In this vein, Neville and Menguc (2006) propose that only considering a stakeholder's independent effect on the firm's CSR is too narrowly framed, as a simple dyadic relationship ignores the relatively complex interaction effect of other stakeholders in the stakeholders' network. The authors therefore introduce the concept of stakeholders' multiplicity, according to which stakeholders sometimes compete, coordinate, or complement each other to exert influence over the firm. For instance, protest groups tend to persuade consumers in order to abstain them from buying a certain product or employees may lobby with governments or engage in "whistle-blowing" to influence the legislative process.

Thus, not only the separate effects of CSR-conscious investors' influence must be considered, when looking at their relevance, but the multiplicative effect of their behavior which considers other stakeholders as well. However, there are no empirical studies which quantify these interactions or multiplicity of effects of investors with other stakeholders on firms' decisions regarding CSR. There only exists anecdotal evidence which shows that interaction effects of shareholders and other stakeholders like environmental activists can lead to significant decisions against a firm: For instance, activists in the Netherlands set various protests to pressurize large pension funds to divest from environmentally adverse companies including oil, coal, and gas companies. ABP being one of the largest pension funds was sued by a climate action group to divest from fossil fuel companies in order to comply with the terms of the Paris climate agreement. Owing to such pressures, ABP announced that it would divest €15 bn worth of investments by the first quarter of 2023.

6 The Problem of Evaluating Firms' CSR Performance

This far, we have highlighted the important and unique ways in which CSR-conscious investing contributes to transforming economies towards more sustainability. However, CSR-conscious investors are faced with one major challenge. They have limited means to assess the CSR performance of firms.

This problem has not been resolved by the increasing number of independent rating agencies over the past years (Boffo and Patalano 2020). The EU Commission has found in a recent consultation that the rating market is not functioning well today (European Commission n.d.-a). The major shortcoming of ratings is related to a lack of transparency on the methodology applied by the provider (European Commission n.d.-a). Additionally, the ratings from different agencies can strongly diverge related to the framework, methodology, metrics, key indicators, qualitative judgment, and weighting of subcategories (Boffo and Patalano 2020). The unaudited and different rating outcomes across providers also raise the question of reliability and biases leading to better ratings for specific firms within the methodology (Boffo and Patalano 2020). Liang and Renneboog (2020) point out a correlation of only 0.3 among different raters, which casts serious doubts on the validity of CSR ratings as compared to a correlation of 0.99 for credit ratings among top raters. Beyond varying methodologies, differences in ratings can also be attributed to deviating definitions of CSR (Chatterji et al. 2016).

Sustainability reporting has gained significant importance over the past years. It has been regulatorily anchored in the EU's Non-Financial Reporting Directive (NFRD) since 2018, thus far, only obliging large companies with more than 500 employees to disclose social and environmental corporate data (Hahnkamper-Vandenbulcke 2021). Yet, with the growing sustainability reporting also of firms outside the scope of the NFRD, many analyses have been performed, identifying several shortcomings in implementing the reporting under the NFRD. Primarily, since no standardized reporting framework is predetermined, a flexibility for firms to choose from several reporting frameworks such as the commonly known Global Reporting Initiative (GRI), the United Nations Global Compact, or the United Nations Sustainable Development Goals (SDGs) remains (Hahnkamper-Vandenbulcke 2021). As a result of the various reporting frameworks, sustainability reports are lacking a comparable basis (Hahnkamper-Vandenbulcke 2021). Additionally, past analyses have repeatedly demonstrated that the disclosed data companies report often exhibit insufficient quality (Alliance for Corporate Transparency 2020). Thereby, reported information is frequently limited to general policies, not including any measurable, science-based targets and key performance indicators (e.g., greenhouse gas emissions) related to these policies (Alliance for Corporate Transparency 2020).

This lack of a harmonized and transparent methodology to evaluate the CSR activities of firms' not only leads to an informational deficit on the investors' side when it comes to firms' sustainability. Moreover, it allows firms to either misstate an exaggerated CSR focus or to conceal potentially harmful information. This practice is often referred to as "greenwashing," a term which designates "sugar-coating" of environmental and social engagement.

Overall, transparent and reliable CSR data from firms are needed to redirect capital flows towards sustainable investments and incorporate sustainability risks into the decision-making process of banks and investors. For this reason, a pan-European sustainable finance strategy was introduced, with one of the primary objectives being the development of a robust and science-based classification system—the EU taxonomy. The EU taxonomy aims to provide a common language for investors, companies, and policymakers on economic activities that can be considered environmentally sustainable (European Commission n.d.-b). Thus, general climate and environmental objectives are translated into science-based, activity-specific criteria measuring the environmental performance of, e.g., firms or financial products. The next section provides the reader with an overview of the EU taxonomy for sustainable activities.

7 The EU Taxonomy for Sustainable Activities

Until 2018 the EU market lacked sustainability-focused regulatory standards providing transparency for sustainable business practices and financial products (Pettingale et al. 2022). Under the Action Plan on financing sustainable growth presented in March 2018, the EU made the first attempt to introduce an EU-wide classification system (the so-called EU taxonomy) for sustainable economic activities with the purpose of reorienting capital flows towards sustainable investments (Canfora et al. 2021). The result was the formation of the Taxonomy Regulation which entered into force in July 2020 (Canfora et al. 2022).

Yet, the Taxonomy Regulation defines only the framework for developing and applying the EU taxonomy. The actual EU taxonomy, including an "operational list" of science-based technical screening criteria for defining environmentally sustainable economic activities, is implemented through so-called Delegated Acts supplementing the Taxonomy Regulation (Canfora et al. 2022). In this way, the EU for the first time intends to provide a common understanding for companies, investors, and policymakers of what is understood as a sustainable investment based on the evaluation of scientific based screening criteria for economic activities (European Commission n.d.-b).

Moreover, the EU taxonomy plays a crucial role in aiming to achieve the goals under the European Green Deal, as the EU has firmly anchored the further implementation and development of the EU taxonomy Delegated Acts at the core of financing the transition (Canfora et al. 2021).

7.1 Key Aspects of the EU Taxonomy Framework

The Taxonomy Regulation (Art. 9) addresses the following six environmental objectives, which are further elaborated in the individual delegated acts:

(1) climate change mitigation,
(2) climate change adaptation,
(3) the sustainable use and protection of water and marine resources,
(4) the transition to a circular economy,
(5) pollution prevention and control, and
(6) the protection and restoration of biodiversity and ecosystems (Gräf and Weidner 2020).

A first Delegated Act (also referred to as "Climate Delegated Act") on sustainable activities for climate change mitigation and adaptation objectives (1)–(2) was already formally adopted in 2021 and has been applicable since January 2022. A second Delegated Act expected for 2022 will encompass the four remaining environmental objectives (3)–(6) and some additional criteria for the climate-related environmental objectives (1)–(2) (European Commission n.d.-a).

Moreover, the Taxonomy Regulation in Art. 3 defines four basic requirements that must be fulfilled for economic activities listed in a delegated act to qualify as sustainable and thus be considered taxonomy-aligned. Thereby an economic activity must:

(a) substantially contribute (SC) to at least one of the six environmental objectives,
(b) do no significant harm (DNSH) to any of the other five environmental objectives,
(c) comply with a set of minimum social safeguards (e.g., with regard to social and human rights) listed in the Taxonomy Regulation, and
(d) fulfill a set of activity-specific technical screening criteria (TSC), defining SC and DNSH for the respective activity (see Fig. 1) (Gräf and Weidner 2020)

Yet, for an economic activity to be considered "taxonomy-aligned," the activity has to be considered "taxonomy-eligible" in the first place, meaning that the economic activity related to a specific code of the statistical classification of economic activities in the EU—Nomenclature of Economic Activities (NACE)—simply needs to be on the list of activities included in the first delegated act (UNEP Fi and EBF 2022). Activities that are not listed and, therefore, are not taxonomy-eligible cannot achieve the status of being taxonomy-aligned (UNEP Fi and EBF 2022). Conversely, this does not necessarily mean that the activities are considered polluting. Currently, the

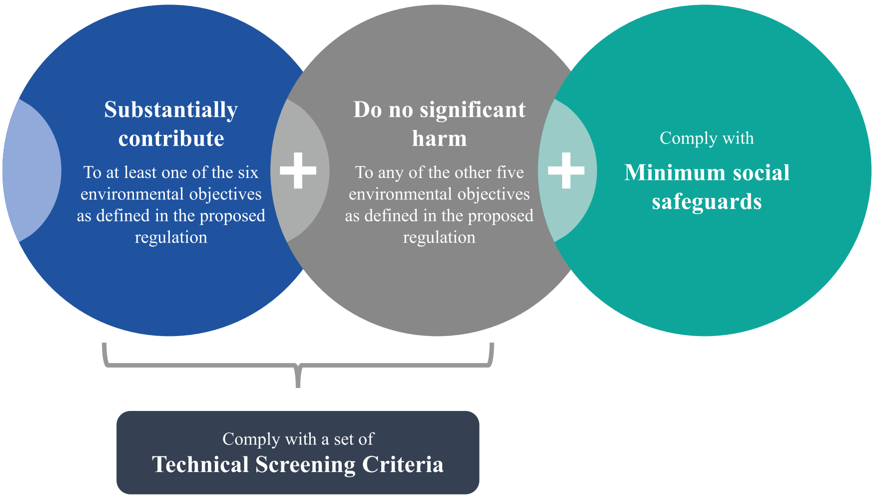

Fig. 1 Requirements for taxonomy-aligned activities (Gräf and Weidner 2020)

EU taxonomy focuses on activities considered to be “having the biggest impact” by making a substantial contribution to the specific objective.

Furthermore, given the complexity of each environmental objective, different criteria can be required for an economic activity to achieve a substantial contribution. In these terms, for the climate-related objectives, three types of economic activities differing slightly in for the way of achieving substantial contribution were categorized:

(1) activities that in and of themselves contribute substantially to one of the six environmental objectives,
(2) transitional activities where there are no technologically and economically feasible low-carbon alternatives, but that support the transition to a climate-neutral economy, and
(3) enabling activities that qualify by making a substantial contribution to one or more of the objectives and where that activity (a) does not lead to a lock-in in assets undermining long-term environmental objectives, considering the economic lifetime of those assets and (b) has a substantial positive environmental impact on the basis of lifecycle considerations (UNEP Fi and EBF 2022).

7.2 *The EU Taxonomy in Practice*

The Taxonomy Regulation mandates three user obligations. On the one hand, the Taxonomy Regulation makes it mandatory throughout the Sustainable Finance Disclosure Regulation (SFDR) for financial market participants whose financial products promote, among other characteristics, environmental or social characteristics or have sustainable investment as their objective, to disclose the share of investments in taxonomy-aligned activities (Canfora et al. 2022). For all other financial products, financial market participants must include a clear disclaimer that the financial product does not consider the EU criteria for environmentally sustainable economic activities (Canfora et al. 2022).

On the other hand, the Taxonomy Regulation also obliges large companies that are already required to provide a non-financial statement under the Non-Financial Reporting Directive (NFRD) to disclose the share of their revenue from taxonomy-aligned activities as well as the share of their investments (CapEx), or where relevant operational expenses (OpEx) (Canfora et al. 2022).

Under Article 8 of the Taxonomy Regulation and the Non-Financial Reporting Directive (NFRD), currently, only around 11,700 large listed companies, banks, and insurance companies with more than 500 employees are obliged to report EU taxonomy-related information (Baumüller and Grbenic 2021). Therefore, the European Commission has adopted a proposal for a Corporate Sustainability Reporting Directive (CSRD) which could extend the scope of the NFRD to include all “large” companies, reducing the threshold from 500 to 250 employees (European Commission n.d.-c). This change would broaden the scope of entities that need to integrate a non-financial disclosure into their management report from 11,700 to about 49,000 (European Commission n.d.-d). Nevertheless, according to the EU definition of small and medium enterprises (SMEs), most (i.e., all non-publicly listed) SMEs would still fall out of the scope. Therefore, SMEs (that are not exceptionally subjected to the NFRD) may only voluntarily disclose their EU taxonomy compliance (UNEP Fi and EBF 2022).

The mandatory corporate taxonomy disclosure aims to stimulate investment in sustainable activities, offer transparency and protection against "greenwashing" to all stakeholders, and provide the financial sector with the data they need to redirect capital to genuinely environmentally sustainable activities (Pettingale et al. 2022).

Lastly, the EU and the Member States are also required to apply the EU taxonomy when setting out measures, i.e., EU or national standards or labels for financial products (e.g., the EU Ecolabel criteria for retail financial products) or corporate bonds (e.g., the EU Green Bond Standard) presented as sustainable) (Canfora et al. 2022).

7.3 EU Taxonomy Applicability and Timeline

The timeline for disclosure obligations differs for non-financial and financial undertakings required to report on the EU taxonomy (see Fig. 2).

The disclosure requirements for corporate reporting on taxonomy-eligibility apply from January 1, 2022, for the climate objectives and are extended to the other four environmental objectives and the reporting on taxonomy-eligibility as well as taxonomy-alignment from January 1, 2023 (Pettingale et al. 2022). The reporting covers the fiscal year ending 2022 or respectively 2023 (Pettingale et al. 2022). For the subsequent years, the reporting scope for different corporate sizes is continuously

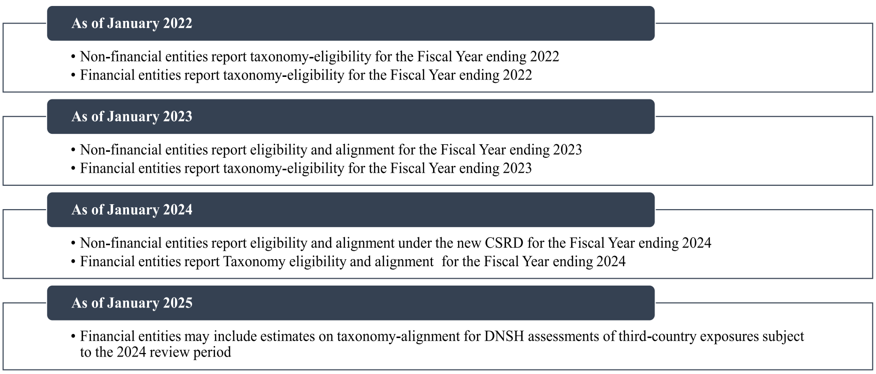

Fig. 2 Disclosure obligations under the EU taxonomy (Pettingale et al. 2022; UNEP Fi and EBF 2022)

Table 1 Overview of the key changes and impacts under the CSRD (Commission 2013; Karatzoglou and Giannetti 2021)

	Current NFRD	CSRD
When applicable?	Fiscal year 2018	Fiscal year 2025
To which companies?	Large public interest entities with > 500 employees, including: • listed companies, • banks, and • insurance companies	All listed companies and large companies (fulfilling two of the following criteria): • > 250 employees, • > €40 M Turnover, • > €20 M Total Assets
Scope of reporting requirements?	Companies should report on: • environmental protection, • social responsibility and treatment of employees, • respect for human rights, • anti-corruption and bribery, • diversity on company boards	Additional reporting obligation on: • "Double Materiality" (companies' sustainability risk + companies' impact on society and environment), • other forward-looking information including targets and progress, • information on intangible assets, • reporting in accordance with the SFDR and the EU. Taxonomy Regulation
3rd party verification	Not mandatory	Mandatory (limited assurance)

extended according to the CSRD. As of January 1, 2024, also, all financial undertakings will need to report taxonomy-eligibility and alignment (before that, only taxonomy-eligibility) of their underlying investment; however, only if corporates have reported this information themselves beforehand (Humphreys 2021).

Further changes to the disclosure obligations on the EU taxonomy will be introduced through the CSRD that will amend the current NFRD, expanding the reporting scope and information scale. Table 1 indicates the changed reporting characteristics anticipated by amending the NFRD through the CSRD.

Thereby, the CSRD is expected to be adopted by the end of 2022, with first reporting obligations anticipated from January 1, 2025, for all large companies as well as all listed small and medium enterprises (SMEs) (UNEP Fi and EBF 2022). Furthermore, as of January 1, 2026, reporting obligations for all listed SMEs are foreseen under the CSRD (UNEP Fi and EBF 2022). Yet, the final application dates for all stakeholders reporting under the CSRD are still to be officially released.

7.4 Limitations of the EU Taxonomy

Although the EU taxonomy is considered a dynamic tool with criteria regularly updated and more activities going to be covered under its scope in the future, currently, only 13 sectors are included in the climate delegated act, with significant industries, i.e., agriculture, being excluded (Pettingale et al. 2022).

Considering the existing narrow framework of the EU taxonomy, including a list of 88 technical screening criteria for the climate change mitigation and 95 for the climate change adaptation objective, the other four environmental objectives (at the moment being under preparation), as well as the social dimension (with currently only a first framework for a social taxonomy being under development) of sustainability, still remain unaddressed (Pettingale et al. 2022; European Commission n.d.-c).

A reason for the limited spectrum of activities within the EU taxonomy lies in its first development phases, including only criteria on activities that have a high impact (high-emitting activities) or high improvement potential (zero-emitting activities); however, not addressing "moderate-emitting activities" with minor impact on the environment (Decoene and Blum 2021). Yet, such activities might be crucial in the transition to climate neutrality and less demanding for defining technical screening criteria (Decoene and Blum 2021).

As a result of the limited number of sectors, activities, and environmental objectives currently being addressed within the EU taxonomy, undertakings may not be able to declare any activities from their portfolio as taxonomy-eligible (Pettingale et al. 2022). Noting that a second Delegated Act addressing the remaining four objectives is currently under development and expected for next year, however, taking a harmonized approach as to the first Delegated Act, including only a limited number of activities and sectors prioritized by high impact and improvement potential (Platform on Sustainable Finance n.d.-a). Furthermore, the EU taxonomy framework provides a limited incentive for undertakings not considered taxonomy-eligible to transition to more sustainable business practices or investments (Pettingale et al. 2022).

Additionally, even though the EU Taxonomy builds on robust and transparent methodologies as well as processes involving external expert groups (e.g., Technical Expert Group, Platform on Sustainable Finance, and Member State Expert Group) with the primary aim of creating a science-based classification for environmentally sustainable activities, the influence of politics is an important parameter of the process itself.

Expert groups, such as the previous Technical Expert Group on Sustainable Finance (TEG) and the Platform on Sustainable Finance (PSF) now anchored in the EU Taxonomy Regulation (Art. 20), play a vital role in the development of the EU taxonomy, bringing together the best expertise on sustainability from industry, the public sector, civil society, academia and the financial sector (European Commission n.d.-e). Their main purpose is to advise the EU Commission on the further expansion of the EU taxonomy, providing recommendations on technical screening criteria based on robust methodologies and scientific evidence (European Commission n.d.-b).

Yet, against the scientific recommendations of the Platform on Sustainable Finance (PSF), a Complementary Climate Delegated Act (CDA) was adopted in July 2022, including specific nuclear and gas activities under stringent conditions within the EU taxonomy (European Commission 2022). Instead, the EU PSF, in its response to the CDA, has advised that activities related to the energy generation from fossil fuels and nuclear facilities are not in line with the Taxonomy Regulation and should rather be considered in an intermediate or amber taxonomy that is under development (Platform on Sustainable Finance 2022). Future EU taxonomy developments and policies especially targeting future generations, have the potential to strengthen the science-policy interface, improving transparency, and making the evidence and rationale for all decisions accessible to all (Allen et al. 2021). Nonetheless, the EU Taxonomy displays one of the most advanced and ambitious approaches to developing a classification system for environmentally sustainable activities.

While the EU taxonomy in its current framework features limitations, the development of the taxonomy will maintain by including further activities over time, as well as updating the technical screening criteria for the activities already included to ensure it always reflects the latest scientific and technological developments. As of now, the EU taxonomy, for the first time, represents a unified classification system labeling activities as sustainable and providing a common language for all stakeholders.

7.5 *Future Developments—The Environmental Taxonomy as the Starting Point for a Social Taxonomy*

In order to achieve the SDGs and meet the financing gap in developing countries, vast investments of about \$2.5 to \$3 trillion a year are needed in these countries for social sustainability. The current EU taxonomy framework focuses mainly on the environmental dimension, only considering social and governance aspects by requiring undertakings to meet the minimum safeguards (Platform on Sustainable Finance n.d.-b).

Thus, while the present EU taxonomy has limited inclusion of social sustainability aspects and an environmental focus, the EU has made its first attempts to develop a social taxonomy (Pettingale et al. 2022). In this context, the European Commission has provided a mandate to a subgroup of the Platform on Sustainable Finance to deliver recommendations on extending the EU taxonomy, including social objectives (Platform on Sustainable Finance n.d.-b).

Following the current EU taxonomy for environmentally sustainable economic activities, the social taxonomy would likewise define socially sustainable activities by adopting the key aspects from the environmental EU taxonomy framework. Thus, the Platform on Sustainable Finance for a future social taxonomy proposes to develop social objectives, adopting the substantial contribution and "do not significantly harm" (DNSH) principle (Platform on Sustainable Finance n.d.-b).

While the EU Commission, with the experts from the Platform on Sustainable Finance, continues to develop the environmental and social EU Taxonomy, antagonizing the current limitations of the EU taxonomy, undertakings should form future reporting and business strategies with the EU taxonomy and the future coming framework in mind.

8 Conclusion

This chapter mainly tried to link CSR-related activities with the classic firm value maximization objective. We conclude that changing preferences among firm stakeholders towards more sustainability orientation reconcile at least to some degree the concepts of firm value maximization and sustainability. The central mechanism behind this harmonization is that stakeholders behave increasingly favorable towards firms that exhibit a higher CSR performance. This favorable treatment increases firm cash flows and reduces the expected returns required by investors and thus leads to an overall increase in firm value, which provides managers with an incentive for CSR engagement. The paradigm of shareholder wealth maximization or firm value maximization thus has the potential to contribute to an effective transformation of economies towards more sustainability. For this mechanism to work successfully, it is however crucial that corporate transparency on the issue of CSR is further improved. The EU taxonomy marks a pivotal step towards achieving more transparency in this domain.

Despite the valid limitations that the EU taxonomy features in its form today, it also marks the starting point for an increasingly regulated disclosure of firms' sustainability data based on a scientific methodology at a time when stakeholders have pleaded for more consistent and transparent sustainability reporting. Furthermore, from 2025 onwards, a considerably broader reporting based on the EU Taxonomy and unified European sustainability reporting standards (ESRS) will be established, indicating that firms cannot continue to rely on disclosing only general policies and data to receive a positive rating or to be labeled as a sustainable investment. Instead, firms will need to base their sustainability strategies on aligning with the EU taxonomy.

Even though firms not falling under the EU taxonomy today might be tempted to wait for further developments or an extended social taxonomy before aligning their business strategy with the EU taxonomy, the principles on which the methodology is designed are clear and, ultimately, it can be expected that the sustainability performance of all companies within the EU will be assessed based on these principles. Moreover, the access to sustainable capital flows will be increasingly interlinked to driving a sustainable transformation based on EU taxonomy-alignment and the adequate disclosure of the relevant data.

The future will show to what extent the transparency introduced by the EU taxonomy disclosures and the availability of corporate sustainability data will prompt a meaningful change in firms' sustainability strategies and whether this will lead to a transition towards a (more) sustainable economy.

There are however limits to what CSR-conscious investing and thus the increased transparency on sustainability can achieve. Generally, CSR-conscious investing is more suited for promoting incremental transformation processes rather than disruptive changes in the economy. This is due to the fact that many firm assets are long-lived. An example of this are power plants. Obtaining financing for a new coal power plant might have become too costly for this energy form to be economically feasible.

However, many coal power plants that are currently still in operation have been funded when carbon emissions were not a relevant concern for investors. Funding considerations do not provide a direct incentive for divesting from these long-lived assets. In addition, particularly high-risk sustainable innovations will not be financed without hesitation even by "green" investors which means that public subsidies and thus risk-taking by the whole society may be necessary. Thus, promoting transparency on firm's CSR performance is unlikely to achieve the transformation pursued by the EU on its own. Other regulatory actions are presumably needed.

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Transformation Towards a Sustainable Regional Bioeconomy—A Monitoring Approach

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Abstract The concept of the sustainable bioeconomy aims to ensure the well-being of both current and future generations while staying within environmental boundaries. However, achieving this goal will require significant changes to existing resource systems, business models, governance systems, and more. Current approaches to monitoring the transformation towards a sustainable bioeconomy lack a regional perspective that incorporates all three sustainability dimensions. To address this gap, we aim to provide an integrated evaluative framework for assessing regional transformation processes towards a bioeconomy. The recent decision to phase-out coal power in Germany presents a unique opportunity to understand the socio-technical dynamics and implementation options for the transformation to a sustainable bioeconomy region in the current lignite-mining region "Rheinisches Revier".

Keywords Sustainability · Biobased transformation · Bioeconomy · Regional development · Monitoring framework

1 Introduction

To satisfy the growing demand for resources without transgressing environmental limits, a rapid transformation with profound interventions by public and private decision-makers is needed (Te Velde et al. 2012; WBGU 2016). The transformation of an economy predominantly based on fossil resources towards a sustainable bioeconomy is a core cornerstone on this route. However, while an economy largely

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P. Letmathe et al. (eds.), *Transformation Towards Sustainability*,
https://doi.org/10.1007/978-3-031-54700-3_8

based on biogenic resources offers many attractive options and opportunities, undertaking and governing its implementation process is complex: it requires major transformations of existing resource systems, value networks, business models, infrastructures, and governance systems with diverse interrelations leading to intended and unintended effects. Existing structures have evolved over a long period under a mostly unsustainable management paradigm. Only recently, holistic, integrated, and sustainable transformation approaches have been considered (Eversberg et al. 2023).

During the last decade, climate change and environmental protection have been at the top of global political agendas. Planetary boundaries ensuring the stability of the Earth system (e.g., atmospheric carbon dioxide (CO_2) concentration and levels of phosphorus and nitrogen in freshwater systems) have been surpassed and the achievement of the 1.5 °C global warming goal remains highly questionable (Kopittke et al. 2021; IPCC 2022). Reducing greenhouse gas (GHG) emissions is key to mitigating the impacts of climate change and to achieving the United Nations (UN) Sustainable Development Goals (SDGs) (United Nations 2015). The European Union (EU) assumes a leading role in this process and aims for defossilization and zero net GHG emissions by 2050 (European Commission 2019). The required transformation goes beyond using renewable energy resources like solar, wind, and biomass as basis for the economy. Instead, it calls for a holistic approach to facilitate societal change (European Commission 2019).

Bioeconomy, i.e., the production, conversion and use of renewable biological resources to create value-added products and services, provides suitable mechanisms for this holistic transformation towards resilience (Galanakis et al. 2022). Especially for carbon-intensive regions where mining and refining of fossil resources is a main economic activity, a phasing out of these technologies and a shift towards bioeconomy promise an economically, socially, and ecologically sustainable future.

The collective promotion of both modern technology (i.e. technical know-how) and improved awareness (i.e. social know-how) on the bioeconomy has been identified as a key policy objective (BMBF and BMEL 2020). Research has shown that today's global sustainability challenges cannot be overcome solely by greater scientific and technological understanding, but will instead require also a greater understanding of the role of people and their social systems (Macht et al. 2023; Zander et al. 2022). Thus, closing this gap has been translated into a strong academic mandate to address the question of understanding "how risk, social networks, and governance can influence the pace of transition to a low-carbon future" (Editorial Nature Climate Change 2016). In a similar vein, current research stresses the need to envisage the entire innovation ecosystem as an indispensable perspective to understand the emerging innovation capabilities of individual corporations, industries, and regions (Adner and Kapoor 2010; Marcone et al. 2022).

For more than a decade, the transformation towards a bioeconomy has been discussed in contested terms, highlighting different perspectives and challenges (Bugge et al. 2016; Hausknost et al. 2017; Pfau et al. 2014). Monitoring approaches address sub-sectors of the bioeconomy country level, and comprehensive frameworks are still in development (Thrän 2022). So far, the perceptions and approaches of different stakeholder groups have mostly been analysed individually (Kuckertz et al. 2020; Vandermeulen et al. 2012; Wensing et al. 2019) or at the national level (Dieken and Venghaus 2020; Sturm and Banse 2021). Since bioeconomy activities are often clustered in subnational regions and driven by both national and regional policies (Overbeek et al. 2016), these approaches fall short of the bioeconomic aspiration to provide a holistic perspective based equally on the three sustainability dimensions, which requires an integrated evaluative framework for regional transformation processes. As bioeconomy is a growing research discipline (Dieken and Venghaus 2020) and several international political agents strive towards implementing bioeconomic patterns at different scales (IACGB 2020), this research gap needs to be closed. We propose to close this gap by providing a comprehensive framework for the assessment of regional transformation processes towards bioeconomy, which was developed using the case of the lignite-mining region "Rheinisches Revier" (RR) in the state of North Rhine-Westphalia in western Germany. From a scientific viewpoint, the regionally integrated perspective allows to reduce the complexity of emerging, dynamic, self-organizing, and larger scale systems, such as the bioeconomy (Urry 2005). The recent decision of the German government to phase-out coal power will initiate major transformation processes in the Rheinisches Revier, creating a unique opportunity for understanding the socio-technical dynamics and implementation options towards an entire sustainable bioeconomy region. Against this background, it is crucial to systematically identify and monitor transformation trajectories for the implementation of a strong bioeconomy in the Rheinisches Revier. These transformation routes need to be, at the same time, (a) desirable (from a sustainability perspective), (b) possible (from a techno-economic perspective), and (c) acceptable (from a stakeholder consensus perspective) and cover all three sustainability dimensions.

We begin with a description of the visions and pathways of bioeconomy transformation (Sect. 2) to underscore the need for a holistic perspective, which is based on the three sustainability dimensions and that addresses all relevant stakeholder groups. To identify relevant determinants for bioeconomy transformation, we conduct a structured literature review (Sect. 3) of current bioeconomy monitoring approaches to highlight the importance of local conditions in bioeconomy transformation, followed by the presentation of the regional perspective on bioeconomy transformation monitoring (Sect. 4). Section 5 concludes.

2 Transformation Towards a Sustainable Bioeconomy

Bioeconomy is a comprehensive concept that aims to address global challenges such as resource scarcity, climate change, and population growth by ensuring sustainable use of natural resources while providing adequate food and renewable resources to a growing population (Lewandowski et al. 2018). Although bioeconomy principles are considered a key contribution to the SDGs, the bioeconomic use of natural resources is not inherently sustainable. The production of biogenic materials for material or energetic use requires scarce resources, particularly land and water (Pfau et al. 2014).

The increased demand for biomass in industrialized countries can cause land use change and biodiversity loss, leading to food security issues in developing countries (BÖR 2015). Over the past decade, the number of bioeconomy strategies at regional and national levels has increased worldwide (Haarich and Kirchmayr-Novak 2022; IACGB 2020; Dietz et al. 2018); however, current strategies address sustainability issues vaguely (Kiresiewa et al. 2019).

In Europe, the concept of a bioeconomy dates back more than 30 years, with the first bioeconomy strategy adopted in 2012 by the European Commission. It defined the bioeconomy as the production of renewable biological resources and the conversion of these resources and waste streams into value-added products (European Commission 2012; Patermann and Aguilar 2018). While the European definition was based on a biotechnology perspective, it aimed to substitute fossil resources with biobased ones (Birner 2018). The National Bioeconomy Strategy of the German Federal Government emphasizes technological progress and the sustainable, circular use of biobased resources to support the country's transition to a climate-neutral economy, pursuing the goal of becoming a globally leading location for innovation in the bioeconomy (BMBF and BMEL 2020). In addition to its strong technological and economic focus, the strategy recognizes the importance of societal opinions and stakeholder expectations regarding the bioeconomy concept, ensuring a successful and smooth implementation (BMBF and BMEL 2020).

Current developments and actions in the bioeconomy are to a large degree policy-induced and thus motivated by research and technology (MKW 2012). As a consequence, the practical and widespread implementation of the bioeconomy will be strongly driven by the introduction of both biobased substitutes and novel products and production processes (e.g., surfactants and platform chemicals derived from biorefineries). However, this transformation will likely implicate also radical technological innovations, which may disrupt existent business models and entire industry logics, as well as innovations in social processes, governance processes, and individual decision-making. A multitude of interrelated actors with different visions, attitudes, objectives, fears, and roles are involved. They will act on different decision-making levels (policy, industry, consumer, civil society, etc.), in different sectors or policy fields (economy, agriculture, environment, energy, consumer protection, etc.), under consideration of differing temporal scales (short-, mid-, and long-term perspectives), and will simultaneously influence the decision-making processes. In the best case, the decision forces initiate measures that positively reinforce each other. Often, however, unintended side effects with unpredictable and likely negative feedback occur (Stark et al. 2022). A possible reason is that the different stakeholders assess their decisions based on their respective and differing contextual frames of reasoning. Especially in the case of radical technological developments, feedback loops, and unintended consequences are much harder to anticipate, making it difficult to adequately integrate them into decision-making. Stakeholder dynamics, their underlying motivations as well as their effects are often not sufficiently considered in mostly techno-economic assessment approaches and, consequently, policy decision-making (Dyer et al. 1992; Lerche and Geldermann 2015).

Research has shown that such comprehensive transformations towards sustainability proceed very slowly, are strongly impaired by path dependencies and lock-in effects, and can only be successful when technological progress meets social acceptance (Gooyert et al. 2016; Hake et al. 2015). Thus, it is crucial for bioeconomic thinking to consider all three dimensions of sustainability at a transnational level to achieve a holistically sustainable bioeconomy. However, the trade-off between economic growth on the one hand and ecological and social sustainability on the other determines the bioeconomy visions and transformation pathways in the current scientific discourse.

2.1 Dominant Visions and Fragmented Perspectives

In the academic literature, three popular visions of the bioeconomy have been identified (Bugge et al. 2016), that differ in the degree how the three distinct sustainability dimensions (i.e. social, economic, and environmental) are addressed. First, in the biotechnology vision, economic growth depends on sector-specific scientific knowledge, patents, and commercialization of research and development (R&D) results. High funding for biotechnology and pharmaceutical companies leads to concentrated growth in regions with these companies. This vision assumes an implicit contribution of technology to sustainability and, therefore, does not regard resource shortages or increasing waste production as a problem. Second, the bioresource vision builds on research and improvements in naturally biobased sectors, such as agriculture, forestry, or fishery. Efficient land use and the avoidance or reuse of industrial side streams connect economic activities with sustainability. Nevertheless, innovation and new technologies are still dominant in upscaling production and conversion of biological resources into marketable products, ensuring economic growth. However, the focus is on interdisciplinary research and collaboration, while new biobased value chains provide employment opportunities in rural areas. The biotechnology and bioresource vision are similar, with economic growth by new technologies and R&D as their core. Third, the bioecology vision is based on sustainability where unequal access to biological resources and knowledge is regarded critically and self-sustaining, circular production and consumption based on local resources is advocated. Natural constraints are respected to ensure ecosystem conservation and soil fertility. By combining the three dimensions of sustainability, "locally embedded economies" are established in this vision (Bugge et al. 2016).

Overall, bioeconomy research is still very fragmented and analyses different transformation aspects in isolation. Thereby, technology and resource-centred visions dominate (Dieken and Venghaus 2020; Dietz et al. 2018), whereas societal considerations are limited to consumer perspectives (Dieken et al. 2021; Priefer et al. 2017). This imposes further challenges for the already missing holistic and harmonized policies needed for a successful transformation (Gottinger et al. 2020)—especially since different stakeholder groups show different perceptions of the bioeconomy and support different bioeconomy narratives. Dieken et al. (2021) find that primarily political actors and researchers indicate a preference for the biotechnology vision, whereas farmers, forest owners, industrial representatives, and social or environmental initiatives tend to favour the bioresource vision, while citizens and consumers mostly support a bioecology vision. Similar results are found by Hausknost et al. (2017) who identify four bioeconomy narratives and evaluate the support by different stakeholders. However, most bioeconomy research focuses on the "golden triangle" of political, industrial, and scientific stakeholders (Dieken et al. 2021; Mukhtarov et al. 2017). For citizens, farmers, environmental, and societal initiatives, the amount of studies is considerably lower than for the other stakeholder groups and focuses on the assessment of biobased product acceptance or adoption. Studies on bioeconomy in social sciences have either a theoretical or a very narrow, case-study focus on aspects of natural sciences, such as technologies in biotechnology, chemistry, or genetics (Sanz-Hernández et al. 2019). The resulting dominance of a techno-economic perspective in bioeconomy research challenges the principles of sustainability postulated by the concept (Dieken et al. 2021).

While technology, biological resources, and ecology appear to be the dominant visions in current bioeconomy research (e.g., Hempel et al. 2019; Stern et al. 2018; Vivien et al. 2019), it must be noted that these represent political and academic idealizations which partly overlap and can be regarded as complementary and not as mutually exclusive (D'Amato et al. 2020). Nevertheless, the three visions and their relative importance determine the pathway selected for bioeconomy transformations.

2.2 Pathways Towards a Sustainable Bioeconomy

Windows of opportunity can enable different pathways that might lead to similar overall transformations (Grin et al. 2011). In the bioeconomy transformation, the overall aim is to replace fossil with biobased resources while ensuring sustainability safeguards. To achieve this, scholars identified transformation pathways and approaches that reflect the target conflicts and trade-offs between the three sustainability dimensions inherent in the visions discussed above and different stakeholders addressed.

Dietz et al. (2018) derive four distinct pathways for a transformation towards a bioeconomy that aims at using a country's comparative advantage and creating synergies across economic sectors, which hence are determined by the availability of natural resources, the existence of a strong research sector, pre-established specific technologies in the country and "country-specific development deficits to be overcome". The fossil substitution pathway (TP1) aims at a complete substitution of fossil fuels by biobased resources. High oil prices and new environmental regulations were the point of departure here, but today the negative example of first-generation biofuels causing land use change and monocultures highlights challenges for mere substitution as a long-term strategy. TP2, productivity increase in agriculture, describes the importance of technological innovations in the primary sector for biomass production, yield loss reduction, and unused land development. As land resources are scarce, this pathway threatens biodiversity by claiming land with high ecosystem services for agricultural production. The third pathway (TP3) focuses on efficiency increases in biomass use and processing. The ability to use biomass more efficiently and recycle waste enables the production of biobased products at a large scale. Concerns arise regarding mixed consumer acceptance of biobased products and the occurrence of rebound effects, where overconsumption of biobased products causes an overall increase in biomass use and counteracts efficiency increases. The fourth transformation pathway (TP4), called "value creation and addition", suggests the application of biological principles and knowledge to produce goods independently of biomass availability. By applying new knowledge in combination with technical innovations, this pathway aims for more ecologically sustainable production methods and the development of completely new products (Dietz et al. 2018). Most countries with dedicated bioeconomy strategies rely on a combination of all four pathways to transform into bioeconomies (Dietz et al. 2018).

Priefer et al. (2017) take a broader perspective on bioeconomy transformation, distinguishing two main directions. The *technology-based approach*, a combination of TP2-4 with the biotechnology and bioresource visions, depends on advances in life sciences and biotechnology as enabling technology for the transformation. Political, industrial, and scientific actors, at both national and international levels, cooperate intensively to establish global value chains and ensure overall growth and employment. Efficiency increases in agricultural production, through breeding and genetic engineering, as well as the use of biological knowledge for new product development, e.g., in large biorefineries provide the basis for the transformation. Sustainability is not a concern, and societal actors are not actively participating in the transformation, but are informed about advantages of the new technologies to foster acceptance (Priefer et al. 2017). The *socio-ecological approach*, in line with the bioecology vision of Bugge et al. (2016), postulates that a bioeconomy can be sustainable under certain conditions. Decentralized agriculture, agro-ecological practices (e.g., nutrient cycling and biological pest control), and the avoidance of genetic engineering ensure a sustainable biomass production. Local and tacit knowledge helps to develop regional value chains that follow natural cycles. Sufficiency approaches, the cascade and circular use of resources, combined with social innovations, respect the planetary boundaries. Research combines natural and social sciences and uses inter- and transdisciplinary approaches. Civil society plays an active role in the bioeconomy, its involvement is crucial and ensured at all levels.

These two approaches are extreme examples of bioeconomy transformation pathways, which can also be implemented in a complementary way. Currently, the technology-based pathway is common, with a limited focus on social sciences and low involvement of societal stakeholders. However, a combination of views that addresses all three sustainability dimensions and considers all societal stakeholders is important to fulfil the principle of the bioeconomy as a holistic concept (Priefer et al. 2017). Even though the popularity of bioeconomy strategies increased in the last decade, countries are aware of the risks and trade-offs that a large-scale bioeconomy implementation brings about (Dietz et al. 2018). In particular, land and water availability and use conflicts as well as global food security are concerns which require a clear hierarchy for biomass use to ensure stable, long-term political decisions (Dietz et al. 2018; Meyer 2017). Inequality as well as climate and health risks are less often addressed in national strategies (Dietz et al. 2018). However, positive contributions to these issues are promised by the bioeconomy and non-fulfilment of these expectations will cause disappointment, doubts about the suitability of the bioeconomy concept, and even social opposition (Meyer 2017). Different approaches towards these challenges are mirrored in contrasting positions and visions of the bioeconomy (Bugge et al. 2016; Pfau et al. 2014; Priefer et al. 2017).

3 Monitoring Bioeconomy Transformation

To manage bioeconomy transformations or adjust pathways (i.e. shift from one to another), indicators are required that provide information about the current situation (Ronzon et al. 2022b). Based on the bioeconomy visions, pathways, and barriers, several important aspects for the transformation can be identified: the availability of natural resources, a strong knowledge base and innovation sector, and biomass conversion technologies (Dietz et al. 2018), suitable market conditions for biobased products (Gottinger et al. 2020), the involvement of civil society (Priefer et al. 2017), as well as targeted policies and their implementation measures (Meyer 2017). As bioeconomy in the RR is still in its infancy, a first holistic assessment is needed, where especially qualitative aspects of the transformation provide insights into current developments, structures, and interconnections at the different levels (Geels 2004, 2011).

As a starting point for the development of a monitoring framework, a literature review to identify qualitative factors with an influence on bioeconomy transformations was conducted. Where available, exemplary considerations for a monitoring system are also presented. Due to its comprehensive overview of publishers in the field of natural and social sciences, as well as technology and humanities, the scientific database Scopus was selected as source for the literature review. Scopus was searched for any of the words “monitoring”, “measurement”, “model”, “assessment”, or “framework” in combination with either “bioeconomy”, “bio-economy”, or “biobased economy” and “indicator*” in the title, abstract, or keywords. This search yielded 626 results. Refinement by consideration of open access publications only and the limitation to journals related to environmental, agricultural, earth, and social sciences, as well as economics, management, and energy narrowed the results down to 304 documents. Thereby, the focus was limited to accessible, socio-economic, agricultural, and environmental considerations of the bioeconomy, which are especially important issues (Fritsche and Iriarte 2014). As the RR’s location is in Germany, the scope of the inquiry was limited to Germany, to ensure suitability of the results for the selected case. However, documents mentioning Germany within a European context were also considered. No restriction on the date of publication was applied, yielding documents from 2014 to 2022 leading to a total of 72 documents. The abstracts and the studies were screened for relevant aspects, such as specific sectors or technologies, stakeholder perspectives, or perceived conflicts. Overall, 30 studies dealt with bioeconomy or circular economy approaches, the latter were included due to their important contribution to a sustainable bioeconomy (BMBF and BMEL 2020).

Three studies used expert opinions to assess drivers and barriers of the bioeconomy transformation and provided information on influencing factors. Based on a global expert survey, Issa et al. (2019) highlight the importance of arable land availability for biomass production and yield increases in traditional farming. Beyond this, waste management and side stream use to increase the biogenic resource base, as well as biotechnology and innovations to develop new biobased materials and products are requirements for a successful transformation (Issa et al. 2019). Hagemann et al. (2016) identify clear, long-term political guidance on the use of biobased resources for food, material, or energetic purposes as crucial for the development of bioeconomy sectors (Hagemann et al. 2016). In addition, global economic developments and national policies affect demand for biomass and consumers' willingness to pay for biobased products, shaping investment into biobased value chains. From their point of view, innovation is the most important determining factor as it influences the possible future development and impacts many other aforementioned factors (Hagemann et al. 2016). Using a Delphi study, Hinderer et al. (2021) underline the importance of a common understanding of bioeconomy to develop implementable action plans at a political level (Hinderer et al. 2021). Additionally, stakeholder awareness of the concept is important for legitimization and acceptance of the respective policies.

From the 30 studies, 19 dealt especially with technological and/or economic aspects of the bioeconomy or with the importance of specific economic sectors. While the bioeconomy sectors discussed are diverse and range from large volume primary biomass production to low bulk, but high-value biologization of processes, most studies deal with the availability of biobased input materials as well as related economic and technological efficiency issues. Efken et al. (2016) for example use employment and gross value added as indicators to determine the contribution of the bioeconomy to the German economy, which accounted for 6% of the gross national product in 2010. In 2017, using labour productivity in addition to employment and value added, (Ronzon et al. 2022b) see the bioeconomy transformation in Germany still at its beginning, but identify agriculture and the food industry as main non-service contributors. More recently, scientists also consider services as an important contributor to the bioeconomy transformation (Ronzon et al. 2022a). In 2017, wholesale, retail of biobased products, as well as services in the food and beverage sector provided more than 60% of employment and value-added of all bioeconomy services in the EU (ibid.). Regarding the sectors addressed in the analysed studies, many evaluate the forest sector or wood-based value chains as main contributors to the bioeconomy (e.g., Budzinski et al. 2017; Jarosch et al. 2020). Thereby, physical requirements for the input material, adequate product design for recycling, and political regulations create central challenges (Jarre et al. 2020). At the global level, land use change (Haddad et al. 2019) and precarious societal conditions (Siebert et al. 2018) are issues often associated with an increasing use of woody biomass.

Biogenic residues, for example agricultural or forestry by-products, municipal and industrial waste, as well as sewage sludge, can increase resource availability and ease pressure on arable land (Brosowski et al. 2019; Kircher 2022). Considering the use of agricultural by-products, Donner et al. (2021) identify biomass storage and logistics, efficient conversion technologies and economies of scale as main techno-economic criteria to ensure price competitiveness of biobased products (Donner et al. 2021). New technologies require joint R&D investments by the public and private sector and subsidies for biobased processes (ibid.). Such technologies like biorefineries for material or energetic purpose and their integration into local value chains are expected to shape the future agricultural side streams valorization (Gontard et al. 2018; Theuerl et al. 2019). However, clear and transparent policies and their communication are needed to avoid sustainability conflicts in the bioeconomy and ensure sufficient availability of food, material, and energy (Horschig et al. 2020; Thrän et al. 2020). Generally, economic and financial aspects are most important for the use of side streams, e.g., by avoiding costs for waste disposal (Klein et al. 2022). In the chemical industry, expectations about contributing to the bioeconomy by shifting from fossil to biobased resources are high (Lokesh et al. 2018; Thormann et al. 2021). Especially bioplastics (Spierling et al. 2020) and biopolymers are subject to studies, where design for recycling plays a key role to ensure sustainability (Hildebrandt et al. 2017).

Overall, eight studies focused on sustainability conflicts caused by the implementation of a bioeconomy. Several underline the importance of a holistic sustainability approach, where economic, environmental, and social dimensions are considered equally (e.g., Fritsche and Iriarte 2014; Kardung et al. 2021). Bringezu et al. (2021) go a step further and consider international implications of domestic production and consumption, showing that for example, the agricultural land used for German consumption is higher than the national availability, causing land use change in other countries. These transnational resource footprints of the national bioeconomy can be calculated for the used agricultural land, forest, water, material (biotic and abiotic), and emitted GHGs (Egenolf and Bringezu 2019). Thereby, the resources consumed or emitted during national production add to the resources consumed or emitted for the production of imported goods, while the resources consumed or emitted for exported goods are subtracted providing the net resource use or emissions (ibid.). Other scientists postulate that the consideration of ecosystem services is important to ensure staying within the recovery capacity of nature (D'Amato et al. 2020; Kircher 2022). In this context, efficiency strategies, e.g., due to innovation and technological developments play a fundamental role for a "smart, innovative, and sustainable bioeconomy" (O'Brien et al. 2015). Moreover, standardization and harmonization of sustainability certificates for biobased products can help manage the scarce resources and increase transparency in the bioeconomy (Majer et al. 2018).

Figure 1 provides a summary of the results from the literature review. Grouped according to the three sustainability dimensions, the relevant factors show the need for a holistic approach, in which efficiency increases and circularity have to go hand in hand with innovations, clear communication, and political action implementation. The economic dimension is dominant, as shown by the higher number of words (8)

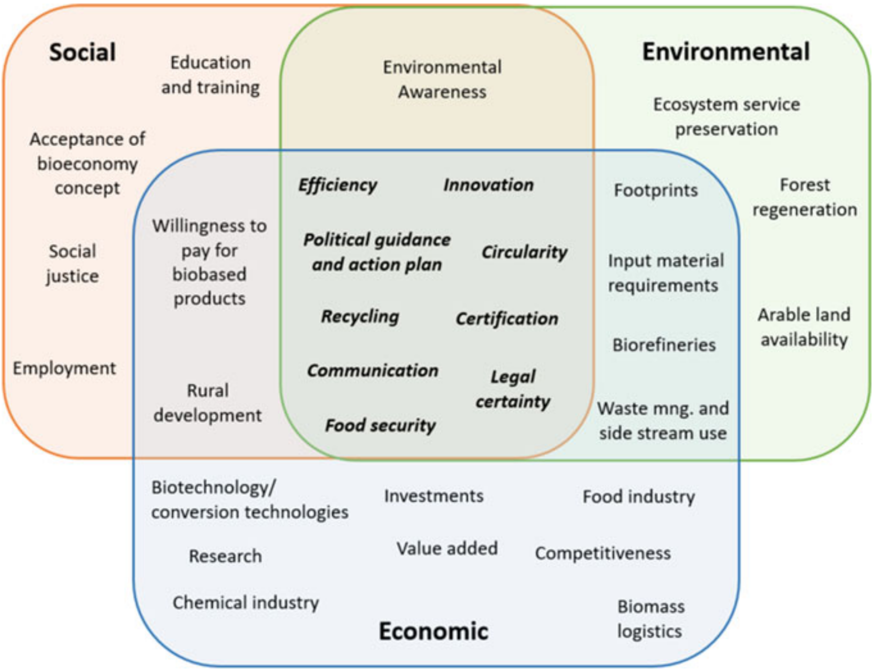

Fig. 1 Determining factors for a holistically sustainable bioeconomy transformation. *Source* Based on 30 studies from literature review. Graphical design inspired by Egenolf and Bringezu (2019)

in the blue square compared to the social (4) and green (3) dimension. However, the latter two have gained importance in recent years and are not regarded as optional anymore, but as required to ensure long-term economic success (O'Brien et al. 2015).

In their study on indicator conceptualization for a sustainable bioeconomy, Egenolf and Bringezu (2019) suggest, among others, developments in consumer food prices, the gender income gap, the number of trade union employees and in-company employees as well as access to public transportation in rural areas as indicators for social sustainability (Egenolf and Bringezu 2019). Environmental sustainability is usually measured by land cover and land use changes, the substitution rate of fossil energy and material with biobased resources, emitted GHGs, and different ecological footprints (Kardung et al. 2021). Average monthly income and value added of bioeconomy sectors, the number of bioeconomy-related R&D projects in SMEs, patents or investments in waste avoidance and recycling are frequently cited indicators for economic sustainability of the bioeconomy (Egenolf and Bringezu 2019).

Overall, the information from the reviewed literature shows the complexity of the bioeconomy transformation and highlights the importance of a holistic monitoring. However, no internationally standardized monitoring framework for this purpose has been developed so far (Bracco et al. 2019). Nevertheless, different institutions develop approaches to determine key influencing indicators and derive monitoring systems (ibid.). To ensure that the results from the literature review are in accordance with these international approaches, an additional targeted revision of national and international bioeconomy principles and monitoring frameworks with relevance for the RR was conducted.

The Food and Agriculture Organization (FAO) of the UN mentions ten principles for a sustainable bioeconomy (FAO 2021). From a societal perspective, (1) food and nutrition security at all levels are the most important criteria. Together with (9) sustainable consumption patterns, they increase (4) social and economic resilience, especially in rural areas. To ensure (3) competitive and inclusive growth, the use of (7) existing knowledge and the promotion of new technologies, in line with (8) sustainable trade practices, is crucial. Regarding ecological sustainability, the FAO highlights the need for (5) efficiency increases and circularity as well as (2) conservation and protection of ecosystems. The achievement of these sustainability aims depends on the implementation of (6) harmonized, inclusive, and transparent governance practices that promote (10) collaboration and cooperation at regional, national, and international level (FAO 2021).

To monitor the bioeconomy, the FAO identifies a dual approach including indicators at the territorial, and product or value chain level as suitable (Bracco et al. 2019). Territorial indicators (e.g., changes in food prices, GHG emissions, turnover in biobased sectors, or primary energy consumption) aim to measure the transformation towards bioeconomy. They are available for all three sustainability dimensions at national, European, and international institutions. If statistical measurement is missing, the FAO suggests the use of good practices as proxies, indicating, for example, the presence of certain strategies. At the level of biobased products and value chains, indicators (e.g. the used amount of water, the amount of biomass produced on protected land or human toxicity and cancer effects) focus especially on the social and environmental dimension (Bracco et al. 2019). Data availability, accessibility, and quality is limited, because every biobased product is different and its sustainability impact depends on the respective producer. Therefore, available, more generic data at product category level or from certifications and labels is often only of limited use (ibid). Thus, the FAO emphasizes the need for more bottom-up information at individual producer level. Indicators or proxies should be specific, measurable, achievable, relevant, and time-bound, as well as in line with the respective bioeconomy strategy and the SDGs (Bracco et al. 2019). To identify indicators and develop a bioeconomy monitoring scheme, the FAO suggests the following steps (ibid):

(1) Stakeholder engagement (iterative),
(2) Choice of relevant territorial level or key products/value chains,
(3) Relevant indicator selection,
(4) Discussion and selection of reference value for each indicator,
(5) Decision on data collection methodology and data availability assessment,
(6) Selection of good practices as additional indicators or proxies (optional),
(7) Sustainability assessment and evaluation of contribution to objectives of bioeconomy strategy, and

(8) Effective communication of results.

At the global level, common indicators and a monitoring design still need to be developed in international agreement, to provide guidance and ensure comparability (FAO 2016). However, flexibility for specific local circumstances has to be maintained. Therefore, the combination of top-down and bottom-up approaches is recommended (ibid.).

The updated Bioeconomy Strategy of the European Union identifies the following five strategic objectives: (1) insurance of food and nutrition security, (2) sustainable management of natural resources, (3) reduction in dependence on (nationally and foreign-sourced) non-renewable resources, (4) mitigation and adaptation to climate change, as well as (5) increasing competitiveness and job creation in the EU (European Commission 2018). These objectives are present in the national bioeconomy strategies of the different member states. A first assessment across member states to identify indicators used or desired in the national strategies, showed similarities for the consideration of the primary sectors as belonging to the bioeconomy, while variations in the inclusion of hybrid sectors were identified (Lier et al. 2018). For example, some countries consider the fraction of the textile or chemical industry using biobased resources a part of the bioeconomy. However, quantification of these parts is difficult, because EU statistics do not segregate biobased from fossil inputs in these sectors (Ronzon and M'Barek 2018).

To monitor the contribution of the EU bioeconomy to all three dimensions of sustainability, the five objectives were mapped to the respective SDGs (Robert et al. 2020). To ensure coherence with other monitoring approaches and strategies, the FAO's ten principles and their criteria were aggregated and mapped to the objectives as well (Giuntoli et al. 2020). Based on the EU's bioeconomy definition, the framework covers primary sectors, value chains in the bioeconomy including recycling and reuse, as well as production processes using biotechnology (independent of the feedstock) (Robert et al. 2020). In accordance with the SDGs, the FAO's principles, the indicator assessment by Lier et al. and further European and international frameworks on bioeconomy-related topics, the five EU objectives were filled with available indicators, to avoid reinventing the wheel (ibid.). For example, objective 1 is assessed using the FAO's indicators on food security, objective 2 is based on indicators from the EU initiative "Mapping and Assessment of Ecosystem Services", while objective 4 on climate change mitigation and adaptation uses data from the IPCC. Indicators from different sources using macroeconomic analysis and Life Cycle Assessment compose objectives 3 and 5 (Robert et al. 2020). Each indicator's suitability was evaluated based on data availability, geographical coverage, methodology, and length of time series (Giuntoli et al. 2020). Identified data gaps were closed with proxies and the selected, basic indicators were processed through harmonization across different scales. With Life Cycle Assessment and footprint calculations, the overall impact of the EU's bioeconomy was calculated to identify synergies and trade-offs and derive expressive system-level indicators that are used for policy decision-making (ibid). The current indicators of the European bioeconomy monitoring are available in dashboard format on the website of the Knowledge Centre for Bioeconomy.[1]

In 2019, Wackerbauer et al. (2019) developed a first attempt to conceptualize a monitoring framework for the German bioeconomy. As in the EU system, they include the primary sector and parts of the industrial sectors using biobased resources as main determinants for the bioeconomy (Wackerbauer et al. 2019). Furthermore, they use information on innovation and education, as well as on cascade use and side stream availability to account for the importance of biological knowledge and circularity in the bioeconomy. Combining top-down and bottom-up data, they assessed the biobased fraction of the oleo chemistry in Germany and verified their results with expert interviews, showing the correctness of their model. However, data availability remains the main obstacle for the bottom-up assessment (Wackerbauer et al. 2019). Bringezu et al. (2020), who provided the first German bioeconomy monitoring report in 2020, agree, concluding that gross value added of the German bioeconomy was €165–265 bn. in 2017, depending on data and calculation methods used (Bringezu et al. 2020). They identify the primary sectors as well as sectors where at least 10% of the input is biobased as belonging to the bioeconomy. The report provides socio-economic (value added, turnover, employment) indicators, which are complemented by various footprints of the German bioeconomy. Based on trends, e.g., organic farming and a reduction in meat demand, broad future developments and their impacts are described (Bringezu et al. 2020).

A stakeholder survey, where the majority (53%) of participants belonged to the science group, evaluated the report as moderately satisfying (Zeug et al. 2021). The stakeholders perceived a tendency towards economic indicators and a lack of consideration of social and environmental aspects, such as gender inequality, working conditions, renewable energy availability and biodiversity (ibid.). In addition, stakeholders criticized the limited alignment of the German monitoring with the National Sustainability Strategy, the SDGs and the European bioeconomy monitoring framework. The results reveal an overall discrepancy between the stakeholders' support for a socio-ecological vision of bioeconomy and their perception of the German and European bioeconomy strategies as "business-as-usual capitalism using additional renewable resources" (Zeug et al. 2021). However, the stakeholders confirmed the need for an annual bioeconomy assessment, where the focus should be on the analysis of synergies and trade-offs together with recommendations for political action (ibid.).

In conclusion, the relevant determining factors for the bioeconomy transformation, identified through the literature review, are in line with the indicators postulated by the EU and FAO. The evaluation of the German monitoring framework highlights the importance of coherence and integration between the different monitors, while underlining development challenges due to complexity. Overall, stakeholders demand a sustainable bioeconomy characterized by food security, production and consumption within the planetary boundaries, innovation, political guidance and societal participation (Hinderer et al. 2021; Zeug et al. 2021).

[1] https://knowledge4policy.ec.europa.eu/bioeconomy/monitoring_en.

4 Bioeconomy Transformation: A Regional Perspective

Practically, all modern bioeconomy strategies rely on innovation as the central driving force for sustainable transformation processes. Accordingly, the literature on regional innovation systems argues that innovation and networks often occur in regional clusters because some forms of knowledge may be limited to specific regions. The reasons lie in face-to-face interaction and the advantages of norms, codes, language or even historical background, which are usually only prevalent in a certain region. The region is seen as the crucial level where innovation arises through knowledge linkage, clusters, and the mutual fertilization of research institutes. Empirical studies show that the emergence, growth, maturity, decline, and possible revival of clusters are determined by the peculiarities of the knowledge infrastructure, supporting organizations, institutional structure, cultural aspects, and policy measures of a particular region.

Regional or territorial development is a long-established approach in development geography, which deals with the dynamics of local development and structural change processes and their determining factors. The role of decentralized decision-making processes in locally diverse development potentials (e.g., availability of natural resources, quality of natural resources, human capital) is of great importance. Following an understanding of bioeconomy as an economic sector and future concept, the question arises as to what role regional differences should play in shaping bioeconomic development strategies. It should be noted that modern bioeconomy concepts generally assume that knowledge-based approaches to biobased value creation will become increasingly important and will increasingly merge with traditional biobased primary sectors (e.g., agriculture and forestry).

This means that for the development of a bioeconomy strategy, strategic objectives and the corresponding funding instruments should be oriented towards regionally diverse development potentials (Stark et al. 2021). For example, the "State Bioeconomy Strategy" of Baden-Württemberg plans to occupy innovative economic sectors "whose added value largely lies in the regions themselves" (Landesregierung BW 2019, p. 40).

4.1 A Sustainable Bioeconomy in North Rhine-Westphalia

In many regions of North Rhine-Westphalia (NRW), there are now bioeconomic visions and projects. Many projects and clusters have been initiated over the last two years, which are partly implemented across district and county borders in various sectors and bring together a large number of actors from agriculture, industry, and science (Stark et al. 2021). The structural and economic characteristics of the regions are also important in this context. For example, in the Arnsberg administrative district, which is characterized by a relatively high percentage of forest area, projects in the field of forestry, wood and paper production are primarily named, while in agriculturally dominated regions such as the Detmold and Münster administrative districts, the agricultural sector is in the foreground and in the Rhein/Ruhr metropolitan region, the chemical and pharmaceutical industry is highlighted (Stark et al. 2021). Although there are already initiatives in many districts and cities to close biobased material cycles, there is still much unused potential in the use of biogenic residual materials. In particular, there are untapped material flows in waste and construction industries, as well as in the agriculture, forestry, and food industries. The exploitation of untapped potential is also reflected in the priority areas (Stark et al. 2021). The promotion of circular-based material utilization and recycling should be implemented more intensively in future. Networking of actors in the region and the development of partnerships between politics, science, and (agricultural) industry have been found to be just as crucial as knowledge transfer, education, and acceptance by civil society, which must contribute to the development of a regional, sustainable bioeconomy in NRW through sustainable consumption behaviour (Stark et al. 2021).

4.2 From Lignite-Mining to a Bioeconomy Region: The Rheinisches Revier

Major transition processes will be initiated by the recent decision of the German government to phase-out coal mining—a decision with considerable effects on the Rheinisches Revier, Europe's largest connected lignite deposit. The impending, large-scale structural change process provides a unique opportunity for developing options to implement important structural and institutional foundations within a regionalization approach towards a sustainable bioeconomy in an entire region and for understanding the underlying socio-technical dynamics.

In 2016, the German government adopted its Climate Action Plan, a strategy for the long-term reduction of GHG emissions focusing especially on the economic sectors energy, industry, buildings, transport, and agriculture (BMUB 2016). The restructuring of the energy sector was identified as a main aim, as it is the key contributor to German GHG emissions (82.8% in 2020) (UBA 2021). Lignite mining, refining, and power generation are the most GHG intensive ways of energy generation, producing 49% of GHG emissions in the energy sector in 2018 (Öko-Institut 2022). Therefore, in 2018, the German government established a Commission for Growth, Structural Change, and Employment which assessed economic development possibilities for affected regions and political instruments to manage the accompanying structural change (BMWK 2022). In its final report published in January 2019, the commission advocated a phase-out of coal-fired power generation by 2038 (Kommission Wachstum Strukturwandel und Beschäftigung 2019). Following this recommendation, the German government decided in 2020 to phase out lignite mining and electrification by 2038 (Federal German Government 2020). The federal government elected in October 2021 aims to speed up this process and complete the phase-out by 2030 (SPD, Bündnis 90/Die Grünen und FDP, 2021).

The implementation of this political decision especially affects the three remaining lignite-mining regions in Germany: Lausitzer Revier (East), Mitteldeutsches Revier (Centre) and Rheinisches Revier (RR) (West) (Öko-Institut, 2022). In these relatively rural regions, the rich supply of cheap energy gave rise to strong supply chains in the chemical and plastics industry that shape both people's identity and regional landscapes (Kommission Wachstum Strukturwandel und Beschäftigung 2019). Consequently, the lignite-mining phase-out is not only an economic challenge but also drives structural changes that extend beyond the borders of the lignite-mining regions (Kempermann et al. 2021). To guide this transformation, the Coal Phase-out Act and the Structural Development Act were adopted by the German government in 2020, detailing how the budgeted €40 billion (bn.) of funding (to be disbursed until 2038) will be distributed across the three regions (Kempermann et al. 2021). The funding shall ensure a smooth and efficient transformation towards a bioeconomy, maintaining the regions' attractiveness for the local population, by creating new jobs, and for companies, by facilitating the creation of new values, rooted in bioeconomic principles, such as resource efficiency, circular economy and technological innovations based on renewable resources (Kommission Wachstum Strukturwandel und Beschäftigung 2019).

To reduce the complexity of such transformation processes and to consider their context dependence, it is useful to evaluate them at regional level (Nielsen et al. 2020). Furthermore, a long-term perspective is required, because societal changes extend over several generations and provide improvement opportunities and trade-offs at different scales that need to be considered to ensure a just transition (Reitzenstein et al. 2021). A key determinant for a successful transformation is therefore the active contribution of all stakeholders (Banse et al. 2020; Bringezu et al. 2020; Leipold et al. 2021). At the regional level, main stakeholders to be considered for the transformation process towards bioeconomy include local and federal governments and political actors, industry and commerce, farmers and forest owners, research, media, social and environmental citizens' initiatives and non-governmental organizations, as well as citizens and consumers (Dieken et al. 2021). Consideration and balancing of all these perspectives is required to facilitate a smooth and inclusive transformation.

4.3 A Monitoring Framework for Regional Transformation

The literature review and especially the revision of the bioeconomy monitoring approaches highlight the transformation's dependence on local conditions. The assessment of the bioeconomy transformation in the RR therefore requires a regional approach (Nielsen et al. 2020). As the transformation in the RR is still in an early phase, quantitative data, for example on SDGs, environmental footprints and a clear attribution of industry sectors to the bioeconomy is not available. Research in statistical databases of the Federal State of North Rhine-Westphalia shows that disaggregation to the district levels of the RR is difficult for many topics, e.g., agricultural practices, due to strict data protection laws (Kuhn and Schäfer 2018). Therefore, a qualitative approach was chosen to obtain in-depth information on the current trends and underlying conditions that influence the transformation in the RR.

To assess the regional transformation, a monitoring framework was developed. It combines Geels' socio-technical perspective, where technology development and diffusion are crucial, with Göpel's (2016) contribution on the importance of mind-shifts. Information on key determining factors and considerations regarding the structural conditions in the RR are also included. The frame for these different contributions provide the Shared Socio-economic Pathways (SSPs) developed by O'Neill et al. (2014). Combinations of socio-economic drivers and the IPCC's representative concentration pathways show possible pathways for societal development and their impacts on climate change mitigation and adaptation (O'Neill et al. 2017). The SSPs' approach is widely used to calculate, e.g., land use change and GHG emissions (Riahi et al. 2017), carbon reduction due to sewage sludge availability (Zhang et al. 2022), developments in wind energy generation (Martinez and Iglesias 2021), changes in forest management and bioenergy supply (Daigneault and Favero 2021), or population developments (Samir and Lutz 2017), associated with the respective pathway. The selected categories and socio-economic drivers by O'Neill et al. (2014) have therefore proven suitable to assess transformations. Besides, the general nature of the indicators facilitates assessments at varying geographic scales. Overall, their application in this manuscript ensures conceptual alignment with global transformation assessments and increases transparency.

To assess the trends in the RR's transformation, a comprehensive framework was developed that captures crucial aspects related to the transformation and considers regional specificities. It serves to identify trends, challenges, and opportunities for a further bioeconomy transformation, which are the basis for forward-looking and comprehensible political decisions. O'Neill et al. (2014) group the socio-economic drivers they use into six categories. The categories can be distinguished into three social ones, including demographics (e.g., population growth, urbanization, and migration), human development (e.g., education, gender equality, social cohesion, and participation), and policies and institutions (e.g., international cooperation, policy orientation, institutions) (O'Neill et al. 2017). Additional categories encompass economy and lifestyle (e.g., growth, globalization, international trade and consumption), technology (e.g., technology development and transfer, renewable energy technologies), as well as environment and natural resources (e.g., fossil constraints, land use and agriculture) (ibid.). Under consideration of the regional context and the importance of technological innovations and mindsets, the SSP categories were renamed to allow for a holistic transformation monitoring in the RR.

A combination of the socio-economic drivers of the SSPs, the identified determining factors, and information on the transformation aims in the RR filled the framework categories with qualitative considerations. A large number of indicators allows for detailed insights while a reduced number is appropriate for providing an overview (Egenolf and Bringezu 2019). To arrive at an intermediate perspective, allowing for details that can be grouped to give an overview, the six categories are

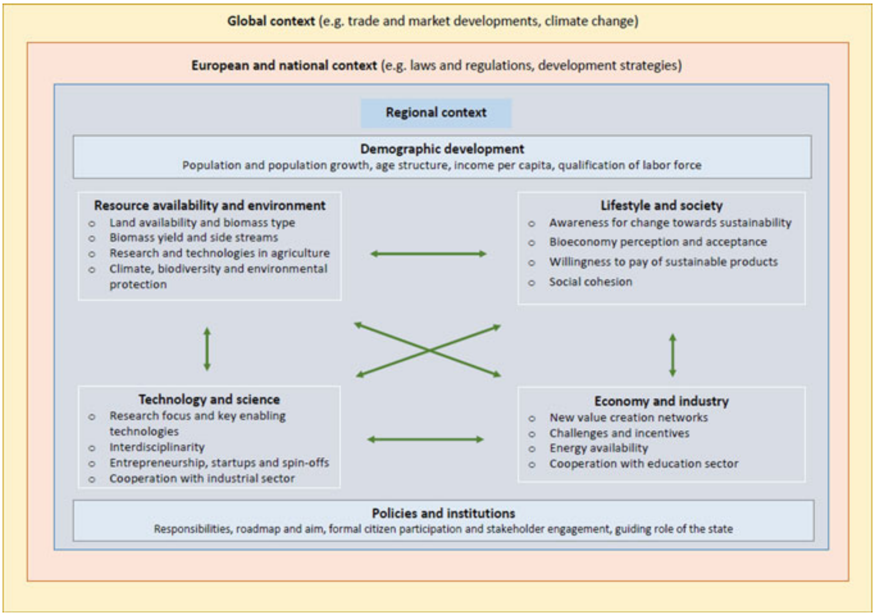

Fig. 2 Assessment framework for the regional bioeconomy transformation in the RR. *Source* Based on BioSC (2022)

represented by four qualitative characteristics each. The developed framework for the assessment of the bioeconomy transformation in the RR is depicted in Fig. 2.

The transformation in the RR is embedded in a wider context of national, European, and global developments, such as environmental policies, market developments, and the impacts of climate change (Hagemann et al. 2016). For reasons of complexity reduction, these aspects are assumed to be external. Looking at the regional context, demographic developments, and policies and institutions establish the frame for the transformation. They are relatively stable in the short and medium term and influence the other categories. Demographic development composed of population growth, age structure, income, and the qualification of the labour force determines the composition of locally available human resources that can take part in the transformation and, e.g., demand biobased goods (O'Neill et al. 2017). Political institutions at regional and national level shape the transformation by identifying the overall aim and managing its achievement (Dietz et al. 2018). Therefore, they need to involve all responsible actors from the different hierarchical levels, which have to coordinate their actions to provide guidance for societal stakeholders (Herberg et al. 2020). Overall, citizen participation and stakeholder engagement are important to raise awareness of the bioeconomy concept, identify concerns and opportunities, and finally to legitimize future political decisions (Hinderer et al. 2021). The category lifestyle and society addresses this aspect and highlights the importance of societal support for a successful transformation (Leipold et al. 2021). The awareness that a shift towards a more sustainable lifestyle is needed marks the first step to communicate the bioeconomy concept to society (Banse et al. 2020). The perception and acceptance of the concept determine societal support for the transformation towards a bioeconomy (Macht et al. 2022), while the willingness to pay for sustainable products, e.g., biobased goods, is important for the implementation of a bioeconomy (Wackerbauer et al. 2019). The transformation in the RR should not lead to a further segregation between employees of the lignite-mining sector and academics in the area of innovation, but instead increase social cohesion (Zukunftsagentur Rheinisches Revier 2021). From an economic and industrial perspective, the success of the bioeconomy transformation depends on the creation of value added in new, circular networks (Banse et al. 2020). An implementation of this change requires different knowledge and skills which need to be taught in schools and training programs, making cooperation between industry and the education sector important (Region Aachen Zweckverband 2019). As many energy intensive companies are located in the RR, ensuring energy availability after the coal phase-out is crucial for the regional economy (Zukunftsagentur Rheinisches Revier 2021). Path-dependencies impose challenges for companies to shift from fossil resources to biogenic inputs. Therefore, incentives and support from the political level are key to a change in the industrial sector (Banse et al. 2020). Innovations and technological developments open up new transformation pathways, so the regional research focus and the identification of key enabling technologies (KETs) shapes the transformation (Egenolf and Bringezu 2019). This requires interdisciplinarity in research teams (Leipold et al. 2021) and cooperation with the industrial sector (BMBF and BMEL 2020) to find practical solutions and implement them through spin-offs and start-ups (Kuckertz et al. 2020). Resource availability and environmental conditions provide boundaries for the regional bioeconomy transformation. Thus, climate, biodiversity, and environmental protection are fundamental to ensure overall sustainability (D'Amato et al. 2020). Due to the strong agricultural focus in the RR, land availability, the selection of suitable crops and adequate biomass yields for the various uses in a bioeconomy determine the transformation's speed and direction (Bringezu et al. 2021). In this context, technologies in agriculture play an important role (Region Aachen Zweckverband 2019). Even though demographics, policies, and institutions frame the developments in the RR, all categories influence each other and are mutually dependent. Only jointly can they contribute to a successful bioeconomy transformation in the RR.

5 Outlook and Discussion

As part of its Climate Action Plan, the German Government implemented the "Commission for Growth, Structural Change, and Regional Development" to prepare the phase-out of coal power in Germany with a proposal for a mix of policy instruments under special consideration of its economic, environmental, and social aspects. In its final report from January 2019, the commission formally proposes the implementation of a bioeconomy as one core element to positively steer the structural change process in the three German lignite-mining regions. As a promising concept for Germany's transformation to sustainability and as an alternative of natural resource management, the sustainable bioeconomy falls naturally into the debate on enabling and shaping system transformations, including the phase-out of coal power. It requires ambitious and far-reaching changes to use biogenic instead of fossil raw materials—biomass and biotechnology instead of coal, oil, natural gas, and petrochemicals. Like the energy transition, the bioeconomy transformation will have to meet a wide range of demands. It will have to bridge the gap between (a) environmental sustainability, (b) techno-economic feasibility, and (c) social acceptance. The negative experiences with the first generation of biofuels illustrate how difficult this balance is to strike. Overall, there is a lack of clear understanding of the possible developments—especially with regard to society's expectations of the bioeconomy.

For the Rheinisches Revier, the commission recommends the development of biomass-based and circular supply chains in cooperation with regional research institutes and universities based on the strong position of the BioSC and local businesses in order to capitalize on existing research and economic structures beyond the coal exit (Kommission Wachstum Strukturwandel und Beschäftigung 2019). The Rheinisches Revier builds on a traditionally strong regional agriculture, already emerging small- and medium-sized enterprises specializing in biomass-based products, process, and services, and the proximity of economic and science organizations located in the region.

Such comprehensive transformations towards sustainability proceed very slowly, are strongly impaired by path dependencies and lock-in effects, and can only be successful when technological progress meets social acceptance. Thus, it is crucial for bioeconomic thinking to consider all three sustainability dimensions to achieve a holistically sustainable bioeconomy. Transformation towards a bioeconomy has been discussed in contested terms, highlighting different perspectives and challenges. Perceptions and approaches of different stakeholder groups have usually been analysed individually or at the national level. Since bioeconomy activities are often clustered in subnational regions and driven by both national and regional policies, these approaches fall short of the bioeconomic objective to provide a holistic perspective based equally on the three sustainability dimensions, which requires an integrated evaluative framework for regional transformation processes. Bioeconomy research is still very fragmented and analyses different transformation aspects in isolation. Technology and resource-centred visions dominate, whereas societal considerations are limited to consumer perspectives. This imposes further challenges for the already missing holistic and harmonized policies needed for a successful transformation. Moreover, current approaches to monitoring the transformation towards a sustainable bioeconomy lack a regional perspective that incorporates all three sustainability dimensions.

To address this gap, we developed an integrated evaluative framework for assessing regional transformation processes towards a bioeconomy. Based on a structured literature review, we first identified determining factors for a holistically sustainable bioeconomy transformation. In a second step, a comprehensive framework was developed that captures crucial aspects related to the transformation and considers regional specificities. Based on a combination of the socio-economic drivers of the Shared Socio-economic Pathways, the identified determining factors, and information on the transformation aims in the Rheinisches Revier filled the framework categories with qualitative considerations. As bioeconomy in the Rheinisches Revier is still in its infancy, our monitoring framework enables a first holistic assessment, where especially qualitative aspects of the transformation can provide insights into current developments, structures, and interconnections at different levels.

In the long term, monitoring of the transformation requires specific and measurable quantitative indicators to assess developments over time (Kardung et al. 2021). However, data protection laws and top-down approaches in national and environmental economic accounting in Germany prevent the evaluation of the current state of bioeconomy development based on publicly available data on NUTS-3 level. Hence, a quantitative assessment of a prospective bioeconomy region must begin with the collection of primary data. The developed framework can serve as a blueprint for this endeavour. The category "Lifestyle and society" requires a representative sample of households to estimate the willingness to pay for sustainable products (e.g., through discrete choice experiments). Societal awareness for change towards sustainability as well as bioeconomy perception and acceptance could be inspired by the outline of the study on environmental awareness conducted by the Federal Environment Agency in Germany (BMUV and UBA 2023). Similarly, the categories "Economy and industry" and "Resource availability and environment" require dedicated surveys addressing both representatives of the biobased industry and the agricultural sector to derive supply and demand of biobased materials and to identify the potential of unused material flows and waste streams. Research and technologies in agriculture as well as relevant indicators in the category "Technology and science" could be derived from secondary sources, e.g., patent and publication data.

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Transformational Research

Ecosystem Services as a Framework for Transformation of the Rhenish Mining Area

Michael Leuchner, Finja Hinrichs, Martina Roß-Nickoll, and Peter Letmathe

Abstract This book chapter discusses the concept of ecosystem services as a potential framework for socio-ecological transformation processes in mining areas toward resilient and sustainable post-mining landscapes. As mining landscapes all around the world are undergoing enormous transformation processes, finding the best balance between economic interests, social implications, and ecological and climate services is of utmost importance. Those mining landscapes provide indispensable regulating, provisioning, and cultural services while preserving or fostering stable ecosystems with high and regional typical biodiversity. Despite their crucial contributions to human well-being, the services in these landscapes are only rarely considered in spatial and landscape planning decisions. With accelerated global changes, those ecosystem services, however, become increasingly important. Thus, the authors propose the concept of ecosystem services and inclusion of biodiversity and discuss mechanisms of qualitative and quantitative evaluation, budgeting, and pathways for decision making. For this purpose, a first basic qualitative assessment of ecosystem service potentials for the transformation of the landscape of the Rhenish Mining Area was performed exemplarily.

Keywords Ecosystem service evaluation and budgeting · Biodiversity and ecosystem functions · Socio-ecological transformation · Post-mining landscapes · Open-cast lignite mining · Sustainable landscapes

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P. Letmathe et al. (eds.), *Transformation Towards Sustainability*,
https://doi.org/10.1007/978-3-031-54700-3_9

1 Introduction: The Role of Ecosystem Services in (Post-Mining) Landscapes

In almost all areas of the world, landscapes are under constant transformation. Land-use changes from natural or semi-natural to anthropogenically utilized areas, e.g., for agricultural purposes or by expanding urban and suburban areas, are almost ubiquitous and pose enormous challenges for nature and society. In particular, ecosystems, their functions, and biodiversity in general are threatened and under pressure. Open-cast mining certainly has one of the strongest impacts on ecosystems, habitats, geomorphology, soil formation, water balance, and cultural landscapes (Gerwin et al. 2023). This leads to long-term changes in the socio-ecological and socio-economic structure of a region (Zerbe 2019). However, post-mining areas can provide versatile, valuable biotope mosaics (Kirmer and Tischew 2019), and high-potential cultural landscapes (Zerbe 2019). One of the major challenges is, thus, the transformation of the open-cast post-mining landscapes by re-cultivation and re-naturalization into sustainable landscapes well-functioning for human and nature purposes in the long term.

An important framework for transformation of landscapes can be the utilization of the concept of ecosystem services (ES) in order to identify potentials and deficits of landscapes. ES constitute an important approach to assess and valuate the *goods* and *services* of nature for human purposes.[1] The assessment quantifies ES in biophysical, monetary, social, or mixed terms to consider the importance of ES supply and demand in policy, economic, or spatial-planning decision making. It can promote the development of sustainable socio-ecological and economic landscapes and in case of this book chapter in particular post-mining landscapes in transformation. Therefore, a spatial explicit and accurate examination of numerous, complex, and interlinked ES, strongly influenced by varying ecosystem functions, biodiversity, and human demands, is necessary. ES have gained a recognized but widely discussed status in international multidisciplinary research. In addition, the concept is extended to policy, economics, and spatial planning (e.g., von Haaren et al. 2016). Although the concept is sometimes discussed controversially (e.g., Gowdy et al. 2010), it offers an enormous potential for assessment of landscapes in transformation.

This book chapter addresses the following three questions: (i) How can ES and biodiversity be qualitatively and quantitatively assessed in landscapes?, (ii) What conclusions can be drawn about the potential of ES in the Rhenish mining area?, and iii) Can the ES assessment contribute to a transformative change? The chapter starts with a basic overview of the state of the art of the concept of ES and introduces the different methods of ES assessment and valuation. This general background is exemplarily applied as a framework to assess the current situation in the Rhenish mining area, Germany, as a current example of a mining region undergoing large transformational processes. Here, a look at ES potentials provides insights into different aspects of ES spatial distribution and their characteristics in the Rhenish mining area. After

[1] For definitions, see Chapter 2.1. *The concept of ecosystem services.*

assessment of the status quo, mechanisms of evaluation, budgeting, and pathways for decision making are elaborated as potential tools for sustainable transformative processes in mining areas. Finally, future perspectives elucidating the transformational impact for the region and a vision for a sustainable post-mining landscape development are provided.

2 State of the Art of Ecosystem Service Assessment and Valuation

This section first provides a general overview about the state of the art of ES research and the concept of ES, before highlighting different methods of ES assessment and valuation such as biophysical, economic, and socio-cultural approaches including modeling and mapping of ES.

2.1 The Concept of Ecosystem Services

ES can be defined as "the direct and indirect contributions of ecosystems to human well-being" (de Groot et al. 2010: 25). This constitutes a further development of the definition used in the Millennium Ecosystem Assessment (MEA) which defines ES as "the benefits people obtain from ecosystems" (MEA 2005a: V) specifying the benefit factor in its relation to an anthropogenic purpose.

In general, the ES concept aims at two interrelated intentions (c.f., Potschin and Haines-Young 2011): (a) to increase awareness of the contributions of ecosystems to human life, and (b) to measure the interrelation of ES potential, supply, flow, and demand for science and decision making. ES can provide crucial approaches to the current landscape potentials and demands that have to be met for a sustainable transformation, in particular in the framework for transformation of mining regions.

While the concept itself is commonly accepted, most frameworks are disputed. Due to the high complexity and variance of socio-ecological systems, they are challenging to understand and model (Potschin and Haines-Young 2011). Ecosystems offer the potential for multiple ES and are affected by other ecosystems as well as human contributions. Holistic approaches are necessary, but so far not comprehensively implementable (Kumar et al. 2010). The supply potential, actual flow, valuation, and demand of ES depend on the respective perspectives as well as local and temporal conditions (MEA 2005a).

2.1.1 Trends in ES Research

Since the 1970s, the benefits of nature for humans through ecological, economic, and social-cultural values, have been studied in increasing detail. In ecological-economic theory, environmental resources have started to be considered again as natural capital in business decision making (de Groot et al. 2017). Since the 1990s, interest in ES increased both in science and practice. Major milestones were the publications of Costanza et al. (1997), Daily (1997), and the MEA (2005a), which investigated the state and change of ES on different scales, assessed future scenarios as well as proposed policies. It had placed ES on political agendas. The Economics of Ecosystems and Biodiversity (TEEB) study (2010) was conducted due to the increased political awareness of the economic significance of the global loss of biological diversity. The objectives of TEEB were to develop stakeholder-oriented methods for economic accounting and valuation of ES. Most of today's frameworks expand on the results of both (e.g., Maes et al. 2013; Haines-Young and Potschin 2018; Newcomer-Johnson et al. 2020). In Fig. 1, the MEA framework of interactions between biodiversity, ES, human well-being, and drivers is conceptualized.

In their review, Potschin and Haines-Young (2011) emphasized the importance of a spatial perspective to offer advantages to characterize the socio-ecological components of ES and to understand their dynamics. For the past decade, ES research has focused particularly on classification, modeling, mapping, and the relationship to ecosystem conditions.

ES research in the European Union (EU) has been strengthened by the adoption of ES in the Biodiversity Strategy 2020 (European Commission 2011) in response to

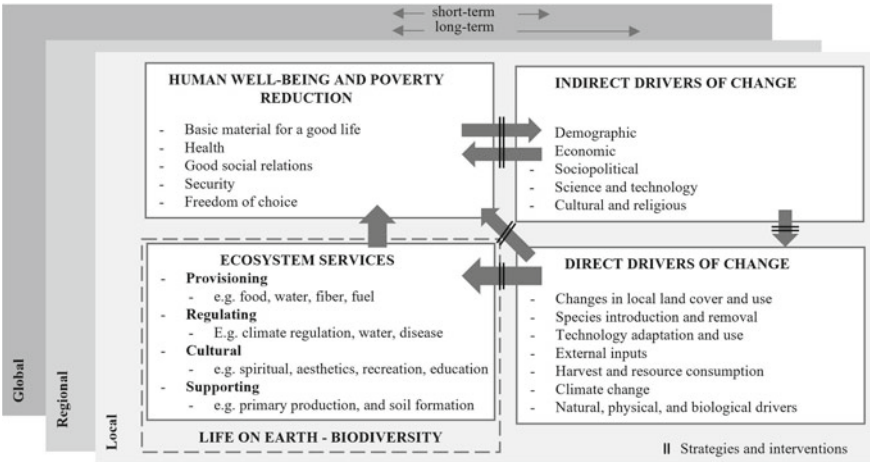

Fig. 1 Millennium Ecosystem Assessment conceptual framework of interactions between biodiversity, ecosystem services, human well-being, and drivers of change. Remark: Today, supporting services are mostly referred to as ecosystem functions, in respect to their intermediate character rather than final output (own representation of the original figure; MEA 2005a)

the Aichi Biodiversity Targets of the International Convention on Biological Diversity (CBD) in 2010. In addition, the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) was established in 2012 (c.f., de Groot et al. 2017). As part of the EU targets, the mapping, assessment, and economic accounting of ES were requested from the member states (European Commission 2011). The implementation was overseen by the working group Mapping and Assessment of Ecosystems and their Services (MAES) and scientifically enhanced by several research projects. The new EU Biodiversity Strategy 2030—as part of the European Green Deal—focuses on the restoration of ecosystems for a sustainable provision of ES (Maes et al. 2020). The concept of ES can also be linked to the idea of Sustainable Development Goals (SDG) on different scales (Yang et al. 2020).

Alongside the EU's framework, other national assessments of ES have been carried out such as the UK National Ecosystem Assessment 2011 and NESCS-Plus (Newcomer-Johnson et al. 2020) and, for example, research on the methodology for measuring and valuing ES has been conducted in China since the mid-1990s (c.f., Liang et al. 2020).

Another trend in ES research is the view of *people and nature* instead of *nature for people* (Mace 2016). Shaping ES research into a post-normal science requires a process of embedding the knowledge gained in wider societal discourses in each subsequent research step. An important difference in a *people and nature* approach is that actions should not be for nature, but by nature. Thus, the recognition of the indispensability of environment and humans and the implementation of nature-based solutions for socio-economic problems from various perspectives should be the target of actions (Potschin et al. 2016).

To achieve such a change, a more uniform concept is necessary. Comprehensive discussions were conducted about how to define, classify, and valuate ES (e.g., Mace et al. 2011; Boyd and Banzhaf 2007; Potschin and Haines-Young 2011). A standardized definition of ES is yet to be determined, e.g., regarding the question of the intrinsic value of nature. In this case, the ethical question arises whether nature should really *serve* humans, which is implied by the nomenclature. Furthermore, the discourse deals with the distinction of *functions* and *services* and into which sections ES should be divided. To what extent ES can be characterized as end products or intermediate services has depended so far on the differentiation and interpretation of individual scientists. This is crucial to whether ES are categorized in provisioning, regulating, and cultural services (e.g., Potschin and Haines-Young 2011; Maes et al. 2013) or additionally in intermediate (Fisher et al. 2009), habitat (de Groot et al. 2010), or supporting services (MEA 2005a). The most common classification catalogs are those proposed by the MEA (2005a), TEEB (2010), UK National Ecosystem Assessment (Mace et al. 2011), and the Common International Classification of Ecosystem Services (CICES) (Haines-Young and Potschin 2018). The individual catalogs offer different designations and subdivisions of the ES.

2.1.2 Comprehension of Fundamental Concept(s) and Classification of ES

One common ES concept model is the *cascade model* by Potschin and Haines-Young (2011) describing the socio-ecological system as a pathway. The pathway links the processes from environmental structure to values of human well-being (Fig. 2). ES are considered as the interface between humans and nature. The model represents an attempt to contextualize inter- and transdisciplinary aspects that must be included in an ES analysis. The understanding as a cascade rather than a step-by-step model emphasized the issue of setting universal boundaries between the labeled stages. Thus, the model is consistent with the description of ES according to Costanza (2016: 18), where ES are "therefore not the product of a linear chain from production (means) to direct benefits for people (ends) with no feedbacks or any of the other complexities of the real world." All ES are, by definition, means to the end of human well-being. In addition, the model offers the opportunity to gain an understanding of the inconsistency in the definitions and ES appreciations. For example, the relationship between the definition of ES as *benefit* used in the MEA and the terminology of *direct and indirect contributions to human well-being* in TEEB becomes apparent. Likewise, the cascade model provides a way to separate intermediate and supporting from final services, e.g., to avoid double counting. It considers that the system is too complex for an exclusive separation. However, the model has difficulties such as the treatment of the term *function.* While, here, it can be understood as the capacity of an ecosystem to provide a potential service (after de Groot et al. 2002), the term can have other ecological connotations. Examples of those are any ecosystem processes or the tasks of ecosystems for human benefit (Jax 2016).

Sustainable management of ES can only be achieved through a supply–demand balance. Therefore, a spatial explicit assessment of ES potential, supply, flow, and demand is necessary (Syrbe et al. 2017). After Syrbe et al. (2017) ES potential is based

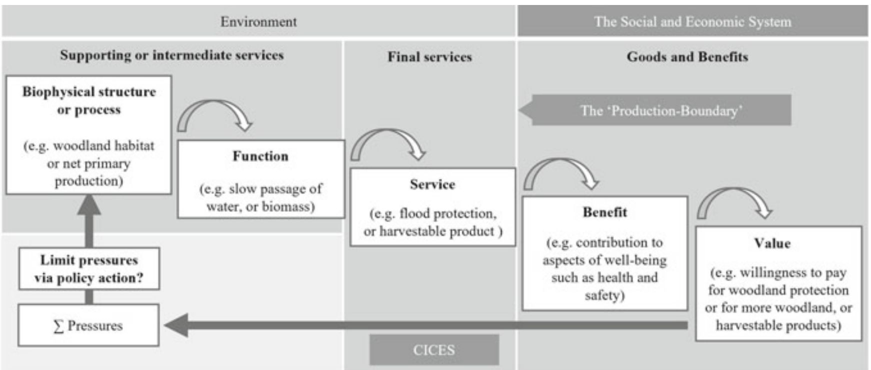

Fig. 2 Cascade model (own representation of the original figure; Potschin and Haines-Young 2011, 2016a)

on the ecosystem properties and condition describing the potential of sustainable provision of an ES; the ES supply is the amount of a service provided by an ecosystem considering the human input within a certain time period, irrespective of actual use. Delimited to the supply, the ES flow is "the amount of ES that are actually mobilized in a specific area and time" driven by the demand (Syrbe et al. 2017: 153). The demand for ES corresponds to the needs by society, stakeholder groups, or individuals. Furthermore, it depends on cultural and individual factors as well as ES availability.

The service providing unit (SPU)/service benefiting area (SBA) approach differs in spatial units that are the source of an ES (supply) and areas that realize benefits from an ES (demand). The spatial relationship between SPUs and SBAs can be in situ, omnidirectional, directional, or decoupled (Syrbe and Walz 2012).

For the assessment, monitoring, and management, an ES classification is needed that can be situation-based and spatiotemporally quantified. CICES is recommended in the EU, whereby the holistic approach as well as the flexible and hierarchical structure were emphasized as its advantages (Maes et al. 2013). It is based on the Systems of Environmental Economic Accounting (SEEA) of the United Nations Statistical Division (UNSD) and the basic terminology from the MEA. Since 2018, a revised version (version 5.1) has been available (c.f., Haines-Young and Potschin 2018). CICES builds on the cascade model. For every ES, ecosystem attributes or behaviors as well as the benefitting purposes are defined. In CICES, classified services should be seen as potential final services which can have either final or intermediate characteristics in different situations (Haines-Young and Potschin 2018).

The question of including abiotic outputs that contribute to human well-being is relevant. In line with the MEA, TEEB, and the IPBES, ES refer to living (biotic) systems. However, some scientists and decision makers include abiotic components of natural capital. Examples can be the engagements of fields to produce wind power or the extraction of fossil fuels (c.f., MEA 2005b; Burkhard et al. 2012; Müller et al. 2020). In CICES, the focus lies on biotic systems. Nevertheless, version 5.1 includes the option to integrate abiotic processes through the holistic approach classifying geophysical processes in ES and abiotic outputs. Additionally, this offers the advantage to deal with services that cannot be distinguished into biotic or abiotic processes easily. An example is the integration of water for drinking purposes which is uniformly classified as ES in standard works. In CICES version 5.1, surface and groundwater used for nutrition, materials, or energy are classified as abiotic outputs to allow a correct allocation (Haines-Young and Potschin 2018).

CICES is organized into five hierarchical levels. The top level comprises the sections based on the MEA: *provisioning services*, *regulation and maintenance services*, and *cultural services*. However, *supporting services* are not included as they underpin the output of final services and are not regarded as separate services but rather as facilitating processes for the other categories (Haines-Young and Potschin 2018). Provisioning services are all nutritional, material, and energy services (including abiotic services such as water used for nutrition, materials, or energy). Regulating services include the moderation of the environment by living organisms in a way that contributes to human well-being. The category of cultural services considers all non-material and non-consumptive services of ecosystems that affect the human mental and physical state. The structure of CICES allows cross-referencing to other classifications for international and temporal comparability (Haines-Young and Potschin 2018).

2.2 Assessment and Valuation of Ecosystem Services

The following section addresses the theoretical background of ES assessments. Most ES assessments are either habitat-based, process-based, or place-based. Habitat-based approaches investigate ES based on the stock, status, or change of biodiversity at landscape levels. Advantages are, e.g., that the method can often work with existing data and can be applied well to conservation issues. Disadvantages can be the ambiguity of relationships between different habitats and their weighting. Process-based approaches start with the structural and functional relationships affecting ES. Such methods especially benefit for a reliable assessment, if modeling alternative assumptions or scenarios is aspired. However, usually, the methods are too complex to accurately represent multifunctionalities. The place-based approach addresses ES as a bundle in a cross-cutting and time-sensitive manner, focusing on socio-ecological systems. This method can be time-/cost-intensive and requires transdisciplinary collaboration but contributes to a specific local comprehension (Potschin and Haines-Young 2016b).

Overall, ES frameworks are similar in their assessment proceeding: ES are measured with selected quantitative and/or qualitative indicators which are afterward contextualized by a valuation system (e.g., MEA 2005a, Maes et al. 2020). Assessments should include the underlying reasons for the inquiry as well as the time-sensitive parameters and delimitations of the study area (Syrbe et al. 2017).

2.2.1 Valuation of Ecosystem Services

Different valuation approaches are theoretically discussed and applied in scientific literature. It is challenging to measure ES value (changes)—especially in comparison. Besides the difficulties of accurate quantification, the question for whom and when a value is generated has to be considered. Values can be plural, context-dependent as well as not-static (Dunford et al. 2017). Valuation is always linked to conscious or unconscious human decisions about ecological systems and their changes. Some say that finding a common value is almost impossible, especially for *intangibles* such as human life or long-term ecological benefits (Costanza 2016). However, in everyday life, a valuation of ES is usually made. Gómez-Baggethun et al. (2016: 103) merged previous definitions that ES "valuation can be defined as the act of assessing, appraising, or measuring value, primarily in terms of worth, meaning, and importance, but also in relation to principles and moral duties toward biodiversity." A division into economic, ecological, and socio-cultural values is widespread in literature (c.f., Potschin and Haines-Young 2011; Costanza 2016; Gómez-Baggethun et al. 2016).

On one hand, economic valuation is the most controversial-debated approach, but on the other hand yet commonly applied (Gómez-Baggethun et al. 2016). It is based on a transfer of supply and demand changes of ES into neoclassic economy theory (Brander and Crossman 2017). An economic valuation, however, cannot stand without a reliable and suitable ecological assessment, a quantitative assessment of ecological indicators is a prerequisite for applying economic valuation methods (Kumar et al. 2010). A common form of economic valuation is the calculation of a *total economic value*. It quantifies how supply and demand behave under marginal ecosystem change (Potschin and Haines-Young 2011). The main problem here is that market data usually do not exist for ES—due to the public good character of most of these services. Therefore, economic values have to be derived directly or indirectly from other data—by analyzing real market transactions related to ES or to indirect related markets (e.g., travel costs of visitors to reach a natural park; technical abatement costs as an alternative to ES). Furthermore, expected consumer behavior in hypothetical markets can be estimated by *willingness to pay concepts* (Gómez-Baggethun et al. 2016). Due to the relatively high comparability, monetized values can be taken into account in economic decisions and contribute to an increased awareness of the social importance of nature (Brander and Crossman 2017). Additionally, it can lead to legal adjustments and "may contribute to address our inability, reluctance, or ideological intolerance to adjust institutions […] to our knowledge of ecosystems, biodiversity, and the human being" (Kumar et al. 2010: 292). Disadvantages of economic valuation are discontinuities in the pricing of ES, a lack of ethic economic guidelines (Gowdy et al. 2010), and the problem of transferring ES to conventional markets (Costanza 2016). Moreover, it lacks the consideration of complex, dynamic, and nonlinear relationships of ES as well as thresholds and tipping points (Kumar et al. 2010; Potschin and Haines-Young 2011).

Biophysical valuation is particularly relevant for process-based approaches and assessments of regulating services. It can be used to compare similar sites for one or multiple services but is less common in decision making. The special difficulty with the biophysical valuation is how to value ES beyond the accounting of ecosystem components, biotic functional traits, or ES (Gómez-Baggethun et al. 2016). Socio-cultural valuation is an umbrella term for valuation methods not based on biophysical or economic assessments. It is given greater consideration in recent literature valuing the cultural, therapeutic, artistic, inspirational, educational, spiritual, or aesthetic contributions of ecosystems. Besides, socio-cultural valuation offers the possibility to take up intrinsic and utilitarian values of nature (Kumar et al. 2010).

Despite the diversion in biophysical, economic, and socio-cultural valuation, the consideration of interlinkages, respective advantages, and disadvantages is necessary. For example, a biophysical value can represent more complex systems than an economic value, but the latter can be more effective in decision making. At the same time, a socio-economic value can reckon cultural aspects and individual desires. A separation of values is therefore not possible. Thus, the leading question of ES valuation should be "What is the relative contribution of, for example, natural capital to sustainable human well-being, in combination with other forms of capital (built, human, social) in a particular context?" (Costanza 2016: 20). The methodologies to value such complex interrelations are difficult to implement and require transdisciplinary collaboration and methodology (e.g., Daniels et al. 2018). Various uncertainties of the technique and limitations of measurement of socio-ecological systems have to be considered (Kumar et al. 2010).

2.2.2 Methods of Ecosystem Service Assessment

For an accurate valuation, a valid metric is needed. Over the years, methods for separated valuation have been developed. To apply ES methods, measurable indicators have to be selected. Indicators represent parameters that are proxies for ES. In TEEB, indicators were defined "as variables communicating something of interest or relevance to policy or decision makers with some logical connection to the object, or the process being measured" (Reyers et al. 2010: 116). Depending on the individual ES, indicators can achieve a precise measurement, e.g., crop yield as an indicator for crop provisioning. Especially for regulating services and cultural services, indicators can only describe more abstract proxies. For instance, a frequently used indicator for climate regulation is carbon sequestration and for cultural services the number of visitors in a park (Maes et al. 2014). Indicators can be distinguished in analyzing the ecosystem function or the generated benefit. It must be considered which step in the ES cascade is involved (Dunford et al. 2017). Suitable ES indicators should be selected by purpose, audience, position in the ES cascade, and availability as well as quality of data. Additionally, they should be spatiotemporally explicit, repeatable, and have a clear linkage to human benefit (Vihervaara et al. 2017). Following the ES cascade, in Fig. 3, some examples of ES with associated indicators are listed.

In ES research, models either analyze the environmental aspects that are fundamental for the supply/demand or model ES themselves. It is prevalently discussed how far an assessment of the ecosystem condition should be included beyond ES measurements (c.f., MEA 2005a, 2005b; TEEB 2010). Ecosystem condition can be defined as "the overall quality of an ecosystem unit in terms of its main characteristics underpinning its capacity to generate ecosystem services" (Potschin-Young

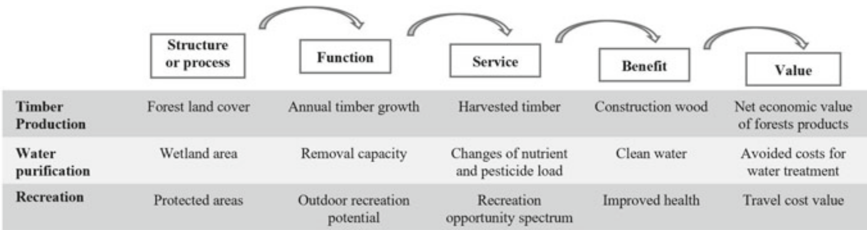

Fig. 3 Examples of ES following the cascade model and associated indicators (own figure based on Maes et al. 2016: 190)

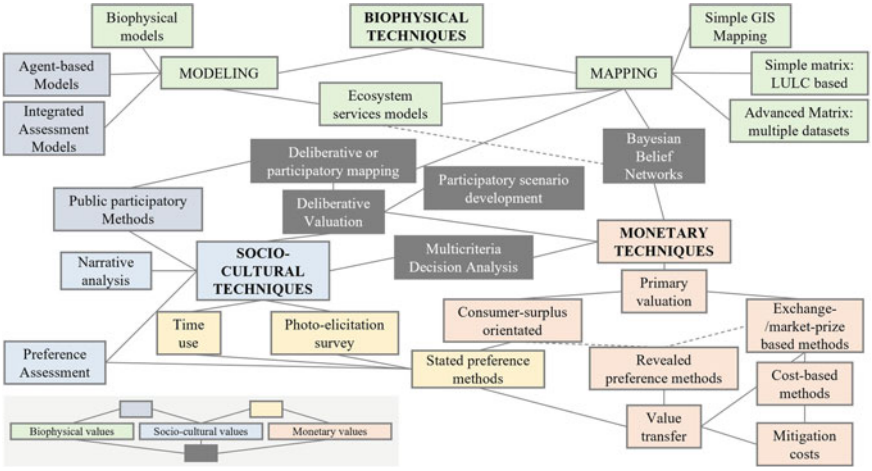

Fig. 4 Schematic spectrum of rough method groups with illustrated interrelations (own simplified representation of the original figure by Harrison et al. 2018). Colors symbolize assignments to valuation divisions

et al. 2018: 18). A condition assessment considers physical, chemical, and biological conditions as well as anthropogenic pressures (Erhard et al. 2017). Problems of condition assessments are, for instance, that there is no clear distinction to the ES potential and that there are difficulties due to lack of knowledge about the interrelationships (Erhard et al. 2017; Rendon et al. 2019). Depending on the purpose, a variety of methods can be used individually or combined to assess ES. In Fig. 4, a spectrum of existing methods is outlined, based on the EU OpenNESS project and examined by Harrison et al. (2018). The methods are aimed at either sectoral valuation or combined approaches, which are marked in the respective colors. In the following section, some biophysical and integrated models will be further described. A challenge for the future is to integrate, map, and predict biodiversity in a meaningful way using existing approaches.

2.2.3 Modeling and Mapping of Ecosystem Services

Spatial ES assessment approaches can either be represented as maps or conducted through mapping. Therefore, direct and indirect biophysical methods are commonly applied. The methods have criterion-specific opportunities and limitations. For the biophysical and integrated analysis methods, focused hereafter, characteristics are summarized in Table 1.

Biophysical ES assessments leverage existing biophysical models such as (1) ecological models (e.g., species distribution models—SDMs), (2) hydrological models (e.g., Soil and Water Assessment Tool—SWAT), (3) soil erosion models (e.g., Revised Universal Soil Loss Equation—RUSLE), and (4) state-and-transition

Table 1 Criteria for selecting different (biophysical) methods after Harrison et al. 2018. X = key item, * = possible item, ~ = rare item, + = only relevant if integrated with other ES modeling/mapping techniques

Criteria	Biophysical models	ES models	Agent-based models	Bayesian Belief Networks	Multicriteria decision analysis	Simple Matrix
Characterization of the current state	X	X	X	X	X	X
Explorations of futures	X	X	X	*	*	
Holistic understanding of socio-ecological system dynamics		*	X	X	*	
Address multiple ecosystem services		X	+	X	X	X
Enables trade-offs to be explored		X	+	X	X	X
Facilitates social learning	*	*	X	*	X	X
Informs decision-makers	*	*	*	*	X	*
Stakeholder participation	*	*	*	*	X	*
Incorporates local knowledge	~	*	X	*	X	*
Easy to comminate				~	X	X
Transparent				*	X	X
Integrated treatment of issue		X	X	X	X	*
Integration across disciplines		X	X	X	X	X
Integration of socio-ecological processes		*	X	*	X	
Integration of spatial scales (cross-scales)	*	*	*		*	
Integration of temporal scales (cross-scale)	*	*	*		*	
Spatially explicit	*	X	*	*	*	X

(continued)

Table 1 (continued)

Criteria	Biophysical models	ES models	Agent-based models	Bayesian Belief Networks	Multicriteria decision analysis	Simple Matrix
Temporally explicit	*	*	X	*	*	*
Requires time series data	*		*	*	*	
Mainly quantitative data	X	X	X	*	*	X
Mainly qualitative data		*	*	X	*	*
Data intensive	X	X	X	X	X	
Address uncertainty	*	*	*	X		
High level of expertise needed	X	X	X	X	X	
Large amount of resources needed	X	X	X	X	X	

models (STMs). In addition, agent-based modeling is viewed as a biophysical model. Agent-based models examine human or organizational interaction levels in relation to decision-making processes (Harrison et al. 2018). Biophysical valuations can be derived by the (social) valuation of final outputs, such as the pollution level of (drinking) water. The data for biophysical models is collected through direct measurements (e.g., field observations) or through indirect measurements. The latter include remote sensing and earth observation, socio-economic data, proxy indicators, and expert-based, statistical, or process-based methods of ES assessment (Vihervaara et al. 2017). Examples of remote-sensing data applied as ES indicators are land use and land cover (LULC), NDVI (Normalized Difference Vegetation Index), water layers, and primary production (e.g., Vihervaara et al. 2017). Remote-sensing and earth observation data provide advantages such as the high spatial coverage as well as regular updating with various spatial resolutions (de Araujo Barbosa et al. 2015). Thus, the heterogeneity within the LULC classes can be taken into account. Most commonly, remote sensing is used to quantify temporal changes in ES. de Araujo Barbosa et al. (2015) noted that the temporal extent of studies focused on single-digit time spans and primarily utilized land cover data. The application of remote-sensing data in ES models is still not widespread, especially in Europe (c.f., de Araujo Barbosa et al. 2015; Campagne et al. 2020).

Integrated ES assessment models combine various sectoral models and are explicitly designed to quantify the results for decision-making purposes (Dunford et al. 2017). Bayesian Belief Networks (BBNs) set likelihood relationships between input parameters (in the case of ES, factors that influence supply such as land cover or soil types) and possible outputs (such as ES supply, demand, or benefits). One advantage of the model is that multiple methods can be considered. Furthermore, the model uses deterministic uncertainty values due to its conditional approach. Multi-Criteria Decision Analysis (MCDA) is often recommended for non-monetary valuations (Kumar et al. 2010; Potschin and Haines-Young 2011; Gómez-Baggethun et al. 2016). MCDAs are flexible approaches to assess trade-offs of multiple ES in different scenarios and to filter out the best possible decision. For this purpose, the relative relationships are examined in terms of economic, social, and environmental impacts between as many parameters as possible (Dunford et al. 2017). However, a big challenge of MCDA lies in the determination of weights for the different criteria.

Mapping approaches have the advantage of providing comprehensible results that distinguish ES supply and demand areas. They are applied for three overarching purposes:

- Simple look-up tables for an overview of ES, using LULC as an approximation of ES
- Quantification of ES by spatial methods in varying complexity and combining literature, expert knowledge, statistics, and quantitative or qualitative field data
- Representation of spatial results of models (e.g., GIS processing of integrated assessment models).

LULC is fundamental for many assessment methods. Versatile information on supply, flow, and demand can be derived from the data through the approximation of ES by ecosystems and change detection (e.g., Burkhard et al. 2012). Existing LULC datasets as well as remote-sensing data can be used. In the European ES assessment, the CORINE land cover (CLC) was applied (Maes et al. 2013, 2020). The CLC is based on Copernicus and currently available for the years 1990, 2000, 2006, 2012, and 2018. The minimum mapping unit is 25 ha (EU 2021). The major critique of the method is the comparably low spatial resolution and neglected heterogeneity within classes (Eigenbrod et al. 2010). Moreover, insufficient timeliness and non-consideration of all occurring ecosystem classes were criticized (Maes et al. 2020; Perennes et al. 2020). The application of LULC data is particularly suitable for ecosystems that are strongly influenced by humans as the ecological heterogeneity is usually lower in these systems, for example, due to the selection of plant species or water management interventions (Perennes et al. 2020).

For mapping implementations, a further distinction can be accomplished in (1) common GIS analysis applications, (2) transferring of biophysical models, and (3) integrated GIS modeling tools explicit for ES assessment. The first implementation includes the matrix method, the classification of ES supply, flow, or demand per LULC (c.f., Sect. 2.2.4). The second method focuses on the analysis of individual ES with biophysical models. The third is designed for interrelations, trade-offs, and scenarios. Most popular examples of integrated GIS modeling tools are InVEST (Integrated Valuation of Ecosystem Services and Trade-offs), ARIES (ARtificial Intelligence for Ecosystem Services), MIMES (Multiscale Integrated Models of Ecosystem Services), and Solves (Social Values for Ecosystem Services) (Palomo et al. 2017).

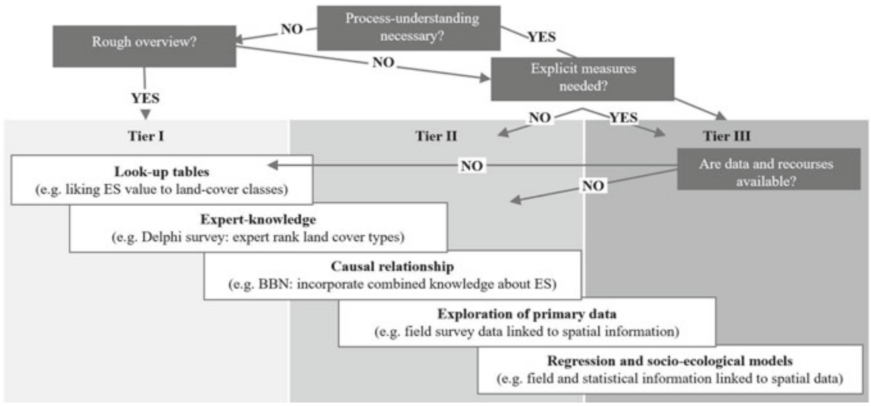

Fig. 5 Decision tree to choose appropriate ES mapping tiers (own representation of the original figure by Grêt-Regamey et al. 2017)

A tiered approach was developed in order to map ES purpose-specific and comparable to other ES assessments (Fig. 5) (Grêt-Regamey et al. 2017). Tier 1 maps encompass, for instance, look-up tables as described previously. ES supply and demand are quantified by proxy indicators based on existing datasets. Tier 2 maps build on the same principle, but link several indicators related to LULC data, for instance, socio-economic or biophysical indicators. Tier 3 maps apply biophysical, integrated, and ES-specific models to achieve a further level of accuracy (Maes et al. 2014). One can recognize that tier 1 maps offer comprehensive overviews, while tier 2 and 3 maps provide more credible results, but require a greater amount of time and data (Maes et al. 2016).

2.2.4 The Matrix Approach

Exemplarily, a matrix approach is described in the following, which will be used in Sect. 3 for the case study of ES assessment in the Rhenish mining area. In contrast to previously described methods, the matrix method targets a general approach to compare the potential, flow, and demand of ES between different biophysical entities via commonly tier 1 maps. The approach is based on Burkhard et al. (2009, 2012, 2014) and has been applied, discussed, and improved in various case studies (Campagne et al. 2020). The approach is based on the supply–demand concept that conforms with the first to fourth step of the cascade model (Burkhard et al. 2014). In the matrices, ES are plotted against geophysical units (Burkhard et al. 2012). Burkhard et al. (2014) applied CLC classes as geophysical units and a classification of ES based on the authors' own compilation (for a detailed list, see Burkhard et al. 2014). The intersections represented the potential, flow, or demand for one ecosystem service within a spatial unit, depending on the purpose of the matrix. The intersections were specified on a relative scale from zero to five (0 = no relevant capacity, 5 =

very high relevant capacity). The values could be determined by different qualitative and quantitative methods, whereby in the matrix of Burkhard et al. (2014) these were mainly based on expert knowledge.

Campagne et al. (2020) reviewed the further development of the matrix approach (2009–2019). The number of studies applying the approach has significantly increased over time with a focus on ES supply (Campagne et al. 2020). Fields of application are, for example, (1) data-scarce areas, (2) the assessment of specific ES or specific geophysical units, (3) impact analyses of spatiotemporal changes, and (4) ES assessment-orientated studies (see Campagne et al. 2020). In reviewed case studies, more than half of the matrix values were determined by literature data transfer, where previously published matrices were applied or values were created by information from scientific literature (Campagne et al. 2020). In Table 2, the potential and the limitations and uncertainties of the matrix approach are listed. The approach by Burkhard et al. (2014) has been repeatedly adjusted considering the mentioned limitations.

Müller et al. (2020: 14) designed a modified matrix for northern Germany on an annual temporal basis which "must be comprehended as a strongly generalized regional prototype, which should be modified and adapted for the respective demanded case study conditions." Compared to the approach by Burkhard et al. (2014), the considered ecosystems and landscape structures were enhanced, the possibility of a complementary assessment of ecosystem conditions was enabled, an adapted scoring system was provided, and an uncertainty assessment was included (Müller et al. 2020).

Since 2009, the method has been refined through expert consultations, case studies, and consideration of the scientific discourse (Müller et al. 2020). The matrix focused on the ES potential. A significant change to the approach by Burkhard et al. (2014) is that the scores were weighted between 0 and 100 points. Although the 0–5 scaling had the advantage of emphasizing the qualitative ranking character, the new score offered the possibility to highlight potentials in a more differentiated way—and, thus, better allow local adjustments (Müller et al. 2020).

In Sect. 3.3, a first assessment of ES potentials in the Rhenish mining area has been conducted utilizing the matrix approach and building the foundation of further necessary investigations. The matrix approach can be used as a first step to a more holistic assessment of ES in mining areas but also other landscapes, which has to include a quantification, e.g., biophysical, aesthetical, monetary, etc., of the individual matrix elements.

3 Ecosystem Services in the Rhenish Mining Area

For more than a century, lignite has been mined in the Rhenish mining area. Today, the three open-cast mining sites of Inden, Hambach, and Garzweiler form the largest German lignite mining region. Over the decades, the cultural landscape has been shaped by the spatial influences of disturbance and reclamation. But reinforced by

Table 2 Potentials, limitations, and uncertainties of the matrix approach; based on Burkhard et al. (2014), Jacobs et al. (2015), Campagne et al. (2020), Müller et al. (2020)

Potential	Limitations/uncertainties
• Simplicity and practicability through the application of LULC data and application of existing indicator data • Variable level of detail and complexity through possible application at different tier levels • Reduction of uncertainties through the integration of an uncertainty and confidence assessment, accurate communication of the methods, and approaches used to determine the matrix values • Flexible adaptation possibilities on local and temporal circumstances and adjusted specific classifications can be used • Comparability • Use of different and multiple methods to quantify the matrix values • High-level correlation by comparison of expert-based indicators of ES with quantitative indicators • Qualitative survey methodology is common in social science and official statistics • Diverse application possibilities in science and decision-making • Inclusion of diverse stakeholders in the determination of the matrix values • Simplification of the reality	• Uncertainties of possible non-objectivity and context-relation of expert-based scores • Need for adaptation to each case study • Incorrectness by value-transfer methods or unsuitable values • Approximation by e.g., LULC data with a lack of information about spatial and temporal heterogony and condition • Insufficient uncertainty recognitions and lack of transparency in the methodology applied to set matrix values • Rather low reproducibility • Selection of experts and stakeholders determine confidence • Lack of model validation • Uncertainties related to selection and knowledge of case study area, selection of analyzed LULC classes, ES, and indicators • Scale of matrix values • Implementation of mapping • Scientific interpretation • Uncertainties due to different definitions within the ES concept as well as different valuation methodologies • High amount of resources is needed to consider parameters such as elevations, slopes, geomorphological, geological, soil elements, climatological, ecochemical, or hydrological changes and neighborhood effects • Uncertainties in delineation of potential, supply, flow, and demand • Potential unintended consequences in decision-making due to misinterpretations • Simplification and generalization of the reality

the German lignite phase-out, a sustainable and prompt transition to a post-mining region is now required. While in Sect. 2 the concept of ES in general was introduced, the large-scale spatial assessment provides various, but still little widespread, opportunities as framework for the transformation of mining areas. The terms and conditions of the scope are outlined by applying the matrix method to the transformational landscape of the Rhenish mining area.

3.1 Research About Ecosystem Services in Mining Areas

In the MEA (2005b), mining is mentioned as one major business activity in conflict with other ES beneficiaries. The mining principles of the International Council on Mining and Metal (ICMM 2020) state as part of their sustainability principles to assess impacts and risks to ES and biodiversity. This is addressed by the implementation of a mitigation hierarchy with the objective to achieve no-net-loss of biodiversity (ICMM 2020). The latter applies to new projects or major expansions of existing projects. The ES recognition by the ICMM in politics, spatial planning, and public suggests that the ES concept can be a valuable concept to assess the cumulative impact of mining activities and initiate political as well as economic responses (Assumma et al. 2022).

Open-cast mining exhibits a strong impact on geomorphology, soil formation, biodiversity, water balance, ecosystems, and cultural landscapes (Gerwin et al. 2023). The socio-ecological and socio-economic structure of a region is changed in the long term (Zerbe 2019). One of the unique features of lignite mining areas is their extensive pit size. Some common impacts on ES are (1) soil erosion and loss of soil ES, (2) deforestation, (3) destruction of ecosystems, habitats, and biodiversity, (4) acid drainage, (5) emissions and noise, (6) landscape degradation, and (7) loss in social ES (Imboden and Moczek 2015; Zerbe 2019; Assumma et al. 2022). In contrast to the negative impacts, open-cast re-cultivated post-mining areas can provide versatile, valuable biotope mosaics (Kirmer and Tischew 2019), and high-potential cultural landscapes (Zerbe 2019).

Based on Boldy et al. (2021) and Assumma et al. (2022), the number of articles that deal with ES in mining contexts is small compared to the rest of ES research. While in the mining context mainly economic methods were applied (e.g., benefit transfer, willingness to pay, and total economic value), the biophysical assessment is in the center of research (Assumma et al. 2022). However, the analyzed examples differ substantially in the applied ES concepts and methodologies. ES assessments, mostly focused on coal, lignite, or metal extraction sites (Boldy et al. 2021), were applied to quantify the cumulative impact of active mining operations and to measure the possible effects of reclamation (Assumma et al. 2022). Overall, positive changes in ES were associated with the post-mining efforts (especially regulating services) and negative impacts with the active mining phases (especially provisioning services) (Boldy et al. 2021). The eight most frequently examined services were *carbon sequestration and storage*, *erosion prevention and maintenance of soil fertility*, *food*, *raw materials*, *waste-water treatment*, *fresh water*, *moderation of extreme events*, and *recreation and mental and physical health* (TEEB classification) (Boldy et al. 2021). Boldy et al. (2021) recommended to conduct further research to achieve comparability through the establishment of consistent definitions, classifications, and assessment methods. Moreover, the analysis of the full ES delivery chain and development of biodiversity is needed including potential, flow, and demand of long-term mining effects on ES.

3.2 The Rhenish Mining Area

The Rhenish mining area designates the lignite mining region located in the Lower Rhine Bay in North Rhine-Westphalia, although there is no uniform spatial delineation. In this work, the Rhenish mining area is delimited by administrative units. The counties of Rhein-Kreis Neuss, Mönchengladbach, Heinsberg, Rhein-Erft-Kreis, Düren, Euskirchen, and the district of Aachen are structural parts of the Rhenish mining area. Chosen as the study area, the core area is limited to 20 municipalities surrounding the open-cast mines of Garzweiler, Inden, and Hambach and including re-cultivated areas of former mining sites. While many affected and interrelated ecosystems are considered, adjacent landscape units such as the Eifel are almost excluded. Figure 6 maps the delimitation of the area with an extent of 1518 km^2.

The Lower Rhine Bay is part of the North German plain characterized by Pleistocene terraces, glacial, fluvioglacial and periglacial processes, and loess sediments (Goetzke 2011). The dominant soil type is Luvisol. Concise natural main units are the Jülich and Zülpich Börde as well as Ville and the Cologne Bay in the east (LÖBF 2005). Moreover, the area includes a small section of the North-West Eifel in the southwest. The Rur and the Erft are the major rivers in the Rhenish mining area. The Rur intersects the Jülich Börde between the open-cast mines Inden and Hambach. The Erft flows eastward into the Jülich Börde along the cities Kerpen, Bergheim, and Grevenbroich. High tertiary lignite resources have enabled the mining in the Lower Rhine Bay since the middle of the nineteenth century (Goetzke 2011).

The region is highly influenced by anthropogenic land use. The total population comprises around 882,000 inhabitants. The municipalities of Mönchengladbach (260,276 inhabitants), Düren (91,350), Bergheim (65,968), Grevenbroich (64,381), Kerpen (61,791), and Hürth (59,602) are the most densely populated (census: June

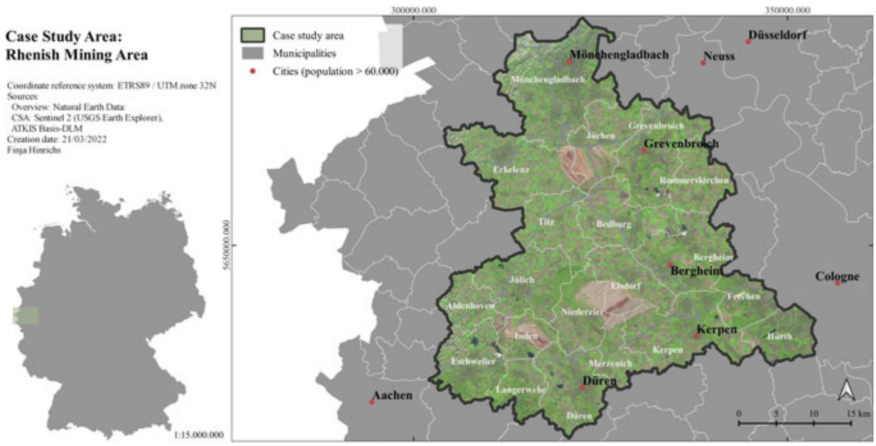

Fig. 6 Rhenish mining area with the three open-cast mining sites of Garzweiler, Hambach, and Inden

2021, IT.NRW 2021a). Highways cut the area with an average daily traffic above 60,000 motor vehicles per 24 h in some sections (census: 2015, IT.NRW 2021b).

In the Rhineland, lignite mining has started in the eighteenth century with small pits in Ville. As the industrialization progressed, mining increased. In the twentieth century, reorganization, rationalization, and merger led to a reduction of open-cast mines from 23 in the 1950s to 8 in the 1980s, hand in hand with increasing extension of the remaining mining sites. In the 1990s, further concentration was carried out on the current three mining sites of Garzweiler, Hambach, and Inden (Pflug 1998).

Today, the open-cast mines are 14.8 km^2 (Inden), 44.2 km^2 (Hambach) (both December 2021), and 20.7 km^2 (Garzweiler) (October 2021) in size (according to ATKIS Basis-DLM). In total, the mining sites take up about 5% of the area. The additional land taken up by operational areas, traffic areas, power plant areas, and dumpsites must also be regarded. In 2020, in the Rhenish mining area 306.2 million m^3 of overburden were processed and 51.4 million tons of lignite were extracted (Statistik der Kohlenwirtschaft e.V. 2021). The maximum depths of the operating open-cast mines are 470 m in Hambach, 230 m in Inden and 210 m in Garzweiler II. With the German lignite phase-out law, reductions in the mining period and downsizing of the originally approved areas have been initiated, in particular for Garzweiler II and Hambach (LANUV n.d.b). The end of the lignite extraction is currently scheduled for 2029 and 2030 for Inden and Hambach and for 2038 for Garzweiler (LANUV n.d.a).

Most effects of open-cast mining on ecosystems and biodiversity in the Rhenish mining area are disturbances by deforestation, the effects on soil structures, and the interference of the water balance (Zerbe 2019; Gerwin et al. 2023). In addition, psychological effects of displacements, protest movements, and distinct cultural landscapes indicate a strong connection to the area and related (cultural) ES (Imboden and Moczek 2015). In the context of the 1.5-degree target of the Paris Agreement, the amount of lignite mined portrays another important position (c.f. Rieve et al. 2021). To what extent the exposition of carbon dioxide has to be considered within the ES approach, e.g., as demand, is not covered extensively in literature. However, re-cultivation efforts provide a variety of ES. Examples are the Sophienhöhe at the northern edge of the Hambach mine, as well as the re-cultivated forests in the municipalities of Hürth, Ville, and Brühl. Ville and Brühl are located southeast of Hürth, outside of the study area. Here, the landscape has been re-cultivated for one century. A productive broad-leaved forest (ES: timber, diverse regulating and cultural services), an artificial lake landscape (ES: diverse regulating and cultural services) as well as habitats for endangered animal species (e.g., Bechstein's bats) (ES: genetic material, cultural services) have developed there (Zerbe 2019).

Figure 7 shows the LULC map of the Rhenish mining area. Particularly striking in the illustration of the LULC pattern is the dominance of the agricultural areas of the Jülich and Zülpich Börde as well as the three open-cast mines. Small settlements and traffic facilities dissect the area. Several highways can be recognized as well as the railroad line between Cologne and Aachen, running in the southern parts and passing through the city of Düren. Dense areas are primarily located in the periphery: in the north the city of Mönchengladbach, in the south Düren, in the southwest

Eschweiler, and in the east Hürth and Frechen. Only some central parts of the cities have a building coverage greater than 50%. Forested areas mark the northern Eifel extensions western of the city of Düren. These reveal the most coniferous forest share within the study area. The courses of the Inde (east of the open-cast mine Inden) and the Erft (east of the open-cast mines Hambach and Garzweiler I) can be identified well by the riverside as small-scale and contrasting structure of LULC elements. Along the linear structures of settlement-related objects, smaller natural landscape elements and diverse ecosystems are located.

Unlike the residential areas, industry and commerce form large-parcel elements, mostly adjacent to the settlements or open-cast mines. Smaller and abandoned mining pits are classified as industrial land use, recognizable by larger and undissected patches. These include the west-rounded industrial areas in the northwestern quarter of the area near the Erft river, which are former operating sites of the Garzweiler I and the Fortuna-Garsdorf open-cast mines (north to south). Other large-scale industrial areas can be assigned to power plants and refining plants: Frimmersdorf (east of Garzweiler I), Neurath (southeast of Frimmersdorf), Niederaussem and Fortuna-Nord (south of Neurath, north of Bergheim), Wachtberg (southwest of Frechen), Knapsacker Hügel/Berrenrath (southwest of Hürth), and Weisweiler (southwest of Inden).

The western edge of the Garzweiler II open-cast mine is classified as sparsely vegetated area. It can be interpreted as near-future extraction sites or might already be excavated partially since the last LULC update. In contrast, sparsely vegetated areas south of Garzweiler I can be described as closed open-cast sites in an early stage of re-cultivation. Similar areas can be found in the western margins of the Inden mine. In the vicinity of the Hambach mining site, the artificial elevation of the Sophienhöhe can be distinguished. LULC at the Sophienhöhe is mainly classified as mixed forest with small water areas, meadows, bushes, and recreational uses. The remnants of the Hambach Forest, as deciduous and mixed forest, are visible at the southeastern break-off edge. The landscape strip eastern of the Erft is characterized by heterogenous structures of agricultural land as well as deciduous and mixed forest. The area is influenced by former mining. Many patches are forestry or agricultural re-cultivated landscape elements. The same applies to the deciduous forest, water bodies, and agricultural areas in the municipality of Hürth. Overall, the coverage with forests and near-natural ecosystems compared to other land-use classes is very small.

3.3 Ecosystem Services Potentials Based on Land Use in the Rhenish Mining Area

The ES potential can be estimated by means of land-use classification. As example of a qualitative approach an ES potential matrix (shown in Fig. 8) is applied on the different land-use types in the Rhenish mining area. The applied matrix is based on the

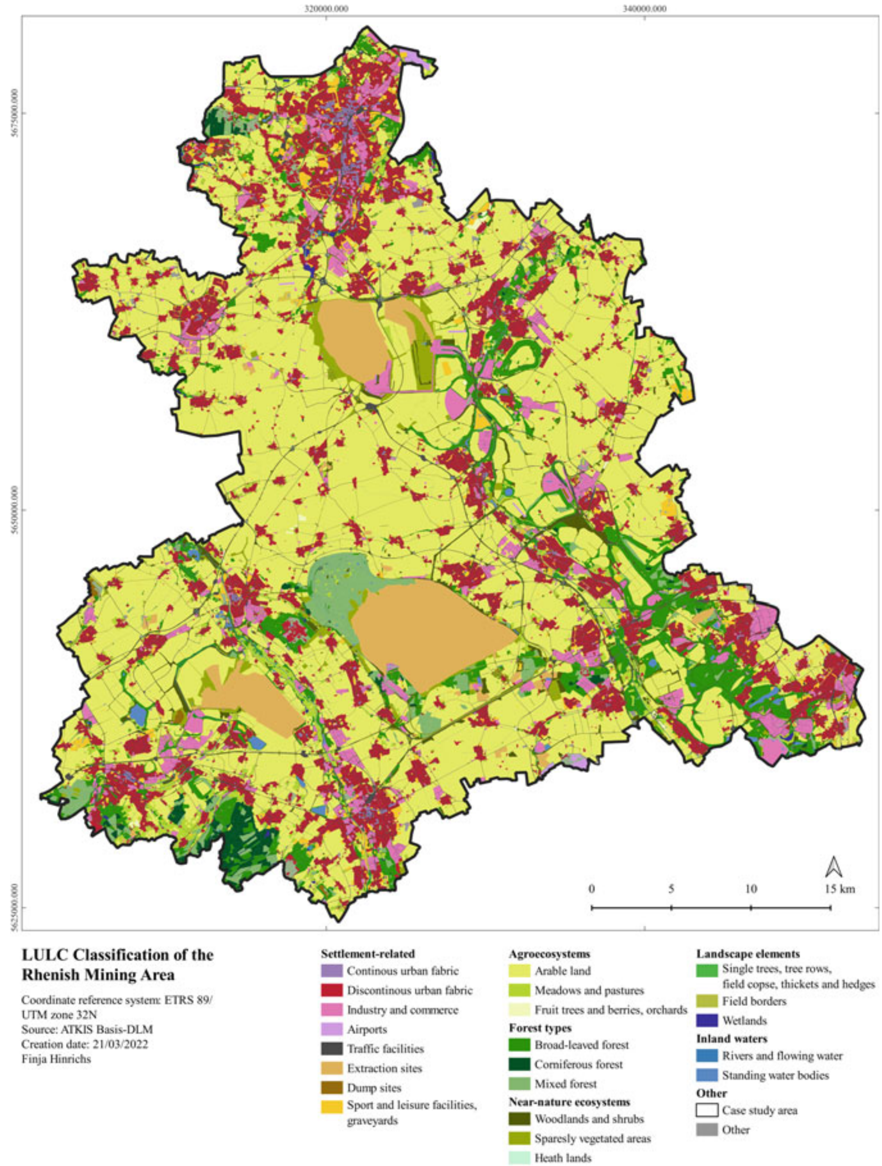

Fig. 7 Land use/land cover map of the Rhenish mining area. The classification of LULC types was performed in accordance to Perennes et al. (2020) based on the ATKIS object catalog (AdV 2011). ATKIS Basis-DLM is provided under the data license Germany—Zero—Version 2.0

design by Müller et al. (2020) (matrix version 6.1) as well as Perennes et al. (2020). Uncertainties of the transfer of expert-based valuation from Northern Germany to the region were recognized and quantified, but not discussed here due to the exemplary character of the approach.

In particular, the matrix by Müller et al. (2020) was applied, whereby missing values of landscape elements were adopted from Perennes et al. (2020). The ES potential matrix was built by listing land-use classes on the *x*-axis and representing ES on the *y*-axis. Only provisioning, regulating, and cultural services were considered in line with CICES. To highlight the qualitative character of the results, the matrix values were defined in the original zero to five range of Burkhard et al. (2014). Therefore, the values by Müller et al. (2020) were normalized as decimal values to this scale, following Perennes et al. (2020). The value '0' indicates no significant potential. The value '5' denotes the highest potential in this matrix. The ES potential matrix is plotted in spatial distribution as Fig. 9. All originally included ES in the matrix by Müller et al. (2020) except for *beach wrack, flotsam organic material* were applied here. In total, values for thirteen provisioning services, eleven regulation and maintenance services, and six cultural services were transferred. Within the provisioning services some abiotic ecosystem outputs must be differentiated, encompassing *ornamentals*, *drinking water*, *abiotic energy*, and *minerals*. These were considered, either because of the significance to the study area or due to the common classification as ES. ES, which were not included but can be of further interest, are such as *genetic material* or *mediation of annoyances* of anthropogenic origin such as smell or noise. For some others, a subdivision could be of interest, for example, *water usage for drinking or non-drinking purposes* (c.f., Haines-Young and Potschin 2018).

In many studies, the selection of the single ES is not reproducibly described. The implementation of the ES potential matrix can provide an alternative way to identify relevant ES or ES-related patterns via a qualitative assessment. Here, the implementation targeted at enabling a comprehensible starting point for future ES assessments in the Rhenish mining area.

The matrix in Fig. 8 in combination with land-use data of the investigated area can provide useful qualitative information on the current potential supply of ES. It certainly cannot quantitatively account for actual supply of the individual ES as the complexity of different site conditions was not considered. But it can give a first overview on the spatial distribution of different ES and, thus, be aligned with information on spatially explicit data on ES demand. The approach can also provide a useful method for the qualitative estimation of future ES due to land-use change by landscape transformation. Figure 9 gives examples of the spatial distribution of ES potentials of current land-use types for provisioning, regulating, and cultural services. The expert-based estimations of respective ES potentials were mapped for LULC classes by their matrix values. The assessment does not provide information on future potentials, which needs to be a next step as also ES demands are considered.

Basic patterns become apparent, identifying areas with high overall potential or for specific ES. In addition to the overall spatial distribution of ES potential, also small-scale heterogeneity of the study area can be assessed (not shown here). Spatially predominant LULC objects were identified as arable land, urban fabric,

Ecosystem Service Matrix

based on Müller et al. (2020) and Perennes et al. (2020)

	Settlement-related								Agroecosystems			Forest types			Near-nature ecosystems			Inland waters		Landscape elements						
Land use/ land cover (LULC) type	Continuous urban fabric	Discon-tinuous urban fabric	Industry and commerce	Airports	Road and railroad networks, traffic areas	Extraction sites	Dump sites	Sport and leisure facilities, graveyards	Arable land	Fruit trees and berries, orchards	Meadows and pastures	Broad- leaved forest	Coniferous forest	Mixed forest	Heath-lands	Woodlands/shrubs**	Sparsely vegetated areas	Rivers, flowing waters	Water bodies***	Single trees	Tree rows	Field copse / thickets	Hedges	Field borders	Wetlands	Other
Crops (human nutrition)	0.6	1.7	0.0	0.0	0.0	0.0	0.0	0.6	5.0	4.4	0.6	0.0	0.0	0.0	0.6	0.6	0.0	0.0	0.0	0.6	0.6	0.6	0.6	0.0	0.0	N/A
Biomass for energy	0.6	0.6	0.0	0.6	0.6	0.0	0.6	0.6	5.0	0.6	2.8	0.6	0.6	0.6	0.6	0.6	0.0	0.0	0.0	1.1	1.1	1.1	1.1	0.0	0.0	N/A
Crops (fodder)	0.0	0.6	0.0	0.0	0.0	0.0	0.0	0.0	5.0	0.6	5.0	0.0	0.0	0.0	0.6	1.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.6	0.0	N/A
Livestock	0.6	1.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.1	4.4	0.6	0.0	0.6	0.6	1.1	1.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	N/A
Timber	0.6	1.1	0.6	0.0	0.6	0.0	0.0	0.6	0.0	0.6	0.0	5.0	5.0	5.0	0.6	1.1	0.6	0.0	0.0	4.4	4.4	1.1	1.1	0.0	0.0	N/A
Fibers	0.6	0.0	0.0	0.0	0.6	0.0	0.0	0.0	5.0	0.0	0.0	3.9	3.9	3.9	0.6	0.6	0.0	0.0	0.0	2.8	2.8	2.8	1.1	0.0	0.0	N/A
Wood fuel	0.6	1.1	0.0	0.0	0.6	0.0	0.0	1.1	0.0	2.2	0.0	5.0	5.0	5.0	0.6	1.7	0.6	0.0	0.0	5.0	5.0	4.4	5.0	0.0	0.0	N/A
Wild food	0.6	0.0	0.0	0.0	0.6	0.0	0.0	0.0	0.6	2.2	1.7	5.0	5.0	5.0	3.9	5.0	3.9	3.3	3.3	2.8	2.8	2.2	4.4	0.0	0.0	N/A
Fish and Seafood	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.7	1.7	0.0	0.0	0.0	0.0	0.0	0.0	N/A
Ornamentals*	0.0	0.0	0.0	0.0	0.0	1.1	0.0	0.0	1.1	0.0	0.0	0.6	2.8	0.6	0.6	0.6	0.6	1.7	1.7	0.6	0.6	1.1	1.1	1.1	0.6	N/A
Drinking water*	0.0	0.6	0.0	0.0	0.0	0.0	0.0	0.6	0.6	0.6	0.0	1.1	1.1	1.1	0.0	0.0	0.6	1.7	2.8	0.0	0.0	0.0	0.0	0.0	2.8	N/A
Abiotic energy*	2.8	2.2	2.2	0.6	0.6	0.6	0.6	0.0	2.8	1.1	2.8	0.0	0.0	0.0	0.0	0.0	0.6	1.1	1.1	0.0	0.0	0.0	0.0	0.0	0.0	N/A
Minerals*	0.0	0.0	0.0	0.0	0.0	5.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.7	0.6	0.0	0.0	0.0	0.0	0.0	0.0	N/A
Groundwater recharge, water flow	0.0	0.6	0.6	1.1	0.6	1.1	0.6	1.7	3.3	2.8	3.9	5.0	5.0	5.0	4.4	3.9	2.8	5.0	5.0	3.9	3.9	3.9	3.9	2.2	4.4	N/A
Local climate regulation	1.4	1.1	0.0	0.6	0.6	0.0	0.0	1.1	2.2	1.7	2.2	5.0	5.0	5.0	3.9	3.3	1.1	3.9	3.9	1.1	2.8	2.2	3.9	2.2	3.9	N/A
Global climate regulation	0.0	1.1	0.6	0.6	0.6	0.0	1.1	1.1	2.2	1.7	4.4	5.0	5.0	5.0	5.0	3.3	1.7	1.7	2.2	3.3	4.4	3.3	3.9	1.7	5.0	N/A
Flood protection	0.0	0.0	0.0	0.0	0.6	0.0	0.0	0.6	1.1	0.6	2.2	1.7	1.7	1.7	1.7	1.7	0.6	3.3	3.3	0.6	1.7	2.2	2.8	2.2	1.7	N/A
Air quality regulation	0.0	0.6	0.0	0.0	0.6	0.0	0.0	0.6	1.1	1.7	1.1	5.0	5.0	5.0	1.7	3.3	0.6	0.6	0.6	1.7	2.8	2.8	2.8	2.2	1.7	N/A
Erosion regulation, wind	0.0	0.6	0.0	0.6	0.6	0.0	0.0	1.1	1.1	2.2	5.0	5.0	5.0	5.0	1.7	2.2	0.6	0.0	0.0	1.7	4.4	4.4	4.7	1.7	1.7	N/A
Erosion regulation, water	0.0	1.1	0.6	1.1	0.6	0.0	0.0	1.1	1.1	2.2	5.0	5.0	5.0	5.0	1.7	3.3	0.6	1.1	1.1	3.3	3.9	3.9	3.9	4.4	1.7	N/A
Nutrient regulation	0.0	1.7	0.0	0.6	0.6	0.0	0.0	1.1	1.7	2.8	3.3	5.0	4.4	5.0	3.9	3.9	0.6	1.7	2.2	3.9	4.4	4.4	4.4	2.8	3.9	N/A
Water purification	0.0	1.7	0.0	0.6	0.0	0.0	0.0	1.7	0.6	2.2	2.8	5.0	5.0	5.0	3.9	3.9	0.6	2.8	2.8	3.3	4.4	3.9	4.4	2.2	3.9	N/A
Pest and disease control	0.0	1.1	0.0	0.0	0.0	0.0	0.0	1.7	1.1	2.8	3.9	5.0	4.4	5.0	3.9	4.4	2.8	1.7	1.7	3.3	4.4	4.4	5.0	3.3	4.4	N/A
Pollination	0.0	2.2	0.0	1.1	0.6	0.0	0.0	1.1	3.9	5.0	3.9	4.4	3.9	4.4	4.4	3.9	2.8	1.7	1.7	3.3	3.3	4.4	5.0	3.3	2.8	N/A
Recreation and tourism	0.6	1.7	0.0	0.6	1.7	1.1	0.0	4.4	2.2	2.8	2.8	5.0	5.0	5.0	3.3	3.3	2.2	4.4	5.0	3.9	4.4	3.3	3.9	2.2	4.4	N/A
Landscape aesthetics + inspiration	0.6	1.7	0.0	0.6	1.1	0.6	0.0	1.1	2.8	2.8	2.8	4.4	3.9	4.4	4.4	2.8	2.2	5.0	5.0	5.0	5.0	4.4	5.0	3.3	4.4	N/A
Knowledge systems	1.1	2.2	0.6	0.6	0.6	1.7	0.6	0.6	2.2	3.3	2.2	4.4	4.4	4.4	2.8	2.8	1.7	4.4	3.9	2.8	2.8	2.8	2.8	1.1	2.8	N/A
Cultural heritage	2.2	2.2	0.6	0.6	1.7	1.1	0.0	1.1	3.9	2.8	2.8	3.9	3.9	3.9	2.8	3.9	1.7	4.4	4.4	4.4	4.4	3.3	5.0	3.3	3.9	N/A
Regional identity	2.2	2.8	0.6	0.6	1.7	1.1	0.0	1.1	3.9	3.3	3.9	4.4	4.4	4.4	3.9	2.8	1.7	4.4	4.4	4.4	4.4	3.9	5.0	3.9	4.4	N/A
Natural heritage	0.6	1.1	0.0	0.6	0.6	0.6	0.0	1.1	1.7	2.2	2.8	4.4	3.9	4.4	5.0	3.9	3.9	4.4	4.4	5.0	5.0	4.4	3.9	2.2	4.4	N/A

Fig. 8 Ecosystem service potential matrix for the Rhenish mining area (own figure based on values from Müller et al. (2020), Perennes et al. (2020)). Darker green indicates higher potential. *abiotic ecosystem outputs, **modified LULC class, ***aggregation of natural and artificial waters

and active open-cast mines. Moreover, the heterogeneous linear structures along water bodies and re-cultivated mining areas were recognized as regions of structural interest. Open-casts, industrial and heavily sealed areas, dumps, and traffic facilities display the lowest ES potential in the area. Key areas of high potential are dedicated to forested patches. Provisioning, regulating, and cultural services are differently pronounced, but a detailed description is not provided here.

Overall, the distribution of ES potentials indicates deficits for a sustainable landscape. This is due to the historical development as a highly productive agricultural area as well as open-cast mining operations with grave impact on the natural environment. For the overall ES potential, the LULC dominance of agricultural areas is decisive. The open-cast mines cause large areas without or with very low ES potential and thus strongly reduce the overall potential. Re-cultivated areas are of special interest as many productive agriculture and forestry sites are included. As providers of

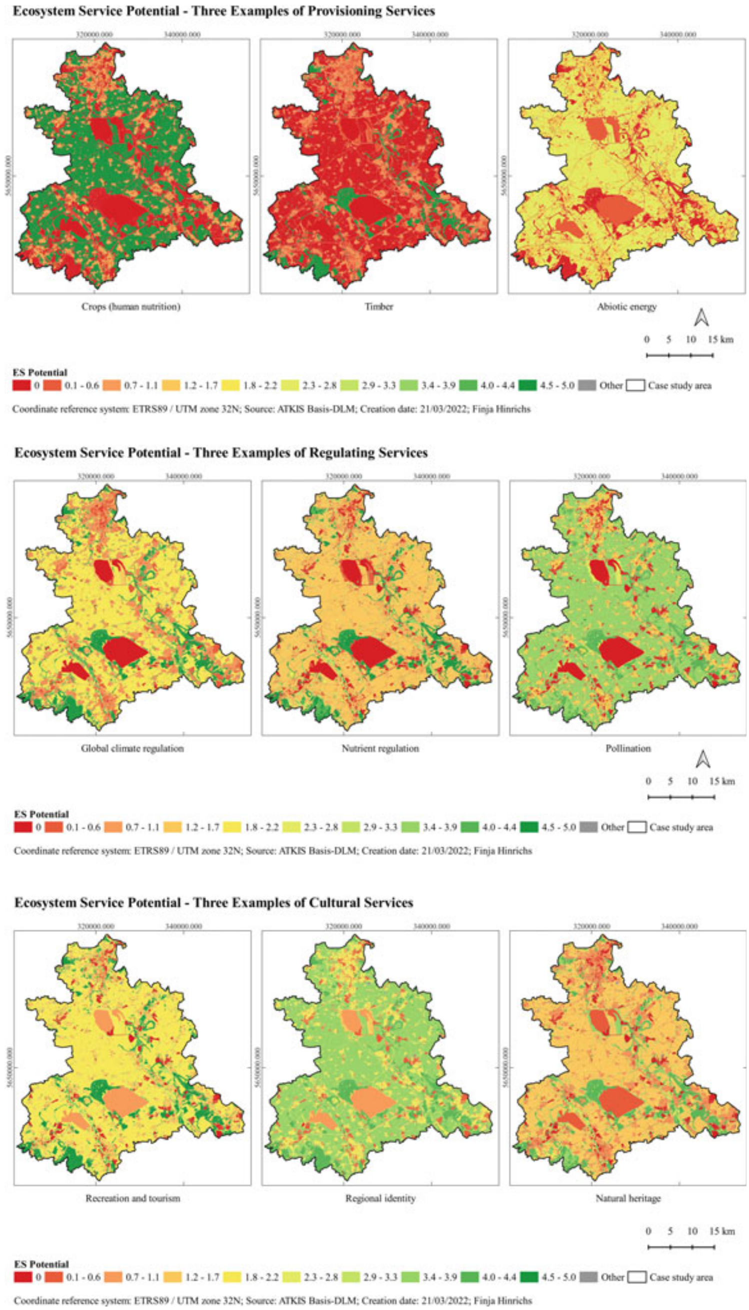

Fig. 9 Examples of provisioning service potential (top row), regulating service potential (center row), and cultural service potential (bottom row) in the Rhenish mining area

high potentials, re-cultivated forests and near-nature elements stand out from overall potential. However, the destruction rate of lignite mining on previous natural areas and forests needs to be considered as well. The remaining areas of the Hambach Forest indicate that today's open-cast mining areas have rendered areas that previously had high potentials to be now nearly irrelevant. The evidence is in line with the current scientific knowledge on ES in mining areas. However, the question about the condition of mapped ecosystems and the subsequent influence on ES arises. Condition analysis is of major interest in current ES research, acknowledging significance of condition for ES potential and supply (c.f., Maes et al. 2020). By disregarding condition indicators, the validity of results for the actual supply is limited. Open questions are, for example, to what extent re-cultivated forest areas have the same potentials as previous ones, or which maturity phase can be considered equivalent to remaining forests in the context of a matrix assessment. Furthermore, condition assessments are essential for determining the potential of agricultural lands. In order to achieve more accurate conclusions, indicators such as cultivation, soils, hydrologic factors, and quality of biodiversity need to be regarded in greater detail. In addition, impact gradients of disturbances need to be considered such as possible contamination, noise, or smell occurring in the vicinity of industrial and mining elements. Possible impacts on surrounding LULC patches limit the ES potential estimation.

Up to date, no statements about the value of ES in the Rhenish mining area can be made due to the lack of knowledge on spatial supplies and demands. Without quantification or alignment with established values, e.g., yield rates or pollution, valuation is only possible in a comparative way. By determining ES demand, initial qualitative statements could be drawn about the potential-demand balance, enabling conclusions about unmet needs or surpluses. In relation to ES demand, provided potentials can be estimated as adequate or inadequate. For instance, agriculture requires higher potentials for regulating services such as *pest and disease control* and *nutrient regulation* (Burkhard et al. 2014). Only statements can be made about which regions of the study area or which patches might be more relevant for ES supply than others. Moreover, the reducing effects of the open-cast mining areas and industrial sites can be spatially highlighted, as well as positive effects by re-cultivation, considering still changed ES supply compared to previous states. ES especially affected by these spatiotemporal processes might be more relevant to assess than others. Furthermore, the scarcity of ES in the study area is obvious. Examples are minimal examined potentials for, e.g., *livestock* and *flood protection*. However, if these are significant, cannot be answered since even low potential might be sufficient if demand is similarly low.

3.4 Recommendations for Future Studies

The outlined example illustrates the purpose and opportunities of qualitative ES assessments by simple look-up maps. For a better estimation and validation of the impact of ES in the Rhenish mining area and for the general implementation on mining regions, a quantification, e.g., biophysical, aesthetical, monetary, etc., of the individual matrix elements is necessary. Overall, a quantification of the potential and an assessment of the supply need to be carried out in order to obtain a valid picture of the specific mining area. For this purpose, a combination of standalone and integrated methods, summarized in Sect. 2, can be used to develop comprehensible qualifications and conclusive evaluation methods. In addition, in this work only the potentials were considered as an example. For a full picture, an assessment of potential, supply, flow, and/or demand is needed, depending on the specific purpose and circumstances of the case study. To prevent misinterpretation in qualification models, reduced uncertainties in matrix values, improved comparability, and continued efforts in standardization of ES definitions and classification are needed. Quantification of matrix values can be implemented, in particular, by using biophysical models. In addition, an equivalent determination of the values of cultural services is necessary. While these are neglected in many assessments of ES, they represent important services for physical and mental health in cultural landscapes. Moreover, a spatial and temporal explicit processing of the matrix can be achieved through ongoing quantifications and revisions specific to the study area, leading to a more accurate overview and general improvement of the matrix implementation.

One key area of content can be the influence of open-cast mining areas on regulating and cultural services. Of particular interest are spatiotemporal developments by different stages of the lignite mining industry cycle and contrasting disturbance-reclamation rates. ES valuation of the supply–demand balance can contribute to an appropriate selection of different re-cultivation measures and spatial planning. Decisive to the evaluation is a development of applicable and meaningful condition assessments. ES-based scenarios offer the possibility to model the aspired biophysical impacts. Thus, sustainable planning steps for a livable environment can be introduced adapted to the regional socio-ecological circumstances. In addition, ES impacts by open-cast mining to agriculture represent opportunities to investigate the linkages between condition, provisioning services, regulating services, and biodiversity in more detail.

4 Mechanisms of Pricing, Budgeting, and Pathways for Decision Making

Both in science and in the public, the concept of ES is broadly accepted. It can hardly be denied that the concept of ES can contribute positively to the conservation of natural ecosystems. This is especially true if the conservation of biodiversity is given a high priority. Approaches to further develop biodiversity conservation and optimization of ES together are complex and need to be carefully evaluated (see also Mace et al. 2012; Reyers et al. 2012). In addition, it can be assumed that the concept of ES does have strong support from the broad public. However, when real-world decisions are to be made, it always becomes problematic when individual interests are affected by the protection and expansion of ES, especially when the decision-making process is fragmented, i.e., it is composed of a sequence of many individual decisions. Often, the individual interests prevail, which means that the desired levels of ES are not achieved. Ultimately, this problem is due to the fact that ES have the character of public goods, where it is almost impossible to price them at their true economic value. This problem is exacerbated when decisions are made on the basis of basic economic data, since ecological aspects are generally not considered at all here, i.e., they are assigned a value of zero.

One of the main reasons for the often inadequate inclusion of ES is the lack of information on their benefits on the one hand and the inadequate structuring of relevant decision-making processes for this purpose on the other. This chapter will shed some light on these shortcomings. The next section addresses the economic pricing of ES, helping to improve the information base. In this context, it is of particular importance that ecological and economic information are combined. This is neither in line with established practice nor do market prices exist for the services to be evaluated, which makes economic pricing of ES challenging. Subsequently, the structuring of the decision-making process is examined. Section 4.2 examines budgeting, a well-established tool used by companies to manage the target-oriented provision of resources. Section 4.3 looks at the structuring of the decision-making process and the necessary involvement of the relevant stakeholders.

4.1 Economic Approach to Consider ES: Pricing Externalities

Economic information plays an essential role in many decision-making situations. This applies both to the resources provided in the context of budgeting processes and to the calculation of the benefits of a decision based on attributable revenues. At the same time, it has been known for many decades that there are relevant costs that decisions do not take into account. These are so-called external costs or externalities, which are borne neither by the producer nor the consumer of a good. Not taking such external costs into account regularly leads to market failures, since third parties are harmed by such decisions and are usually not compensated. Climate change is a good example of such external costs. For decades, electricity was generated almost exclusively with the help of fossil fuels, which was associated with high carbon dioxide emissions. The accumulation of carbon dioxide and other greenhouse gases in the atmosphere then caused climate change, which has very serious negative consequences for the livelihood of many people and for the functioning of many ecosystems. As a result, there are high losses of income, e.g., in agriculture and forestry. The frequency of extreme weather events is increasing and these cause damages to the inhabited and uninhabited environment and people living there. Whole ecosystems are changing with severe consequences for the provision of various ES and biodiversity. An example is the melting of ice sheets, which leads to a rise in sea level and endangers coastal areas worldwide.

For these reasons, policymakers around the world have agreed to substantially reduce greenhouse gas emissions. In the EU, an emissions trading system was introduced as early as 2005 that prices greenhouse gas emissions in order to internalize the external costs incurred. After initially very low prices for permits for carbon dioxide emissions, 1t of CO_2 now costs around €80. Even this price is still considered by many experts to be significantly too low. The German Federal Environment Agency, e.g., considers a price of just under 200 €/t to be appropriate to cover the damage costs of CO_2 (Matthey and Bünger 2019). Prices of more than 400 €/t are even being discussed (Luderer et al., 2018). When such prices are incorporated into energy system models and related decision-making processes, it quickly becomes apparent that renewable energy not only leads to significantly lower external costs, but also represents the best option in macroeconomic terms. The internalization of external costs can therefore be seen as an important innovation driver for the transformation of numerous value chains and markets. In this vein, the internalization of external costs can be seen as a driver for economic and behavioral changes for economic and political decision-making.

The transfer of the external cost approach to ES leads to a further increase in complexity. While resource consumption and emissions are based on measurable flows of materials that only have to be priced, the evaluation of ES requires the consideration of complex cause-effect relationships, specifically when biodiversity is taken into account. One of the first approaches originates from Hein et al. (2006) (Fig. 10). Following the methods of lifecycle assessment, they first propose the definition of system boundaries in order to quantify the ES provided. This is in effect a biophysical quantification that provides the basis for subsequent economic valuation. In the next step, the quantities of ES are priced either in monetary terms or within the framework of scoring models, i.e., through other indicators. In this way, it becomes possible to aggregate the total value of an ES including the preservation or expansion of biodiversity and subsequently, by aggregating the values of all ES, also to determine the overall value of an ecosystem.

Even if this approach is plausibly constructed, it is both incomplete and complexity-reducing. For example, it does not provide suggestions on how to meaningfully incorporate the complex cause-effect relationships in ecosystems, nor does it include higher-level aspects such as increasing or decreasing biodiversity. Furthermore, purposeful approaches must clearly highlight the problem of frequently insufficient data as well as the inclusion of uncertainties with regard to the underlying cause-effect relationships (Sagoff 2011). At this point, for reasons of space, it can only be stated that such evaluation approaches still face considerable challenges and will certainly be further developed in the future (see also Gowdy et al. 2010).

Even if the challenge of pricing external effects is still unsolved, it makes sense to use monetary values (or sometime scores) for different ES, as otherwise there is a risk that these will either not be considered at all or only as a secondary consideration in decisions. Ultimately, it is not a matter of exact values—which are not given even in the case of (often volatile) market prices—but rather of the inclusion in the

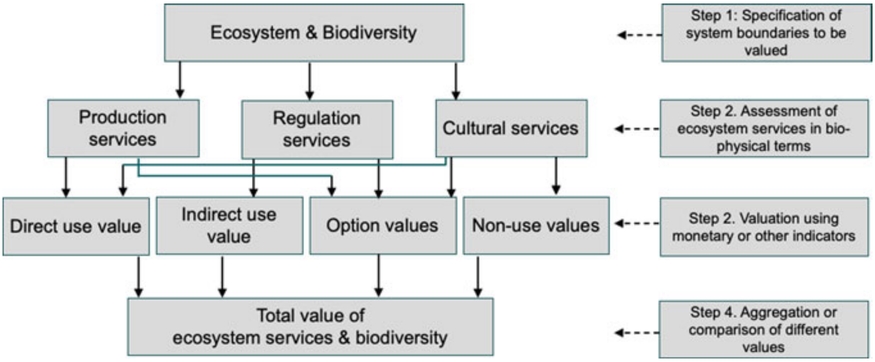

Fig. 10 Ecosystem and biodiversity valuation framework (own figure after Hein et al. 2006)

discussion about the best possible decisions. Such pricing approaches (based on the monetary valuation of ES) also make it possible to make controversial views on the valuation problem visible. However, being aware of the underlying methodological problems, it is reasonable to combine other approaches with the economic pricing of ES. In this context, budgeting approaches are increasingly discussed in order to avoid fragmented decision-making processes to the detriment of the maintenance and provision of ES. Involving various stakeholders is also a promising avenue of placing importance on ES in transformation processes such as in in the Rhenish mining area. Both aspects are discussed in more detail in the following two sections.

4.2 Budgeting

Budgeting is a term established in management and controlling that deals with the allocation of (often financial) resources to an organizational unit, a project or to achieve a goal (Lalli 2012). The budget managers can dispose of the budget within certain limits in order to achieve the goals in their area. Budgeting is often based on a top-down approach in which the total available resources are distributed among different areas. In this way, a balanced allocation of capacities and resources is ensured in the sense of implementing the corporate strategy. This is in contrast to bottom-up approaches, where resources are allocated according to the arising opportunities as well as the persuasive power of individual organizational members. Such pure bottom-up approaches often lead to fragmented decision-making processes in which (strategic) goals can often no longer be pursued as a whole.

With reference to the transformation process in the Rhenish mining area, such fragmentation tendencies cannot be ruled out. Here, too, many actors are (rightfully) involved and decision-making processes are often distributed over the timeline in a small-scale manner. This leads to the fact that, on one hand, decisions are repeatedly made in favor of short-term economic advantages and that, on the other hand, complex and higher-level aspects such as the long-term provision of ES are neglected. Therefore, we advocate for a budgeting approach that establishes land-use plans that balance long-term and short-term interests, based on sustainability goals and the levels of ES to strive for.

A first step would be to define a long-term strategy for the transformation process in the Rhenish mining area and then to define the associated objectives. Corresponding land-use plans could then be derived from this, specifying, for example, what proportion of land should be left in a near-natural state and how agricultural land can be farmed, considering the provision of ES, and how the recreational function of the landscape can be guaranteed. In this sense, the available area would be budgeted, i.e., divided according to land-use types and the ES to be provided or demanded as a result. Such an approach would provide an overarching level for all landscape planning decisions. This would also reduce the danger of fragmented decision-making processes, in which nature-oriented uses are increasingly marginalized in the end.

Such a budgeting approach would, thus, directly address the strategic level and the goals derived directly from it. However, this is by no means intended to avoid the participation of numerous stakeholder groups, but on the contrary: They should be involved at the strategic level from the very start, in order to achieve an early consensus on different types of land use. This will also allow the provision of ES to be given a higher priority, especially when the value of such services is considered in the related decision-making processes. A participation-oriented budgeting approach can thus better ensure the preservation and expansion of ES in the context of transformation processes. Facets of the decision-making process required for this are described in the following section.

4.3 Structural Elements of the Decision-Making Process

A top-down approach does not mean that different stakeholder groups are not involved. On the contrary, they can play an essential role and contribute their expertise in the problem description, the definition of the system boundaries and the land-use strategy. They can also contribute to the success of the respective measures at the local level during (decentralized) implementation.

Figure 11 illustrates a possible structure of the decision-making process. The object of investigation is already defined together with all relevant stakeholders. These can be representatives of environmental organizations, the economy, politics, science, the media, affected citizens, and also future generations (Bogacki and Letmathe 2021). On the basis of the defined system boundaries, the most comprehensive data possible, including relevant cause-effect relationships, should then be collected. Here, all actors play an important role who can either provide data or assess their validity. The created data basis not only reports the actual state, but also creates a basis for the valuation of ES. In summary, this step allows to design a factual basis for the development of a land-use strategy that is as correct as possible and as needed for the specific purpose. Missing data and evaluation uncertainties should

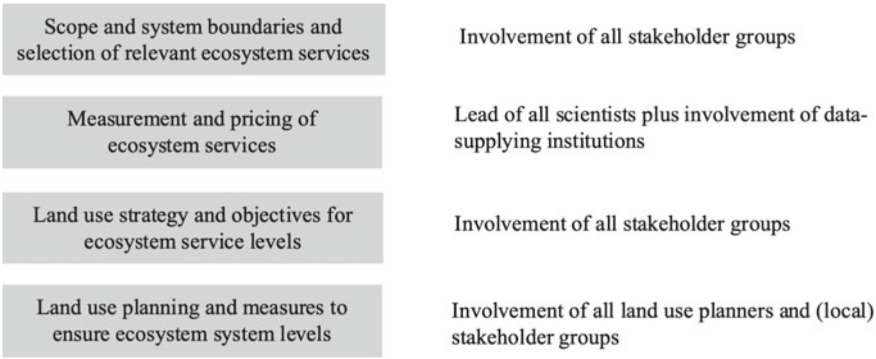

Fig. 11 Decision-making process and involvement of stakeholder groups

be clearly stated, so that deficits in content can be included in the discussion. The documentation and evaluation of ES provide a realistic picture of the current state of knowledge and, thus, form an important basis for the design of a land-use strategy, which also sets objectives for ES to be provided in qualitative and quantitative terms. Since normative questions are the primary focus here, all relevant stakeholder groups should again be included in the definition of strategy and objectives. Overall, these first three steps make it possible to combine normative interests and scientific facts in a meaningful way in order to achieve a good and objectively comprehensible balance of interests between the individual stakeholder groups. Subsequently, the land-use strategy serves as a guideline for deriving specific land-use decisions, which must then be guided by the corresponding budgeting and target objectives. The detailed planning should particularly involve local stakeholder groups in addition to the land-use planners involved. The higher level must then ensure complementarity with the land-use strategy.

The decision-making process described can address the problem of many fragmented decisions with suboptimal results. At the same time, it ensures that all relevant stakeholders are appropriately involved. It also enables a separation of scientific and normative aspects and can therefore facilitate discussions that allow to consider ES and their long-term value.

5 Conclusions

The concept of ES as a potential framework for socio-ecological transformation processes of mining areas toward sustainable post-mining landscapes was introduced using the example of the Rhenish lignite mining area in Germany. The role of regional biodiversity as a basic resource, which is essential for many ES, is undisputed. Despite their crucial contribution to human well-being, these services are only rarely considered in spatial and landscape planning decisions.

For a better estimation and validation of the impact of ES in mining areas, a quantification of ES, such as biophysical, aesthetical, monetary, etc., is necessary. Overall, the exemplary case study demonstrated how the assessment of ES potential can provide a valid picture of a landscape's ES. For this purpose, the matrix method was applied to the Rhenish mining area and qualitative and quantitative methods that can be used (standalone or combined) to develop comprehensible and conclusive evaluation procedures introduced. In addition, the contribution of ES valuation to an appropriate selection of different re-cultivation and re-naturalization measures for spatial and landscape planning was explained. Hence, biophysical modeling using ES-based scenarios is critical to provide better decision support based on applicable and meaningful condition assessments. Moreover, sustainable planning procedures for a livable and sustainable environment can be introduced in regards to the regional socio-ecological situation.

In the Rhenish mining area, many ES potentials show deficits for a sustainable landscape due to the historical development as a highly productive agricultural as well as open-cast mining area with grave destructive impacts on the natural environment. Although, the Rhenish mining area currently shows high potentials for both food and energy provisioning services, even beyond lignite the contribution of these services is too small to promote a sustainable regional development in the long term. Although re-cultivated areas are of special interest as many productive agriculture and forestry sites can be included, nature-based solutions and a certain number of undisturbed pristine ecosystems are crucial for improved biodiversity and ES that cannot be directly exploited economically (i.e., as a provisioning service).

With regard to the contribution of this chapter, further research is needed, as the performed assessment only transferred matrix values from another German region, which can merely be a first step. The development of a matrix for the Rhenish mining area, which takes into account the ecosystem conditions and local circumstances in a quantified way, can lead to a valid representation of the spatial potentials. A non-monetary ES valuation can be enabled by comparison of the potential and demand of the ES assessed. Nevertheless, as part of the transformational process of the Rhenish mining area—as well as other comparable regions—the ES concept can be a suitable approach for a sustainable landscape transformation.

To achieve this objective, we propose a long-term strategic process that bases transformation decision on a multi-layered and holistic approach of including ecological, economic, and social aspects in decision making. To this end, important framework conditions should be defined at the outset and translated into utilization budgets, e.g., in the form of budgeted space that is not used for economic purposes. Corresponding land-use plans can thus be derived by defining areas with different land uses such as protected or near-natural state areas, agricultural land, and forests while considering ES provision. Such an approach would provide an overarching level for landscape planning decisions. This would also reduce the danger of fragmented decision-making processes, in which nature-oriented uses are increasingly marginalized in the end. Stakeholder groups should be involved at the strategic level from the very start to allow a higher priority of the ES provision, especially when the value of such services is considered in the related decision-making processes. A participation-oriented approach can thus better ensure the preservation and expansion of ES in the context of transformation processes.

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Transdisciplinary Development of Neuromorphic Computing Hardware for Artificial Intelligence Applications: Technological, Economic, Societal, and Environmental Dimensions of Transformation in the NeuroSys Cluster4Future

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Abstract Artificial Intelligence (AI) promises economic growth and solutions to global problems but also raises societal concerns. Training AI models has a big carbon footprint due to data processing in fossil-fuel-reliant data centers. If the data centers are outside the European legal space, data processing incurs privacy risks. Besides, reliance on AI aggravates Europe's dependence on non-European chipmakers, whose supply chains can be disrupted. To address such concerns, NeuroSys develops energy-efficient neuromorphic hardware tailored to AI applications that protect privacy by processing data locally. NeuroSys aims to build a chip plant near Aachen in Germany to support Europe's technological sovereignty. This depends on an innovation ecosystem where socio-technical transformations emerge in transdisciplinary collaboration. This chapter introduces NeuroSys as a testbed for studying

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P. Letmathe et al. (eds.), *Transformation Towards Sustainability*,
https://doi.org/10.1007/978-3-031-54700-3_10

how transformation research can contribute to the sustainability and trustworthiness of AI Made in Europe.

Keywords Transformation research · Transdisciplinary collaboration · Innovation ecosystem · Neuromorphic computing · Artificial intelligence

1 Introduction

The promise of AI to transform society for the better has been promoted by tech-companies, scientists, and policymakers since the early 2010s. In the meantime, AI has become so efficient and fast in processing large amounts of data that it can be applied in many economic sectors. AI is not only considered to be the key technology for future economic growth across the globe (Aghion et al. 2018); it is also described as a driving force for achieving the United Nations Sustainable Development Goals by tackling global challenges related to the future of work, climate change, and health care (Vinuesa et al. 2020). AI systems can help companies and public administrations to reduce resource consumption, produce less waste, and optimize energy efficiency in production processes (Nishant et al. 2020). It can further monitor and predict environmental changes to support decision-making in precision agriculture and ecosystem management (Plattform Lernende Systeme 2022). The societal relevance of AI was recently emphasized during the Covid-19 pandemic, when it enabled contact tracing, provided diagnosis support, and contributed to workplace safety (Sipior 2020).

Yet, these promising narratives are accompanied by a growing critical discourse on the ethical, material, and political challenges that AI poses (for an overview, see Garvey 2021). Ethical concerns may refer to the transparency and reliability of AI (Campolo and Crawford 2020). While AI is a generic term used in diverse ways in the media and public discourses (Collins 2021; Nguyen and Herman 2022), technical experts usually use the term to refer to machine learning (algorithms build a model based on sample or training data to make predictions) and deep learning (a subset of machine learning whose algorithm structure mimics the human brain). As it is difficult to understand, even for experts, how deep learning algorithms transform input into output, concerns about transparency and reliability arise, especially in those cases where algorithms are involved in decision-making that affects human beings (e.g., advice on employment) (Campolo and Crawford 2020). This opacity may conceal the fact that automated decisions reinforce existing discrimination due to biases that an algorithm picks up from training data (Benjamin 2019; Chun 2021). In addition, the big data requirements for training algorithms lead to data protection and privacy considerations, for instance, in cases where the algorithms use personal data and make inferences about sensitive information (Hu 2020; Murdoch 2021). In response to these ethical concerns, the European Commission (2020) aims to build a regulatory framework for "trustworthy AI" (p. 10) that protects personal data, privacy, and non-discrimination.

While the socio-ethical impacts of AI applications have been widely discussed over the last decade, the material backbone of these applications has only recently gained attention (Coeckelbergh, 2021; Crawford 2021; Denkena 2021; Van Wynsberghe 2021). The materiality of AI is becoming increasingly relevant because high-performance applications, for example in natural language processing, rely on training large-scale models which takes weeks of computing time, costs hundreds of millions of dollars, and leaves a considerable carbon footprint. Moreover, the production of electronic devices on which AI runs consumes a lot of energy and makes extensive use of plastics as well as raw materials, such as cobalt and aluminum. AI-embedded short-lived end user devices require frequent replacement of these materials whose extraction and disposal incur environmental costs. In recognizing these costs, the European Green Deal suggests incorporating environmental impacts assessments into policies that incentivize sustainable AI applications (Gailhofer et al. 2021).

The material backbone of AI, in particular the production of semiconductor chips, also invokes political concerns. Global manufacturers of semiconductor chips are mainly located in Asia and the USA (Brown and Linden 2011). The global chip shortage during the Covid-19 pandemic revealed the vulnerability of supply chains (Hess and Kleinhans 2021). Moreover, in light of rising protectionism related to a "US-China trade war" (Bown 2020, p. 1), European access to computer chips is threatened (Varas and Varadarajan 2020). To increase resilience toward supply chain disruptions and to strengthen Europe's position in the semiconductor industry, the European Chips Act will provide public investment in support of regional chip design and production (Von Der Leyen 2022). A large part of this investment will feed into the development of energy-efficient transistors for AI applications (ibid.).

In line with European policy-making efforts to address the ethical, material, and political challenges posed by AI, the German Ministry of Research and Education (BMBF) funds the NeuroSys Cluster4Future, which was launched in 2022. NeuroSys is a high-tech innovation cluster that seeks to build an innovation ecosystem around the development of neuromorphic computing hardware for AI applications in the Aachen region of Germany. Neuromorphic computing denotes a computer chip architecture that emulates the neural network of the human brain. This chip architecture is expected to be more energy-efficient than computer hardware, which is based on graphic processing units that are commonly used for training AI models. Not only does energy-efficient neuromorphic hardware promise to reduce AI's carbon footprint, it can also foster data security and privacy because it can be used for mobile edge-computing devices, like sensors and smart watches. These devices process data locally rather than sending them to cloud services owned by foreign companies whose operations do not fall under European data protection laws. To develop neuromorphic computing hardware in tandem with AI applications that respect data protection and privacy concerns, NeuroSys bundles expertise from scientists, engineers, social scholars, industrial professionals, and municipal actors in an emerging innovation ecosystem. The innovation ecosystem consists in an interacting set of diverse actors whose collaboration facilitates the transfer of research results into business models and supports a long-term vision of the project: building a semiconductor chip plant in the Aachen region that will produce neuromorphic computing hardware tailored to specific AI applications for autonomous driving, personalized health care, smart cities, the Internet of Things, and digitalization. A local chip plant would support European sovereignty in the semiconductor industry and place European values (e.g., democracy, open innovation, responsible AI) at the center of chip development. To orient innovation processes toward European values and to incorporate societal considerations in research and development, NeuroSys pursues a transdisciplinary approach that builds structures for innovation ecosystem governance.

The aspirations of NeuroSys go beyond those of ordinary high-tech innovation initiatives because the cluster is not only committed to achieving technological excellence, but also to building an innovation ecosystem in which social, environmental, and economic considerations are integrated in research and development processes. The cluster is thus a prime example of the model of transformation research introduced in this edited volume. By bringing the model from theory into practice, NeuroSys will reveal the opportunities and challenges that emerge in the research process. In this way, it will make valuable contributions to discourses on transformation research (Kollmorgen et al. 2015; Wittmayer and Hölscher, 2017), Responsible Research and Innovation (Owen et al. 2012; Von Schomberg et al. 2013), and adjacent fields, such as integrative research (Fisher et al. 2015; Schikowitz and Maasen 2021), ELSI/A (Ethical, Legal & Social Impacts/Aspects) research (Balmer et al. 2016a; Zwart et al. 2014), and anticipatory governance (Barben et al. 2007; Guston 2014). NeuroSys will help to assess the practical feasibility of transdisciplinary transformation research for contributing to trustworthiness and sustainability of AI made in Europe.

This chapter presents the NeuroSys Cluster4Future as a practical implementation of the Aachen model of transformation research (Letmathe et al., this volume).[1] After introducing the technological background and organizational structure of NeuroSys in more detail, the chapter elucidates how NeuroSys addresses the technological, economic, societal, and environmental dimensions of the model. In this way, the chapter showcases the holistic transdisciplinary approach of NeuroSys, which treats social and technical transformations as being inextricably linked. While the chapter emphasizes the opportunities of such an approach, it also reveals the challenges that may emerge in the implementation phase.

[1] Letmathe et al. (this volume) use 'transformation research' as an umbrella term for three different positionings of research in the transformation process: (1) transformation research which observes and analyzes transformation processes, (2) transformational research that aims at shaping transformation processes, and (3) research transformation which refers to a change in research itself. We do not distinguish between these positionings in this chapter, because NeuroSys endorses all of them. The chapter is included in the section on transformational research in this edited volume because most of the research activities described here fall under this category.

2 Neuromorphic Computing

While the recent history of the semiconductor industry reveals that it has always been forced to adapt to various crises (Brown and Linden 2011), chipmakers now face a fundamental challenge: to explore new ways of organizing a chip that matches recent breakthroughs in AI. Training large AI models on modern microprocessors—central processing units (CPUs) and graphic processing units (GPUs)—consumes high amounts of energy (Prytkova and Vannuccini 2022). A major reason is the von Neumann architecture, in which processing and memory units are implemented as separate blocks interchanging data intensively and continuously on a computer chip (Von Neumann 1945). This data transfer is responsible for a large part of a chip's power consumption while also slowing down the processing speed of the system. These energy and speed costs associated with the continuous movement of data are commonly referred to as the *von Neumann bottleneck*. Recent analyses indicate that increasing demand for computing power in AI applications will likely outpace improvements of digital computing on modern microprocessors (Amodei and Hernandez 2018; Lohn and Musser 2022).

To meet the demands of AI, one possibility is to embrace different software-hardware system architectures, such as neuromorphic computing, which may offer advantages over digital computing for specific applications (Waldrop 2016). To develop neuromorphic computing chips, researchers take inspiration from the brain (Mehonic and Kenyon 2022). In contrast to the von Neumann architecture, there is no separation between data storage and processing in the brain since neurons and synapses perform both functions. Information processing in the neural network of the human brain consumes on average 20 watts; this is several orders of magnitude less energy than what an artificial neural network of the same size requires (ibid. citing Wong et al. 2012). The exceptional capabilities of the brain inspired electrical engineering already in the late 1980s, when Carver Mead at the California Institute of Technology coined the term "neuromorphic computing" to denote systems and devices that mimic some functions of biological neural systems (Mead 1998). As activities under the label have continued to evolve and diversify over the years, the precise definition of "neuromorphic computing" has become a matter of debate (Mehonic and Kenyon 2022; Schuman et al. 2022). In communities of chipmakers, neuromorphic computing generally refers to the engineering of brain-inspired modes of computing. Brain-inspired computer chips can evade the von Neumann bottleneck through in-memory computing. This means that, similarly to the human brain, a single device co-locates memory and processing, which eliminates constant data transfer and significantly improves the system efficiency (Fig. 1). Examples of neuromorphic chips are the Loihi from Intel (Davies et al. 2018) and the True North, a joint venture of IBM and DARPA (Merolla et al. 2014). The True North has a power density of 1/10.000 that of most modern microprocessors (Hsu 2014).

The True North and the Loihi are specialized chips. Whereas CPUs are used for general-purpose chips on which a range of programs can run, software needs to be tailor-made for neuromorphic computing hardware (Prytkova and Vannuccini 2022).

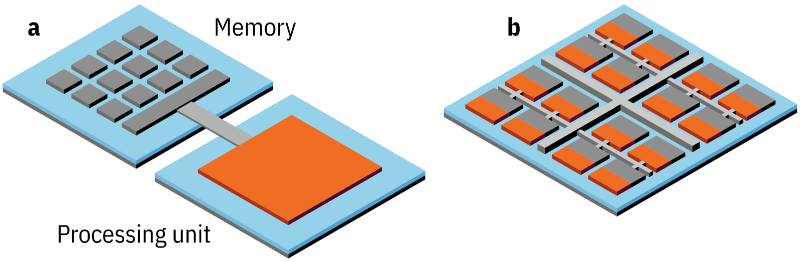

Fig. 1 **a** von Neumann architecture and bottleneck between memory and processing unit and **b** neuromorphic chip architecture

To develop software-hardware system architectures for neuromorphic computing, researchers from multiple disciplines (e.g., physics, material science, software engineering, computer science) need to work together. For these researchers, the following topics are of special interest: neuromorphic materials and devices, neuromorphic circuits, neuromorphic algorithms, applications, and ethics (Christensen et al. 2022). The NeuroSys Cluster4Future addresses these topics by organizing experts from various academic disciplines and industry sectors into distinct projects that engage in collaborative relationships with one another.

3 Organization of the NeuroSys Cluster4Future

The NeuroSys Cluster4Future consists of five projects A–E, each focusing on a different research topic. These topics correspond to the expertise of neuromorphic computing researchers at three prominent research institutes in the Aachen region of North Rhine-Westphalia: RWTH Aachen University, Research Center Jülich, and the non-profit enterprise AMO GmbH. These institutes have previously worked together in NEUROTEC, a research partnership funded by the BMBF since 2019 to develop energy-efficient neuromorphic computing hardware for AI applications in cooperation with industrial partners from the region. Several researchers and companies involved in NEUROTEC from the fields of physics, material science, neuroscience, computer science, and electrical engineering also participate in NeuroSys and have co-created the technical projects A–D (Fig. 2). These projects map onto the value chain of neuromorphic computing, ranging from research on material components of computer chips over the integration of such components in hardware-related circuit designs to case studies on applications of neuromorphic hardware.

Projects A and B focus on basic research. Project A studies the characteristics of memristors; these are material components which have the ability to change their resistance depending on the applied voltage or current. This ability makes them suitable for representing the weights between neurons in an artificial neural network. Memristors are thus important components for creating a hardware architecture that

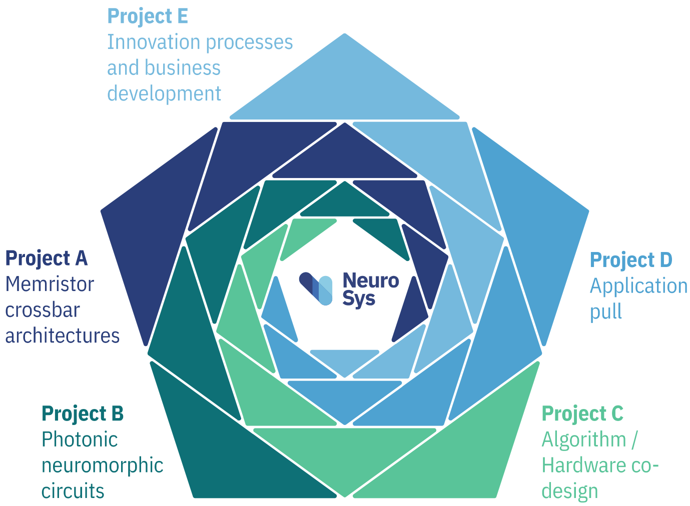

Fig. 2 Organization of the NeuroSys Cluster4Future

is inspired by the neural network of the human brain. While project A draws on microelectronics, project B examines optical signal transmission in neuromorphic hardware. That means that it focuses on using light, rather than electronics, to encode and transmit information. In comparison with electronic signal transmission, optical systems reduce latency and enable high data transmission rates. Researchers from projects A and B collaborate to study the combination of electronic and photonic approaches in neuromorphic hardware.

To exploit the technological potential of neuromorphic hardware for AI systems, project C brings together expertise from hardware-related circuit design, automated system design, and neuroscience. The aim is to develop innovative circuit architectures based on the properties of novel devices and material systems. By means of characterization and modeling, the complexity of the hardware is reduced to aspects that are relevant for exploration on an algorithmic level. In turn, the development of algorithms poses specific requirements for the device properties of neuromorphic hardware. Insights from neuroscience provide impulses for both hardware and software development.

With a focus on software development, project D investigates use cases of neuromorphic hardware. The goal is to prepare and optimize software from specific application areas for neuromorphic hardware. High-performance computing combined with relatively low energy consumption enables the processing of sensitive or time-critical data at the point of use (edge computing). Such potential benefits of neuromorphic hardware for specific AI applications will be evaluated with performance measures.

In addition to the technical projects, NeuroSys includes an additional project—project E—that works further along the value chain, examining the societal dimensions of neuromorphic computing research and development. Project E facilitates an economically viable, ethically robust, socially desirable, and environmentally sustainable development process for the innovations emerging from projects A to D. Economists develop business models and analyze value chains to support the successful market entry of these innovations. Professional management of patent licensing is provided so that the research institutions and industry partners of the cluster can benefit economically from the research results. Social scientists and ethicists study and contribute to the emergence of an innovation ecosystem around neuromorphic computing technologies that takes societal considerations and European values into account in research and innovation processes. As sustainability is considered as a key value, they also help NeuroSys project members to assess and address the environmental impacts of neuromorphic computing research and development.

While the basic outline of the NeuroSys project organization is expected to remain relatively stable, the work pursued within the projects will be dynamic, with actors, expertise, and interests joining the projects over the course of the nine-year funding period. For example, project E may recruit additional researchers with a background in sustainable development and life cycle assessment to deepen investigations on the environmental aspects of neuromorphic computing products. It may also strengthen collaborations with municipal officials from Aachen and neighboring towns as well as societal stakeholders (e.g., environmental groups) when the vision of a local chip plant comes closer to realization. Moreover, the Cluster4Future funding scheme requires NeuroSys to attract industry partners for participating in and financially supporting the cluster. The aim is to stimulate the market transfer of emerging technologies early in the research and development process.

Collaborations between NeuroSys projects, industrial actors, and societal stakeholders are an important condition for the realization of the project goals. As the spiral in Fig. 2 illustrates, these collaborations are intended to intensify over the course of the project duration so that research questions, activities, and outcomes from the different NeuroSys projects and partners will become more intertwined over time. The practical conditions necessary for such close intertwining to occur are regular meetings, joint seminars, and workshops (for examples of these, see Sect. 4.4.). In addition, NeuroSys researchers may have the opportunity to shadow the activities of a foreign project within the cluster to gain a better understanding of other disciplinary norms, practices, and cultures. Another example is the recently initiated NeuroSys Academy, a series of seminars in which early-career researchers explain the basics of their disciplinary fields to one another, discuss work-in-progress, and discover shared interests. The central objective is to cultivate communication, collaboration, and learning across disciplinary divides.

4 Transformation Research in NeuroSys

In considering the NeuroSys Cluster4Future as a whole, the orchestration of its diverse activities resembles project designs in the field of transformation research. The field spans various discourses and approaches rooted in the social sciences

(Heyen and Brohmann 2017). They range from sustainability transition studies and transition management (Geels and Schot 2007; Loorbach 2010; Rip et al. 1998), over innovation studies (Ömer-Rieder and Tötzer 2004; Smith et al. 2010), diffusion research (Rogers 1995; Wilson 2012), and change management (Boje et al. 2012), to literature on post-growth and sufficiency (De Saille et al. 2020; Jackson 2009; Stengel 2011). While there is little consensus on the definition of transformation (Feola 2015), the following examples tend to be associated with the term: the shift towards a low-carbon future (Foxon et al. 2013; Geels 2018), changes in media and communication sparked by the Internet and smart phones (Dolata and Schrape 2013; Küng et al. 2008), and "smart agenda[s]" (Köhler et al. 2019, p. 15) for mobility, urban development, and product manufacturing (Luque-Ayala and Marvin 2015; Manders et al. 2018; Van Agtmael and Bakker 2016). What these examples have in common is that they associate the introduction of new technologies with wider changes in society, economy, and geography. However, what makes a change transformative, whether transformation is radical and/or gradual, and how transformation relates to other concepts, such as transition, regime shift, resilience, and adaptation are topics of discussion in transformation research (Köhler et al. 2019).

This chapter sidesteps these discussions because transformation research in NeuroSys is not predominantly a social science endeavor. Although it resembles engaged social science approaches that initiate and shape transformation processes while describing and analyzing them at the same time (Herberg et al. 2021; see also Feola 2015; Heyen and Brohmann 2017), transformation research is considered as a transdisciplinary undertaking in NeuroSys in which all projects (see A–E in Sect. 3) participate. In NeuroSys, transformation research refers to science and technology development that is intertwined with societal, economic, and regional changes, while also reflexively engaging with processes and outcomes of change. Science and technology development can be considered as reflexive if the researchers involved can position themselves and their work within these wider changes to capture and anticipate how they themselves shape and are shaped by such changes (Stirling et al. 2006).

As these definitions are closely aligned with Letmathe et al.'s (this volume) model of transformation research, this chapter is structured according to the four dimensions of that model: technology, economics, society, and environment. In applying these dimensions to NeuroSys, the chapter demonstrates how a holistic transdisciplinary approach to transformation research can be put into practice. While the technological dimension elaborates on the kinds of technologies developed in the cluster, the economic dimension assesses their potential to enter and transform markets. The societal dimension discusses how building an innovation ecosystem around neuromorphic computing shapes—and is shaped by—structural, political, and cultural changes in the region. Both the societal and the environmental dimension further elucidate how an innovation ecosystem can be steered in order to support socially desirable, ethically acceptable, and environmentally benign research and innovation processes.

4.1 Technology

Technology development in NeuroSys is characterized by a co-design of neuromorphic hardware and tailor-made software. Whereas the design of hardware and software is split traditionally by a well-defined interface—the ISA (Instruction Set Architecture)—new processing principles in the neuromorphic computing domain promote a sequential approach: material and devices are defined first and inform the subsequent development of architectures, algorithms, and applications (Schuman et al. 2022). Quite differently, NeuroSys engages in a co-design process all across the design hierarchy (Fig. 3). In this co-design process, specific needs of algorithms and applications can influence the development of novel devices and material systems; at the same time, novel algorithms and learning models are developed that exploit the technical capabilities of neuromorphic hardware (Aimone 2021). Hence, the high performance of neuromorphic hardware at low energy consumption is a result of innovative connections between new materials and devices and the functions of entire AI systems (Chakraborty et al. 2020).

These connections are subject to a "technology push" and an "application pull" (Grunwald 2019, p. 76). On the one hand, results from basic research on materials and devices can push the development of algorithmic approaches. For example, emerging hardware devices inspired by the plasticity of the human brain can stimulate the development of new neuromorphic computing algorithms, which match how plasticity functions on these devices (Parsa et al. 2020). On the other hand, applications can pull hardware development into specific directions. The accuracy demands of applications can help to define the requirements of a specific crossbar implementation as well as the size and number of crossbars in a corresponding System-on-Chip. The push–pull dynamic requires hardware and software developers to engage in a continuous collaborative process of alignment, for instance,

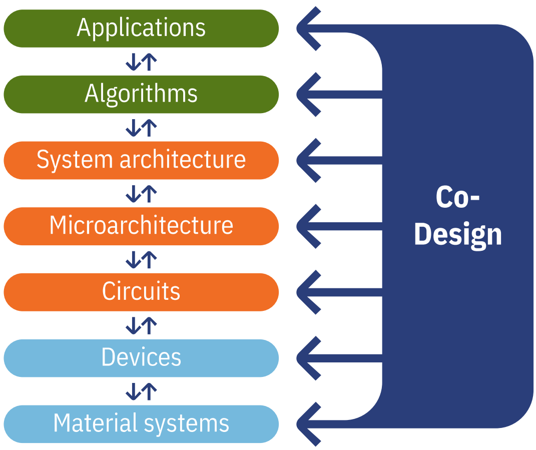

Fig. 3 Algorithm-hardware co-design

between the compute complexity required for highly-performant applications and the capabilities of neuromorphic hardware.

In NeuroSys, the application pull is stronger than in ordinary high-tech projects because industry actors are involved in early stages of the research and development process. Their involvement focuses on use cases of neuromorphic computing technology. Although there is currently no commercial neuromorphic computing technology available, Schuman et al. (2022) predict two wide areas of AI applications. First, neuromorphic computers could accelerate AI operations on personal computing devices, such as smartphones, laptops, and desktops. Neuromorphic accelerators improve battery life by realizing AI operations with significantly less power than today's state-of-the-art accelerators.

Second, low power consumption of neuromorphic hardware is also relevant for edge-computing applications. Edge computing refers to a type of computing where data analysis and processing are performed close to the points of data generation. Instead of sending data to a cloud service for remote processing, edge computing allows data to be processed locally, which supports data security and privacy by reducing network traffic (De Salvo 2018; Li and Huang 2021). These features are relevant for the following application areas: autonomous systems, such as vehicles and drones (Viale et al. 2021); remote sensors, especially in energy-constrained environments (Vanarse et al. 2017); robotics (Cheng et al. 2020); wearable technology and prostheses (Daus 2022; Osborn et al. 2018); and the Internet of Things, which is of particular interest in industrial contexts and smart homes (Fayyazi et al. 2018; Liu et al. 2017).

From this range of potential applications, four use cases are investigated in NeuroSys:

1. A *camera-based measurement device* will be developed for medical applications. The device will generate visual and thermal images of wounds whose diagnoses will be made with the help of neural networks. As the device is supposed to be mobile and light, it could be used in hospitals and care facilities.
2. A *speech recognition and translation system* will be built that relies on edge computing. The system will enable real-time language translation on mobile devices, such as smartphones.
3. A basic technology of *semantic video analysis* will be created for application in different domains. Examples are video editing on smartphones, segmentation of organs on medical images, and tracking of traffic participants in intelligent vehicles.
4. An *invasive medical controller* will be developed, which helps to adjust treatment measures to the changing biological measurements of a patient through reinforcement learning algorithms. Such a medical controller could be an artificial pancreas or a pacemaker.

These cases were selected because they all rely on energy-efficient hardware for mobile use but vary in terms of data: visual and thermal images, oral speech and written texts, video recordings, and biological measurements such as blood glucose concentration and heartbeat. These kinds of data have different features and their processing must satisfy specific demands. For example, the data rate of an artificial pancreas is low, but the device must be highly accurate in predicting treatment measures. Video segmentation systems, by contrast, must handle relatively large volumes of data, but the importance of accuracy varies per application (e.g., video editing for personal use vs. traffic tracking in autonomous cars). By tailoring algorithms to these use cases, NeuroSys tests the potential of neuromorphic computing hardware to satisfy diverging application demands. Moreover, speech recognition and language translation systems as well as semantic video analysis were selected as use cases because they depend on complex AI models which have high demands for their underpinning hardware. Hence, these technologies are "hard" use cases and could become prototypical benchmarks for the development of neuromorphic hardware.

NeuroSys researchers assess whether neuromorphic hardware is as performant as conventional hardware in working with hundreds of millions of parameters. Whereas neuromorphic computing hardware has been shown to outperform conventional microprocessors in terms of energy efficiency (Hsu 2014), Schuman et al. (2022) state that there is yet to appear an AI application for which neuromorphic computing is superior to other deep learning approaches in terms of accuracy (the number of an algorithm's correct predictions divided by the number of its total predictions). The authors anticipate a variety of challenges that could stifle the growth in neuromorphic algorithm and application development, for instance the lack of established benchmarks and metrics to evaluate which hardware system is most suitable for a given application and the integration of neuromorphic computing in a heterogenous computing environment. More specifically, Zidan et al. (2018) outline materials and device challenges of memristor-based neuromorphic hardware as it is developed in NeuroSys.

While enumerating the technical challenges of neuromorphic hardware development would go beyond the scope of this chapter, it is important to emphasize that they indicate a gap between expectations and reality. The history of microelectronic reveals that it can take a long time for such a gap to be closed. It took nearly four decades from the postulation of the memristor by Chua in 1971 until scientists from Hewlett Packard labs made the first operational memristor (Chua 2018; Mainzer 2022). Sometimes, the expectation-reality gap was never closed; several microelectronic devices (e.g., the Josephson junction and molecular electronics) promising to provide alternatives to the dominance of conventional silicon chips were studied for decades but failed to reach practical application and disappeared from view (Mody 2017).

Neuromorphic hardware is nowadays available in research communities, but it has not been used in real-world applications yet. However, market researchers and developers of neuromorphic computing technology predict that neuromorphic chips will be available on the market in about 3–5 years (La Barbera and Huang 2022; Yole Report 2021). Although these predictions are promising, NeuroSys has set itself an ambitious agenda. As the hardware systems and applications studied in NeuroSys primarily target prototype demonstrations in the first three years of the funding period, the cluster starts its activities on a mid-level technology readiness level. This means that the cluster seeks to facilitate an early market transfer of a technology under development whose commercial competitiveness is a topic of ongoing investigation—a task further advanced by the economic dimension of NeuroSys.

4.2 Economics

The economic dimension of NeuroSys supports one of the cluster's main objectives: achieving technological sovereignty for Europe in semiconductor and AI research, development, and production. This objective is aligned with the European Chips Act adopted in 2023. After years of decline in semiconductor investment (Fig. 4), the Chips Act aims to increase Europe's share of global chip production capacity to 20% from its current level of about 10% (Timmers 2022). As the global chip crisis exposed supply chain vulnerabilities which led to production stops (Pennisi 2022), the Chips Act strives to bring parts of the value chain to Europe.

In support of European technological independence, NeuroSys seeks to build an innovation ecosystem in the Aachen region, where neuromorphic computing chips will be designed and produced in close collaboration with companies that incorporate these chips in their products. To ensure the long-term usability of the innovations that will arise from NeuroSys, the economic dimension will evaluate possible business models. Moreover, the value chains of neuromorphic chips and associated products will be mapped to assess their feasibility with regard to its organization structure and the necessary competencies along the value chain. It is important for the establishment of neuromorphic hardware and software in the respective markets to identify possible cost savings, which can affect both the production and the use of the hardware. For this

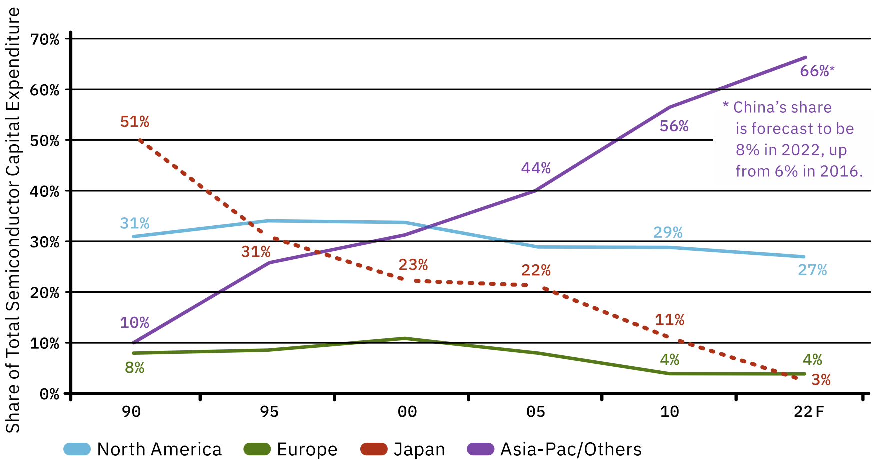

Fig. 4 Semiconductor capital expenditure by headquarter locations (IC Insights cited by European Commission 2022, p. 74)

reason, the study of the cost structures and value chains relevant to the production of neuromorphic hardware and software must be analyzed in detail. The same applies to the markets in which the resulting innovations are applied. This research is a prerequisite for commercializing NeuroSys innovations; it will also inform later analyses of external costs as well as quantifications of socio-environmental impacts.

To stimulate and inform entrepreneurial activities in and around NeuroSys, the economic dimension will quantify the target market potential of neuromorphic computing technologies. The market potential can be assessed on the basis of applications for which neuromorphic computing offers tailored solutions (see Sect. 4.1). However, the market potential of these applications is difficult to estimate at present because neuromorphic computing hardware has not yet reached market maturity. While the exact amount of neuromorphic computing hardware in future applications is still unknown, these applications can be organized into three categories. First, existing applications will be supplemented by neuromorphic hardware. Second, some applications will stimulate a production shift toward neuromorphic hardware because neuromorphic hardware is equally—or better—suited to performing a specific task. Here, the monetary benefit of the unique advantages of neuromorphic hardware will determine when the underlying technology of existing applications will be changed. Third, novel applications will emerge that are not possible or even conceivable with current hardware.

The first two categories target a certain share of existing markets. One of those markets is AI. According to a Statista (2022a) report (using the forecast from International Data Corporation), the global AI market is expected to reach up to 552.3 billion U.S. dollars by the year 2024. This includes hardware (server, storage), software (applications, software platforms, system infrastructure software, application development and deployment), and services (business services, IT services) (ibid.). The market size of machine learning, deep learning, supervised learning, unsupervised learning, reinforcement learning, natural language processing, context-aware computing, and computer vision is estimated to reach 227.46 billion U.S. dollars by 2024 and is expected to rise to 1,591 billion U.S. dollars by the year 2030 (ibid., using the forecast from GlobeNewswire). These estimates emphasize the growing demand for AI applications. Considering only the market for AI hardware, the market revenue is forecast to grow from 15.7 billion U.S. dollars in 2022 to 70.9 billion U.S. dollars by 2026 (Statista 2022b). A major customer of AI hardware will be the automotive industry, whose market size is expected to increase from 30 billion U.S. dollars in 2020 to 55 billion U.S. dollars by 2025 (Statista 2022c).

Although the specific market penetration of neuromorphic computing cannot be anticipated accurately at present, the general market predictions for neuromorphic applications are promising. Therefore, NeuroSys could have an impact on the competitive development of the wider high-tech sector and could transform the labor market in the Aachen region. Students, researchers, engineers, and other professionals will be attracted to the region both for education and employment in neuromorphic computing research, development, and production. To establish a platform for expert training, the university and further organizations involved in NeuroSys plan to develop and offer new fields of study as well as degree programs.

In this vein, university education will be complemented by learning opportunities for industry employees with the support of business development agencies, such as RWTH Innovation GmbH and the Chamber of Commerce and Industry Aachen. Hence, NeuroSys' investments in the local semiconductor workforce complement the high investments of the European Chips Act in semiconductor manufacturing (Heck 2022). This step is crucial to build an innovation ecosystem around neuromorphic computing technologies, which secures their long-term economic success.

4.3 Society

The societal dimension of NeuroSys focuses on the social order which enables and supports the emergence of an innovation ecosystem around the development of neuromorphic computing hardware in the Aachen region. Although the notion "innovation ecosystem" has been adopted with diverging meanings by academic, management, and policy-making discourses (Autio and Thomas 2021; Chhillar 2022), it is used here to denote an interacting set of actors who seek to realize the assumed beneficial outcomes of innovation (Adner 2017). The establishment of such an innovation ecosystem is an essential driving force for the socio-technical transformation process, which Van Agtmael and Bakker (2016) describe as a shift from "rustbelt" to "brainbelt" (p. 23). The authors use the American term "rustbelt" for areas in the USA and Europe which were once powerful industrial sectors but then experienced decline due to the elimination or outsourcing of manufacturing. They observe that some former rustbelts have become brainbelts: local research and development of smart products transform regions into innovation hubs. This transformation is driven by a collaborative ecosystem of universities, small and medium-sized companies, start-ups, local authorities, and a variety of supporters and suppliers. The reason is that one single research institute or company is not in a position to pursue the development of smart products, like computer chips, new materials, biotechnology, and medical devices. To tackle the complex tasks of developing smart products and transferring them into the market, transdisciplinary collaborations need to be established. An innovation ecosystem provides the social, material, and institutional conditions for such collaborations to emerge.

To transform the Aachen region—formerly a coal mining area—into an innovation hub, the NeuroSys project seeks to create an innovation ecosystem around the development of neuromorphic computing hardware. The NeuroSys cluster pools a transdisciplinary set of actors from RWTH Aachen University, Research Center Jülich, the non-profit Research and Technology Organization AMO GmbH, and regional technology companies as well as start-ups. The cluster is not a closed entity; it is the nucleus of an expanding innovation ecosystem. A resource for the organic growth of the ecosystem is the advisory board, which includes regional, national, and European members from science, industry, and society. All involved actors constitute a dynamic system which connects the research and development activities anchored in the cluster with innovation initiatives stimulated by external partners, such as the

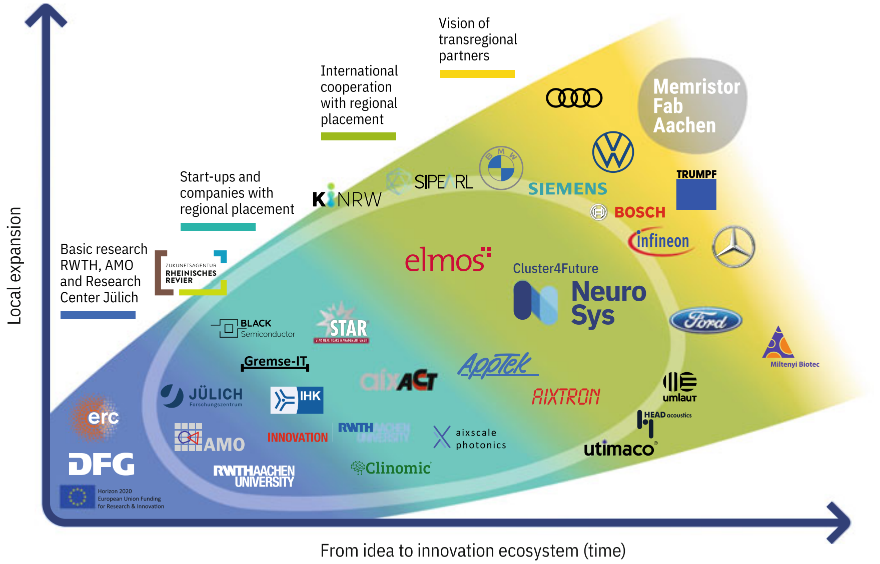

Fig. 5 Innovation ecosystem emerging around neuromorphic computing technology in the Aachen region[2]

City of Aachen, the regional competence platform KI.NRW, and European projects launched under Horizon 2020 and Horizon Europe. NeuroSys is thus a "connector" (Van Agtmael and Bakker 2016, p. 26): an organized group with the vision, the relationships, and the motivation for catalyzing the emergence and growth of an innovation ecosystem (Fig. 5).

To study the development of an innovation ecosystem from a social science perspective, different strands of literature are combined. The *multi-level perspective* is instructive for analyzing transformation processes of socio-technical systems (Geels 2004; Geels and Schot 2007). It distinguishes between three levels: a cultural, political, and material landscape, socio-technical regimes constituted by the practices of different actor groups, and the niche which is the nucleus of innovation. Climate change and associated political calls for sustainable AI, for example, in the European Green Deal (Gailhofer et al. 2021), can be regarded as pressures in the landscape. These pressures create instability in the regimes (e.g., technological and product regime, science regime, user and market regime) which preserve the existing socio-technical system around the use of GPU-based hardware for AI applications.

[2] The figure displays the logos of companies who are a) official members of the NeuroSys Cluster4Future, b) members of the external advisory board, and c) potential cluster members. The following companies belong to the different groups: a) AiXscale Photonics, Black Semiconductor, Clinomic, Gremse-IT, AixACCT Systems, AppTek, RWTH Innovation, STAR Healthcare Management, AIXTRON, ELMOS Semiconductor; b) BMW, Bosch, ELMOS Semiconductor, Ford, HEAD acoustics, Infineon, Siemens, SiPearl, Utimaco, Umlaut; c) Audi, Mercedes-Benz, Trumpf, Miltenyi Biotec.

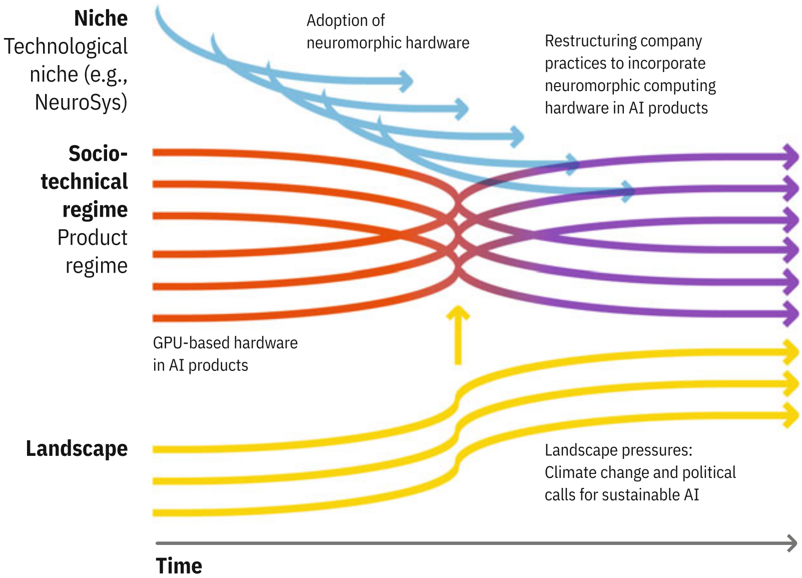

Fig. 6 Multi-level perspective on the transformation pathway of neuromorphic computing hardware (adapted from Geels and Schot 2007, p. 407)

Neuromorphic computing hardware may take advantage of such instability and may break through markets once it has been sufficiently developed in the technological niche of NeuroSys, i.e., a space protected by public subsidies and strategic company investments (Fig. 6).

For a new technology to move out from a niche into companies and markets, *quadruple helix collaborations* can support the transfer. Quadruple helix collaborations are a form of research and innovation in which actors from research institutes, industry, government, and civil society collaborate toward realizing a shared innovation goal (Carayannis and Campbell 2009). Such collaborations are important, especially if public subsidies for technology development come with high political and societal pressure on researchers to find a solution to a grand challenge. These pressures may induce researchers to continue working on the seemingly promising technological solution despite negative outcomes (Geels and Raven 2006). To avoid hype-backlash dynamics (Garud and Karnøe 2003), technological niches could incentivize researchers to flexibly adjust technology development and evaluation routines in response to continual feedback by users, policy makers, and special-interest groups. Such multi-stakeholder learning can occur in quadruple helix collaborations.

The opportunities and challenges that arise from bringing together diverse groups of actors in collaborative projects have been studied in historical and social science scholarship (Mody 2017; Nguyen and Marques 2021; Popa et al. 2020). Collaboration and networking provide support for knowledge sharing, but they depend on relationships of trust. The reason is that research groups and companies may fear the loss of competitive advantage due to knowledge leakage (Bogers 2011; Chesbrough 2003), especially in the current geopolitical climate of the semiconductor industry, where "technology theft" by Asian competitors is suspected (Li et al. 2021, p. 122). While non-disclosure agreements among universities and companies may be time-intensive and cumbersome (Berlin 2017; Parthasarathy 2017), the creation of legal and technological frameworks around a new technology can facilitate market entry in the long run. The development of reporting and benchmarking guidelines across research fields and streamlining quality, security, and sustainability standards across markets and national contexts supports the inclusion of the technology in existing infrastructures, processes, and products (Cheng et al. 2022; Van Den Ende and Kemp 1999).

Another aspect of quadruple helix collaborations is the *participation* of societal stakeholders. Participation has become a key concept in social science literature on the production of knowledge and innovation (Kimura and Kinchy 2019; Lezaun et al. 2017). It is often considered to be the defining feature of "transdisciplinary research," which denotes the collaboration between researchers and non-academic actors (Defila and Di Giulio 2015). Despite the ubiquitous talk about the importance of transdisciplinarity in academic and policy discourses, empirical research on practices of participation reveals that inputs from societal stakeholders and wider publics are often not included in innovation processes (Felt et al. 2012a, 2016; Irwin et al. 2012). One reason is that stakeholders have different interests, goals, and perspectives, which may be in tension with one another (Blok et al. 2015a, b). The tension between economic profit and socio-ethical considerations has been widely discussed in business ethics and responsible innovation literature (Garst et al. 2017; Hahn et al. 2018), and practical strategies to manage this tension have been proposed (Almquist et al. 2016; Long and Blok 2017; Porter and Kramer 2011).

Building on this literature, a holistic approach that takes socio-ethical considerations into account in the process of research and development is embedded in NeuroSys. The following list provides examples of such considerations:

- *Trust in AI:* Social acceptance of AI technologies is conditioned on trust in these technologies (O'Neill 2018; Thiebes et al. 2021). Trust is breached if AI output discriminates on the basis of race, gender, or age, or if data security cannot be warranted (Amoore 2020; Benjamin 2019; Chun 2021).
- *Human autonomy and AI:* Research has shown that users of AI systems are concerned about these systems violating their autonomy, for instance, by paternalistic nudging or impoverishing capacities for self-determination through increasing deferral of decision-making processes to algorithms (Laitinen and Sahlgren 2021; Nagel 2016).
- *Sustainability of AI:* The production of neuromorphic computing hardware is likely to have environmental costs, for example with regard to the extraction of minerals, water, and fossil fuels, which can be undergirded by pollution, extinction, depletion, and war (Crawford 2021; Letmathe and Wagner 2018).

The societal dimension of NeuroSys does not only study the socio-ethical aspects of neuromorphic computing but also helps to sensitize actors in the innovation ecosystem to these aspects. The aim is to facilitate the governance of a "responsible innovation ecosystem" (Smolka and Böschen 2023; Stahl 2022). Responsible innovation ecosystem governance is conceptualized as a "capacity" (Fisher 2007; Guston 2014; Guston and Sarewitz 2002) of actors to integrate the societal dimensions of research and innovation into their work. As capacities are shaped by wider political, institutional, and material structures, it needs to be investigated which socio-technical architecture of the innovation ecosystem supports socio-ethical reflection and responsible decision-making. The evolution of the innovation ecosystem around NeuroSys is thus a socio-technical transformation in which reflexive technology development, collaborative innovation, and responsible governance are intertwined. Instead of probing consumer and public reactions once a specific neuromorphic computing technology is ready for purchase, societal acceptance emerges in a collaborative process of "integrative" (Fisher et al. 2015) research and development. For this purpose, social and technoscientific experts continuously collaborate with one another, rather than engaging in a division of labor. A division of labor is common in technical projects with an add-on social science task force, such as in typical forms of *Begleitforschung* (Kromrey 2017; Schikowitz and Maasen 2021). NeuroSys, by contrast, builds an ecosystem linking social and technological innovation inextricably with each other. In adopting this approach, NeuroSys could become a role model for other regions, technologies, and research projects.

4.4 Environment

NeuroSys seeks to introduce neuromorphic computing to AI-dominated software domains, such as computer vision, speech recognition, and autonomous decision-making, where conventional computer hardware reaches its limits of performance and energy efficiency. High energy demands for training neural networks with deep learning methods are of environmental concern because energy is currently not derived from carbon–neutral sources in many locations, and, where renewable energy is available, it might be better allocated elsewhere (Strubell et al. 2019). Strubell et al. estimate that the process of training a deep-learning natural language processing model consumes roughly the same amount of energy as five cars over the cars' lifetimes (ibid., p. 1). In light of the global climate change crisis, algorithms that can perform mental tasks may not be worth the environmental costs. NeuroSys aims to create more "sustainable AI" (Van Wynsberghe 2021) which reduces the environmental impacts (e.g., carbon footprints) of developing and using AI models.

The environmental dimension of NeuroSys approaches sustainable AI holistically by not equating sustainability with energy efficiency but by adopting a broader view: critical interrogations of "techno-fix" narratives accompany technology development. Techno-fix narratives are based on a dominant rationality in society and policy-making according to which global challenges like climate change can be "fixed" by technological innovation that is advanced by technoscientific experts (Ludwig et al. 2021). Speculative technological innovations are cast as solutions to biodiversity, public health, and climate change crises (Thomas 2015). These narratives do not acknowledge that complex issues like climate change are "wicked problems" (Peters 2017; Rush 2019) that have neither a straightforward problem definition nor a solution because they can be approached from different disciplinary perspectives and may affect stakeholders in drastically different ways. A critical interrogation of a techno-fix narrative related to neuromorphic computing asks whether switching to more energy-efficient computer hardware will indeed reduce the carbon footprints of AI applications. To answer this question, the environmental dimension of NeuroSys follows Bratton's suggestion: "If we really want transformation, we have to slog through the hard stuff (history, economics, philosophy, art, ambiguities and contradictions). Bracketing it off to the side to focus just on technology, or just on innovation, actually *prevents* transformation" (Bratton cited in Thomas 2015, p. 93).

Historical, economic, and societal considerations need to be considered when exploring the relations between neuromorphic computing technology and carbon emissions because of the so-called "rebound effect" (Santarius 2012, 2015; Santarius et al. 2016). The concept denotes an increased energy demand that is driven by efficiency improvement. Santarius distinguishes between different types of rebound effects to explain why energy efficiency improvements often fail to translate into adequate absolute reductions of energy service demand. From the diversity of rebound effects that could be related to neuromorphic computing, two examples are presented here. A *financial rebound effect* may occur if neuromorphic computing hardware is used for new energy-intensive multi-feature AI applications rather than for making existing products more energy-efficient. *Material rebound effects* can result from (a) the energy consumed in the research, development, and production process of neuromorphic computing hardware, and (b) in building new capacities as well as infrastructures necessary for the implementation of this new type of hardware in products.

As neuromorphic computing hardware is still in its research and development phase, the aforementioned rebound effects are hypothetical. Yet, sensitizing researchers, technology developers, industrial actors, and societal stakeholders to potential rebound effects early on in the process helps them make decisions that are oriented toward sustainability goals. In light of financial, material, and structural rebound effects, it is important to balance the economic and social desirability of AI services and products against their environmental costs before investing in their development. An environmental outlook is not only relevant in the "upstream" design and "downstream" regulation of a technology, but also in the "midstream" of research and development (Fisher et al. 2006, p. 490). Välikangas' (2022) case study indicates that global challenges like climate change play an important role in the design and grant proposal writing of research projects, but that their relevance diminishes in later stages as other targets gain precedence, in particular academic excellence. The author suggests that one way of enhancing the interconnection between research and grand challenges is to encourage actors involved in research and development to reflect on the social, ethical, and environmental dimensions of their day-to-day work. Along these lines, NeuroSys incorporates reflexive exercises (i.e., dialogues, group discussions, multi-stakeholder workshops) in the midstream of research and development that probe actors to consider the environmental aspects of neuromorphic computing technology in everyday decision-making (cf. Fisher 2007). In approaching sustainable AI as a socio-technical phenomenon rather than as a technological fix, careful deliberation is required to decide what kinds of applications could be supported by neuromorphic computing in which contexts and at which social, environmental, and economic costs.

5 Conclusion

In applying Letmathe et al.'s model of transformation research to the NeuroSys Cluster4Future (Fig. 7), this chapter highlights that technological, economic, societal, and environmental dimensions of transformation are deeply intertwined. The technology development in NeuroSys introduces a shift away from conventional hardware for AI applications toward neuromorphic computing alternatives, whose emulation of the human brain promises significant energy efficiency and performance improvements. This technological transformation goes hand in hand with economic developments. Successful market entrance of neuromorphic hardware depends on the emergence of a competitive innovation ecosystem that can co-exist and merge with the current regime, sustaining the use of GPUs for AI applications (Dattée et al. 2018; Prytkova and Vannuccini 2022). At the same time, if neuromorphic computing hardware outperforms state-of-the-art technology, it may also accelerate the growth of such an innovation ecosystem. This will become visible in corresponding societal transformations in the Aachen region. NeuroSys plays into regional visions of transforming the Rhenish area into an "innovation valley" (ZRR 2021, p. 222) populated by skilled researchers, engineers, and professionals working at smart manufacturing plants or in co-working spaces within repurposed industrial buildings. The cluster is thus interlinked with the structural transformation of the Rhenish area, where the coal phase-out opens up "experimental spaces of transformation" (Böschen et al. 2021, p. 227) for innovative projects to participate in reshaping the region.

This chapter further emphasizes that active participation in shaping the technological, economic, societal, and environmental dimensions of transformation requires reflexive engagement with technology development and its wider contexts. Following Herberg et al. (2021), who claim that transformation research can only be scientifically grounded, fruitful for society, and ethically responsible if it engages in radical reflexivity,[3] a self-critical ethos is intended to become a defining feature of NeuroSys. To cultivate this ethos, stepping out of disciplinary and professional comfort zones and experiencing disconcerting differences (Hillersdal et al. 2020, p. 74; Smolka

[3] "Diese Ansätze [der Transformationsforschung] können jedoch nur wissenschaftlich fundiert, gesellschaftlich fruchtbar und ethisch verantwortungsvoll gestaltet werden, wenn sie mit einer radikalen Selbstreflexion verbunden sind." (Herberg et al. 2021, p. 7).

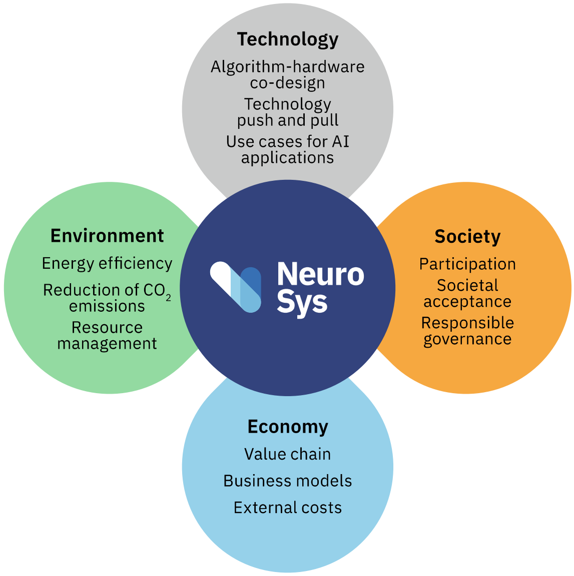

Fig. 7 Aachen model of transformation research applied to NeuroSys

et al. 2021) is a common practice in the cluster—not only across socio-technical divides but also within the technological domain where discussions between material scientists, physicists, neuroscientists, and computer scientists enable interrogations of disciplinary perspectives.

However, one may question whether socio-ethical reflexivity in transdisciplinary work can be cultivated if technoscientific project partners outnumber those with a background in the humanities and social sciences. Five projects within the NeuroSys cluster (see projects A–D in Sect. 3) are technoscientific in nature while only one project (project E) focuses on economic, socio-ethical, and environmental dimensions—an imbalance that is also reflected in funding and workforce. Therefore, the gray petal of the flower depicting transformation research in NeuroSys (Fig. 7) does not seem to be of an appropriate size. Yet, the equal size of all petals was a deliberate choice. It illustrates that reflexive engagement with the economic, societal, and environmental dimensions of neuromorphic computing research and development does not hinge on continuous collaboration with social scientists and humanities scholars. Instead, it is considered as a capacity of all project partners that can be activated and enhanced in such collaborations. In light of abundant literature on the challenges of transdisciplinary collaboration (Felt et al. 2012b; Schikowitz 2020; Viseu 2015) and of consortia resembling the NeuroSys cluster organization (Aicardi et al. 2018; Balmer et al. 2016b; Rabinow and Bennett 2012), the carriers and barriers of capacity building will be investigated. Hence, Fig. 7 illustrates the ambition rather than the actual state of NeuroSys. The ambition to give societal considerations, economic trade-offs, and sustainability concerns as much relevance as scientific and technological quests in everyday work practices will be put to the test in NeuroSys' research and development process.

Last but not least, readers may have noticed that the term "innovation ecosystem"—albeit frequently mentioned throughout the chapter—remains vaguely defined. The reason is that the innovation ecosystem is the object of transformation research in NeuroSys. The aforementioned socio-technical transformations associated with NeuroSys are in one way or another related to an innovation ecosystem emerging around neuromorphic computing technologies. Which shape this innovation ecosystem will take, how far it will reach geographically and institutionally, who will be involved in which role, function, and position are topics to be further explored. More specifically, the following questions will guide future research: What are the different ways to imagine the innovation ecosystem of neuromorphic computing? How do such imaginations shape and how are they shaped by socio-technical transformations? How do place-based factors influence transformation processes and ecosystem evolution? What are specific innovations in this ecosystem? Who could they benefit and who could they put at a disadvantage? How can the innovation ecosystem become both competitive and responsible? How do regional conditions, socio-material structures, and institutional contexts enable and constrain responsible innovation ecosystem governance? In answering these questions, NeuroSys will study and interrogate assumptions of "innovation" and "ecosystem" concepts (Oh et al. 2016; Von Schomberg and Blok 2021). In this way, NeuroSys will strengthen attempts to adopt an innovation ecosystem perspective in transformation research (Führ 2022) and in Responsible (Research and) Innovation discourses (Smolka and Böschen 2023; Stahl 2022).

Acknowledgements The NeuroSys Cluster4Future is funded by the German Ministry of Education and Research (BMBF, grant number 03ZU1106EA). We thank Klaus Mainzer, Danielle Shanley, Philipp Neudert, Frieder Bögner, Tobias Gemmeke, and Alexander Krüger for feedback on earlier versions of this chapter.

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Organizational Transformation: A Management Research Perspective

Ester Christou and Frank Piller

Abstract Organizational transformation is a complex and multifaceted process that involves a fundamental change in the way an organization operates and delivers value to its stakeholders. It can be triggered by a variety of internal and external forces, such as technological change, shifts in the competitive landscape, or changes in market demand. To successfully manage organizational change, organizations must be able to adapt and respond to changing circumstances in a proactive and strategic manner. This chapter reviews important concepts and theories of organizational change from the perspective of management research and examines selected theories and frameworks that have been developed to understand and manage organizational change. Overall, this chapter provides insights and lessons for practitioners and researchers alike. It aims to help readers understand the complexities and challenges of organizational transformation, but also to provide an overview of strategies and approaches to successfully navigate a transformation process.

Keywords Organizational transformation · Effectuation · Institutional theory · Change management · Digital transformation

1 Organizational Change and Transformation

Organizational transformation refers to the process of fundamentally changing the way an organization operates and delivers value to its stakeholders, and may require major changes in the way work is done. It may involve changes to the organization's structure, culture, business processes, governance, and/or external relationships. There are many reasons why an organization may undergo a transformation.

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P. Letmathe et al. (eds.), *Transformation Towards Sustainability*,
https://doi.org/10.1007/978-3-031-54700-3_11

For example, it may seek to respond to a rapidly changing market, new technological opportunities, changing regulatory requirements, or changing norms and expectations in the society in which the organization operates. Consider, for example, the current rise of Generative Artificial Intelligence. Transformer language models (BART, ChatGPT), AI that generates software code (Copilot), or AI that generates images of all kinds (Midjourney, Dall-E) require profound changes not only in higher education institutions, but also in companies of all kinds, for example, in the way marketing copy is written (Peres et al. 2023), in the way innovation processes are organized (Piller et al. 2023), but also in the way job applications are processed. More generally, the rapid growth of available data combined with better machine learning algorithms is changing the way management decisions are made, how operational processes can be automated, and leading to the emergence of entirely new business models. Generative AI thus contributes to the overall demand for digital transformation—the process of using digital technologies to fundamentally change the way an organization operates and delivers value to its stakeholders (Vial 2019; Nambisan et al. 2019). At the same time, digitization is also enabling new ways of working that address individuals' changing preferences for their workplace and work processes. In parallel with this ongoing digital transformation, organizations need to sustainably transform all aspects of their current business models into new, future-proof approaches. As discussed in more detail in other chapters of this book, the mandate for companies to respond to the threat of climate change and related sustainability challenges is probably the biggest driver of organizational transformation today. Overall, we are truly living in "transformational times" (Gruber 2023).

Regardless of its trigger, organizational transformation seeks to make an organization better able to compete effectively in a changing competitive environment (Newman 2000). A related but often distinct concept is *organizational change*, which refers to any change in an organization's structure, processes, or practices (Hage 1999; Weick and Quinn 1999). It can range from small, incremental changes to more significant shifts in the way the organization operates. In general, the term organizational transformation is used to refer to a broader and more far-reaching process than organizational change. Organizational transformation typically involves a deeper level of change and has a greater impact on the organization and its stakeholders. Organizational change, on the other hand, may be more focused and limited in scope and may have a more modest impact on the organization.

Previous research has addressed this difference by distinguishing between first-order and second-order change (Newman 2000). According to Meyer et al. (1993), first-order change refers to changes that involve incremental adjustments to an organization's existing structures, processes, and practices, but do not involve fundamental changes in strategy, core values, or corporate identity (Dutton and Dukerich 1991; Fox-Wolfgramm et al. 1998). These changes are often modest in scope and impact and do not fundamentally alter the way the organization operates. Examples of first-order change include the implementation of new technologies or processes, or the reorganization of existing work teams. First-order change is most likely to occur during periods of relative environmental stability and is likely to occur over extended periods of time (e.g., Tushman and Romanelli 1985). It improves the fit and consistency between an organization and its competitive and institutional contexts, but does not produce fundamental change.

Second-order change, on the other hand, refers to more fundamental and transformative changes that involve a significant shift in the way the organization operates. These changes are often broader and more far-reaching in their impact. Examples of second-order change include the introduction of new business models, the adoption of new technologies that fundamentally change the way the organization operates, or the introduction of new governance structures. Second-order change "takes organizations out of their familiar domains and alters the bases of power" (William 1983: 99). It is a strategic reorientation, an organizational metamorphosis (Meyer et al. 1993), or a change in organizational templates or archetypes (Greenwood and Hinings 1996). Paradoxically, the more adapted firms are to their competitive and institutional context, i.e., the better they are at implementing first-order change, the more difficult it is for them to achieve second-order change (Granovetter 1985; Greenwood and Hinings 1996). Strategies for balancing these two poles have thus become a central topic in contemporary management research (for example, the extensive literature on organizational ambidexterity, e.g., O'Reilly and Tushman 2008; Raisch and Birkinshaw 2008, but also the recent emphasis on paradox theory, e.g., Carmine and Smith 2020; Lewis 2000; Moschko et al. 2023).

In the management literature, three theoretical perspectives for studying organizational transformation (second-order change) can be distinguished (Newman 2000): institutional theory, organizational change theory, and organizational learning theory. We will briefly review these broad schools in Sect. 2. This prepares Sect. 3, where we review selected concepts that have been widely used in previous management research to explain and manage organizational change. In Sect. 4, we then provide a deep dive into a transformation domain that has received a lot of attention in management research over the last decade, namely digital transformation. This focus may serve as an illustration of the theories and approaches described before. We conclude with a brief reflection and outlook in Sect. 5.

2 Three Classic Theories to Study Organizational Transformation

Newman (2000) highlights three theoretical perspectives for studying organizational transformation (second-order change): institutional theory, organizational change theory, and organizational learning theory. These three theories are closely related and overlapping. Their level of analysis can serve as a simplified distinction (Fig. 1): While institutional theory argues at the level of a society (industry), work using organizational change theory is predominantly located at the level of the organization (business unit). Organizational learning emphasizes the role of individuals in an organization where learning ultimately takes place.

Systems perspective: Organizations are embedded in larger systems		
Environmental or societal influence → Need for adaptation and change		
Institutional Theory	**Organizational Change Theory**	**Organizational Learning Theory**
Societal level	*Organizational level*	*Individual level*
Organizations' need to conform to institutional pressures to gain legitimacy	Need of planned and managed change initiatives to address external and internal challenges	Importance of organizational adaptation through knowledge creation, acquisition, and utilization

Fig. 1 Theoretical lenses to analyze organizational transformation

Institutional theory is a framework for understanding how organizations conform to societal norms and expectations (DiMaggio and Powell 1983; Greenwood and Hinings 1996; Meyer and Rowan 1977; Zucker 1987). It is based on the idea that organizations are influenced by a set of institutional forces arising from the social, political, and economic context in which they operate, and that they adopt certain practices and behaviors in order to gain legitimacy and fit into the broader institutional environment. When these societal norms, which include laws, regulations, professional standards, and cultural norms, change (suddenly), organizations must change as well. Thus, institutional theory is often used to understand how organizations adapt to and shape the institutional environment in which they operate, and how they navigate the tensions and trade-offs that can arise between competing institutional logics. This term refers to the underlying values and assumptions that guide organizational behavior and shape the way organizations understand and interact with their environment (Alford and Friedland 1985). Finally, institutional work refers to the actions that organizations take to align their practices and behaviors with institutional expectations and norms (Zietsma and Lawrence 2010). This may involve conforming to existing norms or creating new ones in order to gain acceptance and legitimacy.

Organizational change theory examines the process of change within organizations, which in the context of this chapter can be understood as a process of institutional work to achieve second-order change (Armenakis and Bedeian 1999; Beer and Walton 1987). It is concerned with understanding how and why organizations change, as well as the factors that influence the change process (Meyer et al. 1993; Tushman and Romanelli 1985). Some of the key issues commonly addressed in organizational change theory include leadership, resistance to change, communication, power dynamics, and the role of culture in the change process. Accordingly, a number of frameworks have been developed to explain and understand the process of organizational change. While taking different perspectives, most of these frameworks build on the same few key ideas. Change is seen as a continuous process, a constant and ongoing process rather than a one-time event. This means that organizations must be able to adapt and respond to changing circumstances in order to remain relevant and successful—a perspective that refers to first-order change rather than transformation (Tushman and Romanelli 1985). Organizational change can involve both technical and social aspects. Technical change may involve the adoption of new technologies or processes, while social change may involve changes in the way people work together or interact with each other. Much of the change literature emphasizes the importance of considering these aspects together when implementing change (Hanelt et al. 2021). Effective change often requires strong leadership to guide and direct the process. This may include providing a clear vision for the change, communicating the benefits of the change to stakeholders, and building support for the change (Konopik et al. 2021; Eisenbach et al. 1999). Leadership is also needed because change can be difficult. Changing the way an organization operates can be a challenging process, and it is not uncommon for people to resist or be resistant to change. Understanding and managing this resistance is an important aspect of the change process (Kotter 1995).

Finally, *organizational learning theory* focuses on how organizations acquire, process, and apply new knowledge and information to adapt and improve. It is based on the idea that organizations are open systems that interact with their environment and can learn from their experiences (Levitt and March 1988; Schulz 2002). Organizational learning refers to the process by which organizations, and especially the individuals who make up that organization, acquire, process, and apply new knowledge and information in order to adapt and improve (Schulz 2002). Organizational learning can take many forms, such as learning from past experiences, learning from the experiences of others (e.g., through collaboration or benchmarking), or learning from new technologies or processes. It involves the integration and application of new knowledge and information in ways that help the organization adapt and improve. Organizational learning is an ongoing process that takes place throughout the life of the organization, continuously adapting and improving based on new information and experience. As a broad field of study, there are a variety of different approaches to organizational learning, each with its own unique perspective on how organizations learn and how that learning can be facilitated. But again, most approaches share some key ideas, including the perspective of learning as a social process. Organizational learning involves the interaction and communication of individuals within the organization. It is not just an individual process, but rather a collective process involving the sharing and integration of knowledge and ideas (Levitt and March 1988). Therefore, learning is influenced by the culture of the organization: An organization's culture plays a significant role in shaping its capacity to learn. A culture that values learning and encourages experimentation and risk-taking is more likely to facilitate learning than a culture that is resistant to change (Cook and Yanow 2011). At the same time, learning is contextual. The specific context in which learning takes place can have a significant impact on the process and outcomes of learning. Finally, organizational learning requires reflective practices, i.e., the deliberate and systematic examination of one's own experiences and actions. It allows organizations to critically evaluate their experiences and identify opportunities for improvement.

Overall, institutional theory, organizational change theory, and organizational learning theory are complementary perspectives that try to explain how firms respond to change: Institutional theory focuses on the influence of external change and pressures on organizations. Organizational change theory then explains how organizations react to external influences by adapting their existing structures. Lastly, organizational learning describes how organizations learn from past failure and success and thus have the ability to apply this knowledge on upcoming situations, in which organizations need to rethink their existing structures and strategies in order to successfully perform change.

3 Selected Concepts and Frameworks Supporting Organizational Transformation

In this section, we complement the general theoretical overview from the last section by reviewing three streams of literature that we believe provide representative insights into different theoretical approaches in management research to studying change at the organizational level: dynamic capabilities, effective decision making, and transformational leadership. As noted in the introduction, the prior literature often does not distinguish between first-order and second-order change. However, we are confident that the following selection of concrete approaches can contribute to a holistic understanding of transformation research.

The three concepts selected for review in this section have been widely used in previous management research to explain and manage organizational change. We acknowledge that our choice of these concepts is our own and rather subjective. We have tried to cover different aspects of management research that can provide the readers of this interdisciplinary book—which is primarily aimed at an audience beyond the field of management and economics—with a "representative" introduction to how previous research in our field (management research) has investigated the broad field of "transformation." We have tried to select three complementary perspectives: *Dynamic capabilities* added the notion of second-order change to the strategic management literature. Their level of analysis is the firm or business unit. *Effectuation*, on the other hand, is a relatively new concept that originated in the entrepreneurship literature to explain change and transformation in start-ups. It has only recently been transferred to the context of managing change in established organizations. Its level of analysis is the way entrepreneurs and managers (teams) deal with uncertainty and use transformations in their environment as a driver for change. *Transformational leadership*, finally, recognizes the importance of leadership behavior as a facilitator of organizational change and transformation and takes an individual-level perspective of a company's top leaders.

3.1 Dynamic Capabilities

Firms are constantly in the process of adapting, reconfiguring, and recreating their organizational resources and capabilities in order to remain competitive (Wang and Ahmed 2007). In this context, the notion of *dynamic capabilities* has been widely explored in the strategic management literature. Dynamic capabilities refer to "organizational and strategic routines by which firms achieve new resource configurations as markets emerge, collide, divide, evolve, and die" (Eisenhardt and Martin 2000: 1107). Conceptually, they extend the established resource-based view (RBV) of the firm, a theoretical framework that explains how competitive advantage is achieved within a firm and sustained over time (Eisenhardt and Martin 2000). The RBV views an organization as a set of resources. These resources are heterogeneously distributed across firms. Resource differences between firms persist over time and can explain differences in competitive advantage across firms (Amit and Schoemaker 1993). While the RBV has been seen as a key addition to the previously dominant market-based view of the firm (Porter 1980) and has received much general agreement and attention in the management literature, a key criticism of the RBV has been that it is based on the assumption that the market is static and does not address dynamic developments (Teece et al. 1997; Eisenhardt and Martin 2000). The traditional set of resources captured by the RBV explains when and why a firm can gain competitive advantage due to its unique set of capabilities among a set of given competitors in a market. But the traditional RBV could not explain how firms compete in dynamic markets, how and why certain firms have competitive advantage in unstable environments and situations of unpredictable change. In the seminal paper introducing the idea of dynamic capabilities, Teece et al. (1997) argue that in dynamic markets where the competitive landscape is changing, a different set of resources and capabilities forms the source of sustainable competitive advantage, dynamic capabilities.

Conceptually, dynamic capabilities are organizational and strategic routines that allow firms to effectively sense and shape their environment in order to pursue new opportunities and respond to changing circumstances (Eisenhardt and Martin 2000). These capabilities include the ability to continuously learn, adapt, and innovate to create and exploit new sources of value (Grant 1996; Teece and Pisano 1994). Dynamic capabilities include both the creation and use of resources, such as knowledge, skills and organizational structures, and the processes by which these resources are managed and mobilized (Teece et al. 1997). They include the ability to reconfigure and redeploy resources in response to changing environments and opportunities, and to build new capabilities as needed. Teece (2007) describes the development of dynamic capabilities as an unfolding process of sensing, harnessing, and reconfiguring firm resources. This conceptualization of dynamic capabilities suggests that firms should have the capacity for the process to first sense and shape opportunities and threats, second seize opportunities, and third maintain competitiveness by enhancing, combining, protecting, and, when necessary, reconfiguring the firm's intangible and tangible assets (Teece 2007).

The *sensing mechanism* identifies customers with unmet needs and develops technological opportunities. The capabilities required are therefore threefold. Before directing innovation efforts, organizations must identify target market segments and customer needs, and they must be able to assess developments in the business ecosystem. Organizations also need to harness internal innovation and manage internal innovation processes. Accordingly, external sources of innovation must also be tapped, which are suppliers and complements, exogenous science, and customer engagement in open innovation (Teece 2007; Schoemaker et al. 2018).

Seizing capabilities refer to the ability to mobilize resources, address needs, and exploit business opportunities to create value and mitigate risk for the organization. Seizing capabilities pay special attention to the value of partnerships, realigning the boundaries of the firm and integrating these concepts into the business model (Teece 2007, 2014). With the integration of external partners and information sources, the need for decision-making protocols emerges. The organization must also determine the boundaries within which it operates. This includes decisions about the design of alliances to develop capabilities, as well as the management of integration, in- and outsourcing, and the value of co-specialization within the value network, all while protecting intellectual property and designing an organizational culture for innovation (Teece 2007, 2014).

The final building block, *transforming or reconfiguring capabilities*, refers to the continuous recombination and reconfiguration of resources and structures under changing environments to support business models (Teece 2007). This mechanism highlights the need for organizations to continuously renew their resource base. Effective management of internal and external resources, as well as knowledge management, enables effective and continuous realignment of resources (Teece 2007, 2014). To be successful, top management teams must possess entrepreneurial skills to adapt to and influence an ever-changing business environment. Effective decision making and transformational leadership, which will be explored in the next sections of this chapter, can be seen as constituting such entrepreneurial capabilities.

Overall, dynamic capabilities are a key factor in a firm's ability to compete and succeed in today's rapidly changing business environment. Empirical research on dynamic capabilities has mostly examined the relationship between a firm's dynamic capabilities and firm performance. It is generally supported that all three mechanisms of dynamic capabilities, namely sensing, seizing, and transforming, have an effect on the firm's long-term success (Rindova and Kotha 2001; Torres et al. 2018). They enable firms to continuously learn, adapt, and innovate to create and exploit new sources of value. We believe that the core idea of dynamic capabilities can also be applied to the higher level of transformation research as conceptualized in this book. Future interdisciplinary research needs to apply the concept of dynamic capabilities to higher level domains where transformation takes place: an industry, a region, a society—or the world.

3.2 *Effectual Decision Making*

While dynamic capabilities is a theory that developed in the context of strategic management in established organizations, another theory that can contribute to the study and management of organizational change is *effectuation* (Sarasvathy 2001, 2008; Fisher 2012). The term describes a decision-making approach that is particularly relevant in contexts where the future is uncertain and available resources are limited. It involves focusing on the resources and capabilities that are already available and using these resources to actively shape and create opportunities, rather than simply reacting to them. Effectuation involves taking calculated risks, being flexible and adaptable, and building a network of relationships and collaborations (Fisher 2012). Effectuation logic can be applied at different times in a firm's development depending on what type of change the firm is going through (Ko et al. 2021).

Effectuation is often explained in contrast to causation, the typical decision-making approach traditionally taught in management schools. Causation involves identifying a clear goal or objective and then developing a plan to achieve that goal based on a clear understanding of the causal relationships between different variables (Sarasvathy 2008). Competitive advantage in these models is conceptualized as largely determined by competencies related to the exploitation of opportunities and resources controlled by the organization (Chandler and Jansen 1992).

In a now famous example, Sarasvathy (2008) further explained the dichotomous concepts of effectuation and causation. She suggests the metaphors of a jigsaw puzzle for the causation approach and a patchwork quilt for the effectuation approach. In the puzzle, an entrepreneur's task is to take an existing market opportunity and use resources to create a competitive advantage. In the puzzle builder's view, all the pieces are there, but they need to be put together in the right way. In the patchwork quilt approach, the entrepreneur is asked to develop an opportunity by experimenting and incorporating new information as it becomes available. The patchwork quilter sees the world as a changing state shaped by human action (Sarasvathy 2008). Overall, the key difference between effectuation and causation is the level of uncertainty and predictability in the context in which they are used. Causation is more relevant to predictable and stable contexts, while effectuation is more relevant to uncertain and unpredictable contexts-such as those typical of organizational change and transformation. Effectuation assumes that an overall strategic goal is not clear from the outset. Decision-makers use a logic of non-predictive control and focus on "choosing between possible effects that can be created with given means" (Sarasvathy 2008).

Originally developed as a theory to explain the success of serial entrepreneurs, effectuation has received considerable scholarly attention in recent decades (Perry et al. 2012). Its application has been extended far beyond entrepreneurship circles to fields such as creativity and innovation (Blauth et al. 2014), marketing (Coviello and Joseph 2012), and operations and project management (Midler and Silberzahn 2008). Effectuation has also received attention in the field of research and development processes. Brettel et al. (2012) suggest that mobilizing an effectual mode of decision making can positively affect R&D performance, especially when innovativeness is high. Based on this study, Blauth et al. (2014) find that the use of an effectual decision-making logic has a positive impact on practiced creativity, while the use of a causal logic seems to have a negative impact on creativity. These relationships become stronger as the level of uncertainty increases. Nevertheless, recent research suggests that effectuation and causation even complement each other in the pursuit of highly innovative projects (Yusuf and Sloan 2015).

Future research has yet to establish a formal link between effectuation and organizational change. However, both concepts involve the process of adapting and responding to change in order to create value. Organizational transformation often involves significant changes in the way an organization operates, which can be difficult and uncertain. In these situations, an effectuation-based approach can be useful to help the organization focus on the resources and capabilities it already has, and to use those resources to actively shape and create new opportunities in the face of uncertainty. We see great potential for establishing effectual decision making as a core concept for transformation management as understood in the context of this book. However, future research needs to establish the links between these concepts in greater detail.

3.3 Transformational Leadership

While dynamic capabilities explain how a specific set of resources can enable organizations to implement second-order change, and the establishment of an effectual decision-making logic can enable an incumbent organization to cope with the uncertainty typical of organizational change, the final concept discussed in this section as a potentially fruitful framework from management research to establish an interdisciplinary transformation framework is *transformational leadership*. In recent decades, an increasing number of researchers have recognized the importance of leadership behavior as a facilitator of organizational change and transformation (Higgs and Rowland 2008; Oreg et al. 2011). Our brief review of key concepts in the three foundational theories of managing organizational change, as described in the introduction to this chapter, also pointed to the role of leadership. A wide range of expectations have been proposed for the role of a leader in an organization undergoing change: For example, leaders should act as visionaries, advisors, change agents, or consultants (Felfe 2006). Thus, there is no clear definition of the concept of leadership in past and current research, but rather a variety of definitions. These definitions differ not only in terms of the leader's role within the organization, but also in terms of various factors such as the characteristics of leadership behavior, the leader's influence on organizational goals, organizational success, culture, and employee performance and satisfaction (Yukl 1989).

Past research has been consistent in assigning organizational leaders the primary responsibility of directing followers toward the achievement of organizational goals (Zaccaro and Klimoski 2002). A pragmatic definition by Northouse (2021: 24) builds on a core assumption, a leader's significant influence on followers, and defines *leadership* as "a process whereby an individual influences a group of individuals to achieve a common goals." Leaders are considered to have a broad ability to influence employee performance and well-being (Lok and Crawford 2004). In this regard, studies have shown a relationship between organizational outcomes and different leadership styles (Waldman et al. 2001). This research proposes that leaders exhibit a specific (leadership) style, which is a combination of personal characteristics and behaviors of leaders when interacting with their team members. For example, Bommer et al. (2005) suggest that leaders' values are reflected in employees' attitudes toward change. The authors find that leaders' openness values are negatively related to followers' intentions to resist organizational change. Higgs and Rowland (2008) argue that group-focused leadership practices and behaviors have a positive impact on change success. Berson and Avolio (2004) find a link between a leader's style and communication skills and his or her ability to raise the organization's awareness of organizational change. Thus, there is growing evidence that leadership traits and behaviors influence the success or failure of organizational change (Higgs and Rowland 2008).

Within the literature on leadership styles, the theoretical concept of Bass (1985), which distinguishes between transactional and transformational leadership, deserves recognition in the context of this chapter. Bass' theoretical model groups the behavioral patterns of supervisors toward their employees into two different dimensions. According to Bass (1985), leadership behavior can first be described by comparing two leadership styles, transformational leadership and transactional leadership. Transformational leadership is characterized by the adaptability of the leader. The leader is able to identify current challenges and respond to them in a timely manner (Bass et al. 2003). It is also characterized by the "transformation" of the values and attitudes of employees and the resulting increase in employee motivation and performance (Felfe 2006; Waldman et al. 2001). Thus, transformational leadership focuses on inspiring and motivating followers to not only achieve their goals, but also to strive for personal and professional growth. Transformational leaders seek to engage followers in a shared vision and empower them to take responsibility for their work and development.

Transformational leadership involves four key components—the "four Is": idealized influence, intellectual stimulation, intellectual input, and individualized consideration. *Idealized influence* describes the behavior of transformational leaders who serve as role models and inspire their followers to strive for excellence. They demonstrate integrity, honesty, and authenticity and are able to earn the respect and trust of their followers. This component describes leaders as both professional and moral role models (Felfe 2006). *Inspirational motivation* proposes that transformational leaders are able to inspire and motivate their followers by articulating a compelling vision and helping them see the purpose and meaning behind their work and the change required. Leaders motivate followers by instilling optimism and enthusiasm for achieving set goals and the organization's mission and values (Bass et al. 2003). *Intellectual stimulation* means that leaders encourage their followers to question established tasks, think critically, challenge assumptions, and seek new and creative solutions to problems. Transformational leaders encourage creativity and innovation in their followers (Bass et al. 2003). Finally, *individualized consideration* suggests that transformational leaders provide individualized support and development to their followers, encouraging them to identify and develop their strengths and potential in a targeted manner. Leaders take on the role of a mentor (Bass et al. 2003). Research has shown that transformational leadership can be effective in a variety of settings and can lead to improved performance, job satisfaction, and commitment among employees (Liu et al. 2010). However, transformational leaders must be authentic and genuine in their interactions with followers, as insincere or manipulative behavior can undermine trust and effectiveness (Felfe 2006).

Transactional leadership, on the other hand, is a leadership style that focuses on establishing clear expectations and rewards for achieving specific goals and objectives. Transactional leaders use a system of rewards and punishments to motivate and direct their followers and provide feedback and guidance to help them achieve their goals. Thus, transactional leadership is characterized by a clearly regulated exchange relationship between leaders and followers (Felfe et al. 2004; Felfe 2006). Transactional leadership has two key components. First, transactional leaders use contingent rewards such as praise, recognition, and tangible incentives to motivate and reward followers for achieving specific goals and objectives (Felfe 2006). Second, transactional leaders engage in management by exception. That is, they use a system of monitoring and feedback to identify and correct deviations from expected standards and performance (Bass et al. 2003).

Transactional leadership can be effective in situations where there is a clear and defined set of goals and tasks, and where there is a need for stability and predictability. However, it may be less effective in situations where there is a need for creativity, innovation, or adaptability. However, when comparing transformational and transactional leadership styles, transformational and transactional leadership should not be seen as opposing behaviors, but can be used simultaneously by leaders depending on the situation (Felfe et al. 2004). Transformational leaders promote a common understanding of strategic goals that align with the organization's vision. In addition, they create a learning environment that encourages employees to question ways of working in order to translate specific goals into actions. The effectiveness of strategic goal implementation depends on how well leaders in an organization perceive and clarify the goals, translate them into more specific goals tied to the respective units, and then foster an open learning environment to facilitate the pursuit and successful completion of the goals (Felfe et al. 2004). Transactional leaders, on the other hand, as a more instrumental leadership style, provide a concrete platform from which leaders can actively engage with followers in implementing change. The reinforcing and rewarding nature of transactional leadership would underpin specific engagement behaviors, such as providing information that emphasizes personal impact. Thus, transformational and transactional leadership styles are thought to be complementary, albeit situational, during organizational change (Tushman and Nadler 1986).

Overall, the theoretical concepts of transformational leadership and organizational transformation are strongly related. Transformational leaders are able to inspire and motivate their followers to embrace change and strive for excellence, and to build the skills and resources needed to successfully manage organizational transformation. As a result, they play a critical role in driving and managing organizational transformation efforts.

4 Digital Transformation

Digital transformation is challenging executives across industries (Correani et al. 2020). Most recently, COVID-19 urged leaders to rethink existing internal systems and move toward digital transformation, recognizing the strategic importance of technology in their organizations. Current research has not reached a consensus on what exactly digital transformation is (Warner and Wäger 2019). Despite the lack of an explicit definition, digital transformation is always associated with organizational change: Organizations need to adapt to the general expansion of digital technologies—defined as the combination and interconnection of myriad, distributed information, communication, and computing technologies (Bharadwaj et al. 2013). Thus, digital transformation can be linked to the organizational change initiated by the proliferation of digital technologies (Hanelt et al. 2021).

Digital transformation refers to the process of using digital technologies to fundamentally change the way an organization operates and delivers value to its stakeholders (Vial 2019; Nambisan et al. 2019). It involves the integration of digital technologies into all areas of the organization, including its business models, processes, and operations, to enable new forms of value creation and improve performance (Hanelt et al. 2021). The core proposition is that digital technologies enable new forms of value creation. Digital technologies, such as the Internet, mobile devices, and artificial intelligence, enable organizations to create new forms of value that were not previously possible. For example, they can be used to improve customer experiences, create new products and services, or streamline operations. These technologies also have the potential to disrupt traditional business models and create new opportunities for organizations (Hinings et al. 2018). They can enable organizations to reach new markets, create new revenue streams, and challenge established players in their industry. In this section, we use the domain of digital transformation as an example to review the state of research in the management discipline on organizational transformation.

Prior research has established that digital transformation requires a holistic approach (e.g., Appio et al. 2021; Hanelt et al. 2021; Vial 2019). Digital transformation is not just about implementing new technologies, but rather about fundamentally rethinking and changing the way an organization operates. It requires a holistic approach that considers the impact of digital technologies on all aspects of the organization. This often involves a change in the culture of the organization, as it requires a different way of thinking and working. It also requires new skills, new ways of collaborating and communicating, and a willingness to embrace change and take risks. Accordingly, the concept of dynamic capabilities has been specified for digitalization, as we will review in the next subsection. Previous research has also derived a number of process models for digital transformation that capture the need for a holistic process. Finally, at the end of this section, we discuss how the state of transformation can be measured by introducing the idea of a digital maturity model—which can be seen as prototypical examples to inspire future research on organizational transformation.

4.1 (Dynamic) Capabilities for Digital Transformation

The emergence of new technologies, and thus new opportunities for organizations, has reshaped business models across industries (Liu et al. 2011). Hence, digital transformation is more complex than just integrating new digital technologies into the existing organizational structure and processes. In this context, the idea of dynamic capabilities has been adapted to the field of digitalization (Konopik et al. 2021), building on the notion in previous research in strategic management that the existence of dynamic capabilities has a positive impact on competitive advantage in dynamic environments (Drnevich and Kriauciunas 2011; Li and Liu 2014). For digital transformation, Warner and Wäger (2019), for example, found that firms need to build a system of dynamic capabilities to be successful in digital transformation. Hanelt et al. (2021) proposed that firms with high levels of dynamic capabilities have higher levels of digital maturity than firms with low levels of dynamic capabilities. In addition, Konopik et al. (2021) state that organizational capabilities relevant to digital transformation are equivalent to the dynamic capability approach of three mechanisms: sensing, seizing, and transforming. Companies rely on a specific set of dynamic capabilities along their digital transformation process, namely strategy and ecosystem formation, innovation thinking, technology management, data management, organizational design, and leadership. We briefly review these aspects in the following.

Capabilities related to *strategy and ecosystem formation* refer to the adaptation of existing business models during the digital transformation process (Warner and Wäger 2019). They also include the formation and management of ecosystems that span multiple organizations, functions, and industries initiated by digital transformation (Berman and Marshall 2014; Hanelt et al. 2021). The formation and management of digital ecosystems requires the ability to identify the key stakeholders and partners involved in the ecosystem and to establish clear roles, responsibilities, and expectations. This may involve creating governance structures and mechanisms to facilitate collaboration and coordination among stakeholders. Second, it is important to establish the technical infrastructure and platforms that will support the ecosystem, such as cloud computing, data analytics, and API management. Finally, companies need the ability to design business models and revenue streams to support the ecosystem and ensure that the ecosystem's value proposition creates value for all stakeholders (Matt et al. 2015).

Innovation thinking refers to organizational capabilities that enable the emergence of innovations from within or outside the organization (open innovation). Innovation thinking enables organizations to identify and explore new possibilities, challenge assumptions and existing ways of doing things, and experiment with new ideas. It also involves the ability to think creatively and see problems and challenges from multiple perspectives, which can help generate novel solutions (Hinings et al. 2018). Involving the customer in the innovation processes (co-creation) is a key element here, especially by focusing efforts on improving the customer experience (Elmquist et al. 2009). This also includes the development capacity to enhance products with digital technologies (Warner and Wägner 2019).

Digital Technology Management. Intuitively, digital technologies play a critical role in the digital transformation process. Technology management as a digital transformation capability therefore involves the strategic planning, acquisition, and deployment of technology resources, as well as the ongoing management and optimization of these resources to deliver maximum value. This includes activities such as technology roadmap development, vendor management, and technology portfolio management (Konopik et al. 2021). Effective technology management is a critical capability for digital transformation because it enables organizations to identify and adopt the most appropriate technologies for their needs, integrate these technologies into their operations, and continuously optimize and evolve their technology stack in response to changing business needs and the evolving digital landscape (Besson and Rowe 2012).

Data management refers to organizational capabilities related to the handling, security, and capitalization of data. It is critical to digital transformation because it enables organizations to collect and analyze data from a variety of sources, including internal systems, customer interactions, and external sources. This data can be used to optimize business processes, improve decision making, and identify new opportunities (Haffke et al. 2016). Data management also includes ensuring the quality, integrity, and security of data, as well as the governance and compliance of data-related activities. This is important because organizations rely on accurate and reliable data to make decisions and maintain the trust of their stakeholders. A specific capability discussed in this context is managing the tension between sharing data with third parties, enabling better decisions at the system level, and maintaining competitive advantage at the firm level (Konopik et al. 2021).

Organizational design. The structural and procedural organization must adapt to support digital transformation strategies. Changes may be triggered by new or adapted business models or new technologies (Hess et al. 2016). Effective organizational design is critical to digital transformation because it enables organizations to align their structure, processes, and systems with their strategic goals and objectives and create the conditions for innovation and agility. This may involve redesigning roles and responsibilities, implementing new processes and systems, or introducing new governance structures (Hinings et al. 2018).

Leadership finally involves creating a culture and leadership style that supports digital transformation and encourages collaboration, creativity, and continuous learning. This is important because digital transformation often requires significant changes in the way work is done, and a supportive culture and leadership style can help facilitate these changes (Eisenhardt and Martin 2010; Matt et al. 2015). Interestingly, the leadership construct has been largely neglected in the general dynamic capabilities literature (Schilke et al. 2018). However, an appropriate leadership style is a key requirement for the successful transformation of organizations (Nadkarni and Prügl 2021) and for overcoming internal resistance from various stakeholders during the transformation processes (Matt et al. 2015).

In conclusion, dynamic capabilities are an important consideration for organizations seeking to undertake digital transformation. Dynamic capabilities refer to an organization's ability to continuously adapt and evolve in response to changing circumstances and opportunities. They include the ability to sense and respond to change, to learn and innovate, and to recombine and leverage resources and capabilities in new ways. Dynamic capabilities help organizations navigate the uncertainty and complexity of digital transformation and continuously adapt and evolve in response to changing circumstances and opportunities. However, developing dynamic capabilities is not easy and requires a significant investment of time and resources. It also requires a culture and leadership style that supports change and continuous learning, and encourages collaboration, creativity, and experimentation.

4.2 Digital Transformation Process Models

A second stream of research has focused on providing frameworks and process models to address the question of how organizations can successfully undertake digital transformation. It is widely recognized that digital transformation is a process consisting of various stages (Hess et al. 2016; von Leipzig et al. 2017; Sebastian et al. 2017). Process models for digital transformation refer to frameworks or approaches that organizations can use to guide their digital transformation efforts. These models typically provide a structured approach for identifying and prioritizing digital opportunities, implementing new technologies and processes, and measuring and tracking progress. This process model perspective is consistent with earlier change management literature, which suggests that transformation is a process that evolves through stages, rather than a short-term response to external events. Among these well-established models, four are particularly noteworthy:

- *Kotter's eight-step change model* outlines a process for leading organizational change that includes creating a sense of urgency, forming a guiding coalition, creating a vision, communicating the vision, empowering others to act on the vision, creating short-term wins, consolidating gains, and embedding new approaches in the organizational culture (Kotter 1995, 1996).
- *Lewin's change management model* is based on the idea that change involves moving from one state (the "unfreeze" stage) to another (the "refreeze" stage) and involves three steps: unfreezing, changing, and refreezing. Unfreezing involves breaking down the existing state and creating a willingness to change.

Changing involves implementing the new ideas or processes. Refreezing involves reinforcing the changes and making them the new norm (Lewin 1947).

- The *ADKAR model*, developed by Jeff Hiatt (2006), is a goal-oriented change management model that focuses on the individual and helps organizations understand and manage the change process from the individual's perspective. The model consists of five elements that form the acronym of its name: Awareness, Desire, Knowledge, Ability, and Reinforcement.
- According to the *six-step change management model* (Beer et al. 1990), change is realized by solving concrete business problems. The first step is to diagnose the specific problem. The definition of the problem situation then helps to create commitment to change. Then, a vision of change is developed that defines new roles and responsibilities. Next, the vision should be properly communicated to stakeholders to gain support and consensus. The change is now implemented and, in a next step, institutionalized with formal systems. Finally, the progress of the change process is monitored and adjustments are made if necessary.

Most change models proposed for digital transformation combine elements of these classic models. For example, Hess et al. (2016) identify four dimensions of a digital transformation framework. These four dimensions are the use of technology, changes in value creation, structural changes, and financing digital transformation. First, the firm should determine a strategy for the use of technology: Companies can either create their own technology standards and become market leaders, or serve and adapt to already established standards. Then, using new technologies means changing the value proposition of the company. Structural changes, i.e., "variations in a firm's organizational setup" (Hess et al. 2016, p. 341), have to be considered, as digitizing products or services requires a recalculation of the existing business scope, as potentially new customer segments are taken into account. Subsequently, an assessment of whether products, processes, or capabilities are primarily affected by the changes will further determine the scope of the restructuring. Substantial changes may require the creation of a separate division within the company, while limited changes are more likely to require the integration of new activities into the existing company structure. Finally, taking into account these three dimensions of the transformation process, the financial aspects, which are both drivers and constraints of the transformation, are analyzed (Hess et al. 2016). An assessment of all these four dimensions helps companies to formulate a company-specific strategy for digital transformation.

The model proposed by von Leipzig et al. (2017) also focuses on the initial phase of developing a digital strategy as a starting point for digital transformation. Following Deming's Plan-Do-Check-Act (PDCA) cycle (Deming 1982), it postulates an iterative rather than a linear process for initiating digital transformation. To successfully overcome the challenges of digital transformation, in the first stage, managers should be aware of the need to change their existing business plan by analyzing customers, the market, competitors, as well as other industries, as customers may expect the same level of digital services regardless of the industry (von Leipzig et al. 2017). In the second stage, benchmarks should be used to compare their position with other companies and analyze strengths and weaknesses. In the third stage, an assessment of the costs resulting from selected changes in the business model will then prepare the implementation of the digital strategy. In the fourth stage, feedback mechanisms include customer and employee perceptions and comparisons with peers. With each subsequent iteration, the company should elaborate on the feedback and adjust its capabilities.

Sebastian et al. (2017) propose a process model of digital transformation for large incumbents based on two distinct strategic priorities: a customer engagement strategy and a digital solutions strategy. A customer engagement strategy aims to deliver a superior, innovative, personalized, and integrated customer experience through an omnichannel experience that allows customers to order, inquire, pay, and receive support in a consistent manner from any channel. A digital solutions strategy, on the other hand, is appropriate when the company's value proposition is reimagined through the integration of products, services, and data. The core of this digital strategy is anticipating customer needs rather than reacting to them. In the first phase of a digital transformation process, companies must therefore make the right assumption about their future by choosing one of the two strategic priorities. The second stage is to build an appropriate operational digital backbone, such as a customer database to access customer data and/or a supply chain management system to provide transactional visibility. The third step is to build a digital services platform, which means setting up APIs to access the necessary data. With the help of IT partners, companies can then build the infrastructure to analyze and support the digital services. In Phase IV, the digital services platform is further deployed, integrating the needs of customers and stakeholders. Finally, in Phase V, a service culture should be instilled from the top down. It is crucial that business and IT teams work together to create and deliver business services, as "designing around business services will become the way most companies do business" (Sebastian et al. 2017).

In summary, process models are an important consideration for organizations seeking to undertake digital transformation. Process models provide a structured approach to guide digital transformation efforts and can help organizations identify and prioritize digital opportunities, implement and scale digital initiatives, and measure and track progress. It is important for organizations to carefully select and tailor a process model that aligns with their specific needs and goals, and to be aware of the limitations and challenges of each model. Process models should also be flexible and adaptable in the face of changing circumstances in order to continuously learn and improve the model as needed.

However, even when following a specific process model for digital transformation, established organizations can fail (Brenk et al. 2019). In a recent study, Moschko et al. (2023) investigate why organizations fail to achieve their initial ambitions for a digital transformation process. They build on the observation that managers often perceive tensions when engaged in a transformation process (Appio et al. 2021; Brenk et al. 2019; Moschko et al. 2013). To examine these tensions, Moschko et al. (2023) turn to paradox theory (Hahn and Knight 2021; Lewis and Smith 2014). Paradoxes are "contradictory yet interrelated elements that exist simultaneously and persist over time" (Smith and Lewis 2011, p. 382). These paradoxes cause actors to experience tensions, "defined as stress, anxiety, discomfort, or tightness in making choices and moving forward in organizational situations" (Putnam et al. 2016, p. 68). For leaders, tensions are problematic trade-offs that need to be resolved or avoided during a change process. Attempts to resolve one of these tensions and paradoxes often create others, resulting in what are known as knotted paradoxes (Smith and Lewis 2022), which can occur at multiple levels—from the individual to the organization to society. As Moschko et al. (2023) show, the notion of (knotted) paradoxes can help managers shift their conceptual frameworks to better understand the complexity and interdependent dynamics of transformation processes. Thus, the development of a paradoxical mindset supports managers in successfully executing a digital transformation process.

4.3 Digital Maturity

A final concept from the digital transformation discourse is the idea of digital maturity assessments. The term *digital maturity* refers to "the ability to respond to the environment in an appropriate manner through (digital) management practices" (Bititci 2015). Digital maturity models are frameworks that assess an organization's current level of digital maturity and provide a roadmap for improving digital capabilities. The models typically distinguish different levels of digital maturity, each representing an increasingly advanced level of digital capabilities. One of the most prominent models was developed by MIT's Center for Information Systems Research (CISR), based on research into the digital practices of leading companies (Westerman et al. 2011). It differentiates digital maturity into two dimensions, digital intensity and transformation management intensity. Companies that are mature in the digital intensity dimension invest in technology-enabled initiatives with the goal of changing the way the company operates, i.e., customer engagement and internal operations (see Fig. 2). The second dimension, transformation management intensity, addresses the creation of leadership capabilities needed to successfully execute a digital transformation. Transformation intensity involves a strategic vision of the planned digitalization, the necessary governance and commitment, and the relationships with IT and business partners implementing technology-driven change (Westerman et al. 2011).

Depending on the level of digital maturity along these two dimensions, the authors differentiate five different maturity stages, each representing a progressively more advanced level of digital capabilities:

Level 1: Digital Novice: These are organizations with only limited digital capabilities, focused on automating existing processes.
Level 2: Digital Apprentice: At this level, organizations are starting to explore new digital technologies and are beginning to integrate them into their operations.
Level 3: Digital Practitioner: These are organizations that have established a strong foundation of digital capabilities and are actively seeking out new digital opportunities.

Maturity Dimension	*Digital Intensity*	*Transformation Management Intensity*
Indicators	Technology-enabled initiatives in: - Customer Engagement - Internal Operations	Leadership capabilities including - Vision - Governance - Engagement - IT-Business Relationships
Examples	Location-based marketing, connected products, mobile sales, digital design, real-time monitoring of operations	The vision of firm's future, evolving the culture, cross-silo coordination, new skills

Fig. 2 Digital maturity dimensions (Westerman et al. 2011)

Level 4: Digital Experts are organizations that have fully integrated digital technologies into their operations and are continuously innovating and experimenting with new digital initiatives.

Level 5: Digital Leader: At this level, organizations are a leader of digital practices in their industry ("lighthouse sites") and are driving industry-wide digital transformation.

Organizations can use a digital maturity model to assess their current level of digital maturity, identify areas for improvement, and develop a roadmap for improving their digital capabilities. The model is particularly useful for organizations that want to understand how their digital capabilities compare to those of their peers and competitors, and to identify areas for investment and improvement. Figure 3 shows another maturity model for digital transformation, based on different dimensions of an organization that are impacted as the transformation progresses (Azhari et al. 2014). The authors depict eight dimensions of digitalization, namely strategy, leadership, products, operations, culture, people, governance, and technology. Organizations are assigned to one of five maturity levels, depending on the extent to which the dimensions are met. Companies classified as unaware are those with little or no digital capability. They lack awareness of the need for digital transformation. Companies at a conceptual level are typically those that offer a few digital products but do not yet have a digital strategy. Those with a defined level of digitalization are companies that have already gained experience with pilot implementations and have partially formed a digital strategy. At the point where a clear digital strategy is developed, an organization is classified as integrated. Finally, a transformed company is one that has fully implemented the digital strategy into its operations and business processes.

In the more specific context of the manufacturing sector, the term Industry 4.0 has been used to describe the digital transformation of manufacturing. Increasingly, research examines digital readiness in the context of Industry 4.0 to assess whether manufacturing firms have the necessary capabilities to undertake this transformation. The "Industry 4.0 Maturity Index" (2016), developed by the FIR Institute at RWTH Aachen University, illustrates a step-by-step approach to implementing Industry 4.0.

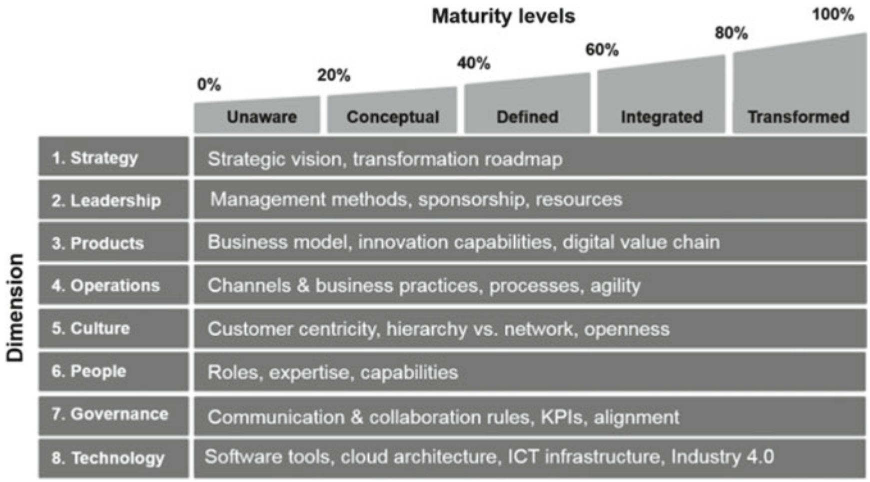

Fig. 3 Digital maturity of an organization (Azhari et al. 2014)

The maturity model has already been validated in manufacturing companies. It integrates the entire value creation process within the company, including development, logistics, production, as well as service and sales. In each of these areas, a comprehensive analysis of the respective Industry 4.0 maturity level is carried out. The steps that move a company from Industry 3.0 to Industry 4.0 are based on its use of data and analytics to gain visibility into its manufacturing processes, transparency into what is happening and why, predictability of future states and events, and finally adaptability, i.e., the ability to generate data-driven prescriptions for future behavior.

Another maturity model in the context of Industry 4.0 is the "IMPLUS—Industry 4.0 Readiness" model (Lichtblau and Stich 2015). The authors distinguish six levels of readiness, ranging from "Level 0: Outsiders" to "Level 5: Top Performers." The authors developed a questionnaire as a tool to measure the structural characteristics of the companies, their knowledge about Industry 4.0, their motivations and obstacles during the Industry 4.0 journey. Furthermore, the companies are grouped into high-level categories as newcomers (level 0 and 1), learners (level 2), and leaders (level 3 and above). Newcomers consist of companies that have never initiated any projects, learners are companies that have initiated their first projects related to Industry 4.0, and leaders are companies that are compared to other advanced companies in their projects to implement Industry 4.0 initiatives. The dimensions of the questionnaire are: "smart factories," "smart products," "data-driven service," "smart operations," and "employees." Using the model, company profiles and main barriers in the listed dimensions are identified, which serve as a basis for creating action plans for companies to improve their Industry 4.0 readiness (Lichtblau and Stich 2015).

Inspired by this stream of digital transformation research, future research could develop an organizational transformation maturity model to assess an organization's current level of readiness and capability to undertake organizational transformation efforts, and to provide a roadmap for improving these capabilities. Such a model could be particularly useful for organizations seeking to understand how their transformation capabilities compare to those of their peers and competitors, and to identify areas for investment and improvement. The model would consist of different levels of maturity, each representing an increasingly advanced level of readiness and capability for organizational transformation. However, simply translating Westerman et al.'s or other digital maturity models into an organizational transformation setting is probably not enough. A more sophisticated approach would also take into account the goals of the transformation process, i.e., the realization of societal goals (e.g., sustainability goals), and the extent to which the transformation progress has enabled novel approaches to achieving these goals. In a further step, such a model could also enable an ex-ante simulation of potential transformation activities, predicting the impact of their successful implementation on these overall objectives. However, building such a model is a complex undertaking that requires a large interdisciplinary research consortium.

5 Conclusion

Organizational transformation can be a complex and challenging process, as it often involves significant changes to the way work is done and can have a major impact on employees, customers, and other stakeholders. While there is a large body of existing research, our review of selected literatures indicates a number of areas where more research could be fruitful. One important question for future research is how organizations can sustain transformational change over the long term. Many organizations initiate change programs that are successful in the short term, but fail to achieve sustained change over the long term and reach their initial higher ambitions (Moschko et al. 2023). It is important to understand the factors (and their antecedents) that contribute to successful long-term transformation, like leadership commitment, employee engagement, and alignment of organizational culture with the desired change.

Secondly, research is required how to effectively manage resistance to change. Resistance to change is a common phenomenon in organizations and can significantly impede the success of transformational initiatives (Antons and Piller 2015). Understanding the sources of resistance, as well as effective strategies for managing it, is critical for successful organizational transformation. Related to this issue is future research how to effectively measure the impact of organizational transformation in order to steer the change initiative, but also to measure the effectiveness of countermeasures against resistance to transform. Measuring the success of organizational transformation is challenging, and traditional metrics such as financial performance may not provide a complete picture of the impact of transformation on the organization. Future research should focus on developing more comprehensive measures of the impact of transformation on organizational culture, employee engagement, customer satisfaction, and other key performance indicators.

Another important question is how to effectively manage the human side of organizational change at the micro-level. Transformational change can be stressful for employees, leading to anxiety, uncertainty, and resistance. Future research should focus on identifying effective strategies for managing the human side of organizational change, including communication, training, and support for employees. Related to this is the question of how to effectively manage the cultural aspects of organizational change. Organizational culture is a critical factor in the success of transformational initiatives. Future research should focus on identifying effective strategies for managing the cultural aspects of organizational change, including leadership development, communication, and employee engagement.

Answering these and many other questions will provide management scholars and the audiences they address (academia, but especially corporate managers and stakeholders) with the insights needed to manage the complex process of organizational change and transformation. Given the need for organizations to master the current digital (AI) revolution alongside their mandatory sustainability transformation (and addressing all 17 of the United Nations' social development goals), we believe that those organizations that strive and succeed will be those that have first acquired the skills and behaviors to master second-order change.

To conclude our chapter, we asked the institution that is perhaps most transforming our personal lives as academics these days, the *ChatGPT Transformer Language Model* (Bouschery et al. 2023), to list the top five success factors for organizational transformation. We'll end our chapter with its response—because we couldn't have summed it up better:

In summary, these are the top five success factors for organizational transformation:

Resistance to change: People are often resistant to change, especially if it involves significant disruptions to their work or lifestyle. Organizations may need to overcome this resistance by communicating the benefits of the transformation and helping employees understand how it will impact them.

Communication: Ensuring that all stakeholders are kept informed about the transformation and its progress is crucial. This can be particularly challenging in large organizations with multiple levels of management and employees working in different locations.

Managing the change process: Effective change management is key to ensuring that the transformation is successful. This includes identifying the steps needed to implement the changes, establishing a timeline for the transformation, and providing resources and support to those affected by the changes.

Maintaining momentum: It is important to keep the momentum going during the transformation process. This can be challenging, especially if there are setbacks or delays.

Measuring success: Establishing clear metrics for measuring the success of the transformation is important. This can help organizations determine whether they are achieving their goals and make necessary adjustments as needed.

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Transformation of Work in the Textile Industry: Perspectives of Sustainable Innovation Processes

Andrea Altepost, Adjan Hansen-Ampah, Wolfgang Merx, Stefan Schiffer, Bernhard Schmenk, and Thomas Gries

Abstract What makes innovation processes in industry succeed? The basic assumption of this paper is that not only technological, but also social—especially work-related—factors have a decisive impact. While processes of sociotechnical system design are established interdisciplinarily and have arrived at least in many large companies, to the best of our knowledge it still is a novelty in industrial contexts to also add the concept of sustainability to this perspective. Energy and circular economy as well as a shortage of skilled workers dominate the concerns of companies. At the same time, technologies such as artificial intelligence (AI) are traded as a beacon of hope to strengthen competitiveness and contribute to more efficient, resource-conserving economic activity (e.g., Lukic et al., BCG 10.01.2023, 2023).). With the design of AI-supported work systems in the textile and related industries, the WIRKsam Competence Center for Work Research wants to show how the use of artificial intelligence, with appropriate work design, can promote both innovative, human-centered work and economic competitiveness, so that the two benefit from each other. The project aims to strengthen the industrial backbone of the Rhenish mining area and to create attractive conditions and opportunities for skilled workers. In this way, a sustainable result of the various transformation levels in the area of structural change, digitalization and the future of work can be achieved, which lays the foundation for shaping further future transformation processes in an innovative way. In this paper, we develop central questions originating from this claim that need to be considered in the aforementioned transformation processes in the areas of people, technology and organization, because they can be decisive for success.

Keywords Transformation · Work · Artificial intelligence · Living Labs · Structural change · Sustainability

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P. Letmathe et al. (eds.), *Transformation Towards Sustainability*,
https://doi.org/10.1007/978-3-031-54700-3_12

1 Introduction

This paper elaborates on a number of transformational issues that arise when AI is to be deployed in a work system. In November 2021, the starting signal was given for WIRKsam, a competence center for work research on the use of artificial intelligence (AI). It is designing and researching AI-supported work in companies in the Rhenish mining area, a traditional coal and textile area which is at the beginning of a far-reaching structural change due to the phase-out of lignite mining. Up to now, the identification of production-related and work-science objectives, the concretization of applications and the analysis of the current situation dominate the current work. Currently these activities raise more questions than expert knowledge and analyses can answer. There are both case-specific and generic questions arising as to how the individual company changes can succeed in the context of the overarching transformation processes—in particular digitalization, transformation of the world of work, sustainability and social megatrends such as demographic change. Systematizing and connecting these transformation processes by means of solution approaches and iterative testing is an initial added value of the WIRKsam approach. Facing the pressure of the narrative “If you don’t use AI, you won’t survive in the competition”, companies and employees are usually unable to raise these questions themselves for a variety of reasons and they are therefore unable to work competently on the conception and implementation of their change. Not only do they lack experience and knowledge regarding artificial intelligence, they are often also unfamiliar with the sociotechnical perspective, the options for the design of work and the organization with help of the new technology—only if these prerequisites are met, it is possible to truly establish innovative changes in the company that exploit the opportunities offered by the technology. In this article these questions are derived step by step. As far as already possible, we present first approaches to solutions. Section 2 first introduces the initial situation in the Rhenish mining area as well as the structure and goals of the competence center. Section 3 sheds light on the transformation of work in line with the so-called MTO principle of ergonomics (*Mensch, Technik, Organisation*; Strohm and Ulich 1997; Ulich 2013) from the perspectives of people, technology and organization as well as their interactions. We explore the question of how these perspectives are interwoven with the above-mentioned transformation aspects, which role technical and social innovations play in this process, and what this implies for the adaptation of companies to the changing conditions. The subject of Sect. 4 is the approach taken in WIRKsam. First, we show how we apply the MTO aspects in the WIRKsam procedure model. We then introduce the WIRKsam living lab as the crystallization point of the research effort as well as the joint, participative development of work systems together with companies, employees and further stakeholders in the Rhenish mining area.

2 The WIRKsam Competence Center Between Initial Situation and Transformation Tasks

2.1 Initial Situation

Innovative technologies such as artificial intelligence are seen as having great potential for overcoming economic, ecological and also social challenges (e.g., PLS 2022; Zukunftsagentur Rheinisches Revier 2021: 79). AI offers a wide range of technologies that can address an extremely broad spectrum of use cases. This makes it the subject of auspicious promises (Heinlein and Huchler 2022: 6) as well as horror scenarios (e.g., Bitkom n.d.). We agree with the authors of the KI.Me.Ge position paper that public discourse needs dialog formats and platforms (Heinlein and Huchler 2022: 7). Work-related AI applications are no exception. In order to promote a realistic approach to AI technologies and an informed debate, we have to take into account two things at the same time. For one, we see the very personal experience of those involved as a central key to making the subject of the debate tangible. Moreover, essential characteristics and effects of AI technologies can be shaped and need to be shaped. Thus, the use of technology alone does not automatically create an improvement in competitiveness. It is linked to various design parameters in the company, such as the working conditions, interests and expertise of the employees. Gondlach and Regneri (2021:5) cite results of a study by Bitkom Research (Berg and Dehmel 2020) and conclude "that any fears such as those of more control or misuse of data do not represent reservations about technology, but mistrust of the people who have the power to use the technology maliciously". From the point of view of the sociology of technology, this is a very narrow perspective since it does not take into account the options for action that are already inherent in technology and a "co-action" of technology (cf. e.g., Rammert and Schulz-Schaeffer 2002: 23). However, engaging in this discussion would certainly go beyond the scope and the context of this paper.

With its funding line "Zukunft der Wertschöpfung - Zukunft der Arbeit: Regionale Kompetenzzentren der Arbeitsforschung", the German Federal Ministry of Education and Research (BMBF) has created an instrument that makes it possible to test and research the design of new forms of work in the context of AI deployment. Four of the competence centers also address the profound structural change implied by the imminent phase-out of lignite mining (Presse- und Informationsamt 2023). One of these is the WIRKsam competence center in the Rhenish lignite mining area between Aachen and Düsseldorf/Cologne. Here, a far-reaching structural change is imminent as a result of the phase-out of lignite mining. Many hopes for strengthening competitiveness are therefore pinned on the use of innovative technologies such as artificial intelligence (e.g., Zukunftsagentur Rheinisches Revier 2021: 79). At the same time, the Rhine Valley is a traditional area of the textile industry, which offers an ideal testing ground for the use of artificial intelligence due to its enormous spectrum of production and finishing processes. The wide range of possible applications for AI can be mapped here to the greatest extent possible. WIRKsam's use cases were therefore selected from the textile industry and related sectors. The fact that the textile industry still exists in the area today is due to its high plasticity in the structural change processes of past decades (Presse- und Informationsamt der Bundesregierung 2023). This industrial branch has been affected by serious processes of structural change, which have manifested themselves, for example, in the relocation of further production and market shares to Asia, pressure to automate due to German wage rates or also changed demand for textile products. In this case, the success of the transformation is measured in terms of economic competitiveness or—to put it in a nutshell—the survival of the company. In the service of this goal, traditional cotton and silk weaving, for example, was largely replaced by the development and production of technical textiles. Another example is automation technology: Originally introduced to increase the efficiency of needle production, it became a successful product in its own right. New customers and markets were accessed, and new needs were addressed, for example in medical technology or in the construction industry. Along with the products and markets, the production processes innovated as well, with the result that the textile industry in Germany today stands as a high-tech sector with an enormously wide range of applications "from heart valves to tailgates", in the construction sector and also in textile machine construction.

Nevertheless, the sector, like all other industries, is facing further challenges for change. The structural change itself is ultimately part of the desired climate and energy turnaround in Germany, which, by legal means, but also for marketing reasons, points to the need to integrate sustainability criteria into corporate strategy. The phase-out of lignite mining is forcing entire regions and their companies to reorient themselves. The Russia-Ukraine war is further exacerbating the problem and causing supply chains that were already severely affected by the COVID-19 pandemic to collapse. This is accompanied by changes in legislation (e.g., Climate Change Act, Supply Chain Act) to which companies must respond. The pandemic also highlights another key problem for industry: the shortage of skilled workers. High levels of sickness during the pandemic made the lack of qualified personnel and young people interested in working in the (textile) industry visible, which actually is a permanent problem, not least against the background of demographic change in Germany. The textile sector is particularly affected by this, as its average age is even higher than in other industries (e.g., Flaspöler and Neitzner 2020: 7). Suppliers to the lignite industry in particular are faced with the task of "opening up new innovation and business fields and proactively shaping structural change" (Mine ReWIR n.d.). The textile industry can not only contribute its strengths and experience from previous structural change processes. With its high demand for skilled workers and great economic potential, the textile industry and related economic sectors offer valuable future prospects for the employees affected by the lignite phase-out, but also for the companies in the entire Rhenish mining area, which WIRKsam helps to develop in cooperation with other regional actors and initiatives.

2.2 *Competence Center WIRKsam*

AI is changing work: an often-repeated postulate. But how exactly does this happen? And what scope is there for using the opportunities offered by technologies to achieve economic and work-related goals without relinquishing control over possible risks?

These are the central questions that the WIRKsam competence center is addressing. From its perspective, talk of the transformation of work means that it does not passively suffer technology-induced changes, but that work must be actively designed with the interests of stakeholders, especially employees, in mind. Therefore, design potentials for the development of innovative work and process flows with artificial intelligence are identified and prototypically implemented in the production environments of application partners. The focus is on three operationally relevant fields of action:

- securing and transferring knowledge,
- planning and making processes more flexible and
- securing and increasing product quality.

Three research partners—Institute for Applied Work Science (ifaa), Mobile Autonomous Systems and Cognitive Robotics, Institute of Aachen University of Applied Sciences (MASKOR), and Institute for Textile Technology of RWTH Aachen University (ITA)—are therefore working in WIRKsam to develop innovative work and process flows with artificial intelligence—together with companies from the Rhenish mining area and their employees. The starting point is the operational problems of currently nine application companies. While MASKOR is driving forward the custom-fit design and selection of suitable AI processes, it is the responsibility of three IT companies (so-called "enablers") to implement the systems on site in the application companies and to integrate them into the textile production process in collaboration with specialists from textile technology. Ifaa and a work-science team at ITA are responsible for designing and researching the work-science aspects. Together with employees, managers and other stakeholders of the respective company, the conception and design of AI application and work design as a sociotechnical system are practically implemented and scientifically researched in the concrete use case. In this way, the transformation of work, the digital transformation and the economic transformation are intertwined within the framework of structural change since, as we mentioned before, innovative digital technology in particular is expected to help in addressing economic challenges and implementing solutions. However, digitalization in itself also represents a transformation and a challenge for companies. A widespread approach to manage this transformation is technology consulting, e.g., based on maturity models that determine the current level of digitization in companies and derive recommendations for action to solve operational issues with digital technologies (Bitkom and DFKI 2017; Bitkom 2022). In times of a shortage of skilled workers in industry, however, it is also becoming increasingly clear that the digital transformation—especially superimposed by the other disruptions described above—poses considerable challenges for employees and managers. In this respect, WIRKsam resorts to the idea of the “MTO approach” (Strohm and Ulich 1997; Ulich 2013). This abbreviation stands (in German) for Mensch (German: human), Technik und Organization (German: technology and organization). It aims to develop a holistic understanding of a work system and to address human-related, technical and organizational factors in an integrated manner. An overarching process model ensures systematic implementation. We will discuss this in more detail in Sect. 3. Against the backdrop of the structural change situation described in Sect. 2.1, the task is to go beyond the individual use cases and make companies fit for the future by not only exploiting the opportunities offered by AI technologies in the best possible way, but also by developing competencies and mindsets that will also enable companies to cope with future innovations. After completion of the funding phase (until October 2026), the competence center is to be permanently anchored in the Rhenish mining area.

2.3 WIRKsam in the Context of Transformation Tasks

Each of the transformation events in the Rhenish mining area, as has already become clear in the previous sections, can be broken down analytically into various aspects of transformation, but these develop in strong mutual dependence. In this paper, we therefore dare attempt to trace the transformation of labor in the context of the interconnections of the diverse transformation strands or areas where there is pressure to transform, using the exemplary WIRKsam project with its holistic claim. In this section, we will first summarize the content of WIRKsam and situate it in the various transformation strands, which also include sustainability issues. We will then refer to the three levels of the Aachen Transformation Model.

The central theme of WIRKsam is the transformation of work in the context of the use of artificial intelligence. This does not necessarily mean a causal chain in which problems in production are solved by AI, which in turn creates the impetus to change work. In fact, reasons lying in the work context, such as heavy demands on employees due to errors in human-made process planning can also initiate the introduction of an AI system. We have already touched on the fact that the initial situation in the Rhenish mining area includes other drivers for far-reaching changes in the area’s work environment; for example, structural change with changes in demand with regard to relevant qualifications, the shortage of skilled workers and social changes concerning the value and characteristics of work, but also the need to take ecological sustainability aspects into account in corporate strategy, as mentioned in Sect. 2.1. How these drivers, (AI) digitalization and work design are interlinked is an interesting question in itself, which can be explored in the scope of WIRKsam using the application examples. The participatory approach of the competence center is particularly suitable for this purpose, in which the interests of the various stakeholders as spearheads of these dynamics play an essential role. More precisely, one could ask whether and how structural change activities in the mining areas as an overall transformation shape these interrelationships in a specific way. A variety of arguments are put forward in favor of digitalization in industry, even beyond structural change. A particular argument is strengthening of the competitiveness of companies as we pointed out above. For lignite suppliers undergoing structural change, new business models play a major role here in addition to classic efficiency gains, such as changes to the product portfolio and orientation toward other regional markets. While job losses due to loss of competitiveness and/or changes in qualification requirements are feared by suppliers, there is a shortage of skilled workers elsewhere, and the textile industry in particular is facing the problem that the age development already described years ago (e.g., Altepost et al. 2017) is now manifesting itself in concrete retirements of considerable parts of the workforce. The preservation of their experiential knowledge is therefore also an urgent requirement for all WIRKsam partner companies. Added to this are resource and energy problems, as described in Sect. 2.1, as well as other social megatrends including the transformation of social value systems, e.g., the demands of employees for work-related aspects—among others academization and work-life balance—or the greater involvement of men, also via legislation, in family care tasks with help of parental leave. Reducing the workload of the remaining skilled workers, qualifying them for new technologies and new tasks and increasing the attractiveness of industrial jobs are therefore also objectives that WIRKsam's partner companies hope to meet during the digital transformation, often by using artificial intelligence. To extrapolate this into a generic ability to address social and technological change in the future and to shape it ourselves, sustainability seems to us to be a key, not only in the ecological sense, which we want to bring into the innovation processes in companies with WIRKsam. In the following section, we clarify the concepts that are fundamental to the relevant transformations: sustainability, artificial intelligence and work design.

2.4 *Central Terms for the Transformation of Work in the Context of Further Transformation Processes*

In this section, we will first go into detail about sustainability. Then, we will lay out our understanding of artificial intelligence and how it relates to sustainability and to transformation processes. Third, we explain the ergonomic basis of the WIRKsam approach, the MTO principle for analyzing and designing work systems.

Sustainability

Sustainability is, without a doubt, one of the most often used and most important terms of our time. Already in 1995, the German news magazine "Der Spiegel" went so far as to dub *Nachhaltigkeit*, the German word for sustainability, "Wort des Jahrhunderts"[1] (Der Spiegel 1995, p.14). An effect of the cultural, societal and political importance of the term is a multiplicity of different meanings, interpretations and concepts (Grober 2010). This becomes especially evident when comparing today's

[1] Translation: "Word of the Century".

most common everyday use of sustainability, i.e., referring to concepts geared toward overcoming ecological issues and crises, with its initial meaning, which can be understood as the concept of (economic) consistency and longevity. In what follows, we very briefly outline the development of sustainability as term and concept before coming to our understanding of AI.

The term (and concept of) sustainability was coined by Carl von Carlowitz in 1713 with regard to forestry (Dieckmann von Brünau 2013). His goal was to achieve a form of forest management which allows for "nachhaltende Nutzung" (von Carlowitz 1732) of trees in order to ensure long lasting (financial) yield. To achieve this goal, von Carlowitz postulated that the number of trees logged should be limited to the amount of trees regrowing, thereby guaranteeing a continuous and long-term supply of wood (von Carlowitz 1732). Von Carlowitz combined this forest management concept with socio-ethical principles and suggestions concerning energy efficiency, e.g., the usage of fuel-efficient ovens, and the substitution of wood with other sources of fuel, e.g., turf (Grober 2010). Even though these combined efforts seem modern, even by today's standards, and could be regarded as the predecessor of sustainability models such as the "Triangle of Sustainability" or the "Three Pillars of Sustainability", they focused clearly on economical and not ecological or social issues (Dieckmann von Brünau 2013, p. 8; Grober 2010). It was not until 1972, when the Club of Rome (CoR) introduced its report "The Limits to Growth" (Meadows et al. 1972), that sustainability started to gain the political dimension the term bears today (Meyer and Hansen-Ampah 2019). The report states that growth—referring to economic and population growth alike—is, in fact, not infinite but limited by the natural resources of our planet (Meadows et al. 1972). While von Carlowitz construes natural resources as local and as something that can be exploited for economic profits, CoR conceptualizes natural resources and the effects of their exploitation globally and in terms of the capacity of these resources to sustain life. This is exactly why pollution is the central ecological factor and a central element in CoR's report. Even though "The Limits to Growth" offers no formal definition of sustainability, the adjective *sustainable* and the verb *to sustain* are used throughout the report to delineate a "world system that is: 1. sustainable without sudden and uncontrollable collapse; and 2. capable of satisfying the basic material requirements of all of its people" (Meadows et al. 1972, p. 158), thereby combining von Carlowitz' economic stance with newfound ecological and, in part, social considerations. In 1987, the UN Commission on Environment and Development (WCED) further expanded CoR's position by taking intergenerational justice into account. In its report "Our Common Future", also known as the "Brundtland Report", the WCED (1987, p. 36) offers the first definition of *sustainable development* as development that meets the needs of the present without compromising the ability of future generations to meet their own needs. It contains within it two key concepts:

- the concept of 'needs', in particular the essential needs of the world's poor, to which overriding priority should be given; and
- the idea of limitations imposed by the state of technology and social organization on the environment's ability to meet present and future needs.

The fact that the "Brundtland definition" remains unspecific for the most part, neither people's needs nor the means to meet them are defined, has both benefits and drawbacks. The main advantage is that the definition encompasses any and all economic, ecological and social factors which prove to be detrimental to next generations' well-being, e.g., pollution, child labor, or CO_2-induced climate change. The chief disadvantage of the open definition is that it offers no insights on which factors to consider, how they should be weighed and prioritized, which specific goals should be achieved and how to do so. This, in turn, led to definitions and models such as the aforementioned "Triangle of Sustainability" and "Three Pillars of Sustainability" which, on the one hand, further emphasize the different subsystems (social, economic and ecological) which should be addressed. On the other hand, domain-specific definitions, which focus on certain aspects such as resource efficiency or sociopolitical dimensions (Opielka 2017; Renn 2017), have been developed. One of the most recent and important additions to the conglomeration of sustainability concepts are the 17 Sustainable Development Goals (SDGs) and their accompanying 169 targets developed by the United Nations (2015). Although these SDGs do not comprise a definition, as the denomination suggests, they incorporate many of the aspects found in the definitions and concepts of the previous decades and make clear what should be understood as sustainable development (see Fig. 1).

Although the SDGs offer a clearer understanding of the specific areas in which sustainability should be achieved than previous concepts, they nonetheless can be regarded as an elaboration of the three domains of sustainability mentioned

Fig. 1 Graphic depiction of all 17 Sustainable Development Goals (United Nations 2015, p.14)

above, namely social, ecological and economic sustainability. Therefore, the criticism voiced by Opielka (2017) concerning models that are based on the aforementioned tripartite extends to the SDGs as well. He states that such models inherently create a twofold opposition. The first opposition is between social and economic sustainability, which creates a phenomenon well-known as class antagonism. Opielka locates the second opposition between the aforementioned area of tension (class antagonism) and ecologic sustainability. One of the results of this "double ambivalence" (Opielka 2017, p. 11) is ecological standstill, an effect that currently becomes evident in the political decisions and concessions made by Germany's Green Party. These oppositions can not only be witnessed on a societal level, but also on the level of individual companies. On the one hand, entrepreneurs and managing boards are interested in financial profit and the economic sustainability of their companies. On the other hand, works councils and unions are interested in the well-being of employees. As before, ecological sustainability is not in the position of a "laughing third party" but instead takes a back seat behind the other interests. Instead of conceptualizing the three pillars of sustainability as a postulate which states that these three domains constitute a conflict-free sustainability strategy, we understand the model as a typology which explicitly allows for conflicts between the pillars. Such conflicts can be witnessed in use cases in which the AI in question causes decreased production output, e.g., due to the added computing time for quality control. In such cases, production managers might urge the argument that the company's economic standing suffers from such an AI-based innovation of work. The shop floor employees, on the other hand, benefit from the innovation since the new system takes over tasks which are deemed monotonous, physically or mentally demanding, or even hazardous to health. In other cases, the AI helps to increase production output, e.g., due to faster and more precise machine settings, at the cost of higher energy consumption due to new and powerful computer hardware. The first example results in a conflict between the pillars of economic and social sustainability while the second results in a conflict between the pillars of economic and ecological sustainability.

Even though management prototypically focuses on economic sustainability and workforce, and its representatives favor the social pillar, the questions of prioritization and mutual dependence between them cannot be answered in a fully generalized sense. This is because ever-changing external factors (cp. Geels 2014) such as the Russo-Ukrainian War, demographic change, or changed legal frameworks heavily impose a shift in strategy. This can mean that a once neglected pillar suddenly gains importance and thus is highly prioritized by a company, as can be observed regarding the shortage of skilled workers and the corresponding concessions some companies are now willing to make. Aside from adapting to these external factors, every company must find its own way to deal with potential or manifest conflicts between the pillars, to prioritize its sustainability goals for itself and to re-produce or modify this prioritization in accordance with the prospect of success concerning specific measures and strategies as well as the organizational values and the willingness and capability to invest resources in order to live up to them.

Concerning the conflicts and interdependencies between the pillars addressed in the examples, we received the note that a systemization of these would be interesting.

We agree. However, such a systemization is not possible in the scope of this contribution due to the multitude of aspects which are covered. We will gladly provide the outcomes of our research in WIRKsam for a potential meta study.

2.5 Artificial Intelligence

Since the WIRKsam competence center will look at how artificial intelligence will change or even transform work and processes, this notion is central. The term artificial intelligence was coined by John McCarthy and colleagues in a research proposal from 1955 (McCarthy et al. 2006). While there is no single, commonly agreed upon definition of AI, in this chapter we refer to it and understand it as the set of techniques required to create intelligent behavior in artifacts following a description by Nilsson (1998). From today's perspective we are still nowhere near replicating human-level intelligence in machines, not in acting and clearly not in thinking. That is why we restrict the level of intelligence of artificial intelligence in the discussion to the concept of acting rationally in a technical sense (i.e., not in the sense of sociological terms of rational choice). That is, we want a computer program to act as a rational agent, capable of goal-directed behavior that selects its action to optimize some performance measure. For a more detailed account we refer the reader to Russell and Norvig (2020). The European Union set up a high-level expert group on AI. This group compiled a definition of AI (High-Level Expert Group on Artificial Intelligence 2019) that tries to convey a basic and joint understanding that can be used as a common base for future discussions and the group's work. In a similar effort Kersting et al. (2019) present their view on what constitutes the field of artificial intelligence. In principle, both assessments are in line with our understanding of what AI is.

Methods of artificial intelligence in the above sense cover a large area of topics, ranging from knowledge representation and reasoning over planning to machine learning. While the latter is overly prominent in today's perception of AI in the public, particularly in the form of deep learning, it only makes up a part of what techniques are used in AI. Furthermore, not all machine learning can be considered AI either. Humm (2020) presents a landscape of AI that shows the broad field of applications of artificial intelligence and the range of topics that it spans. Not all techniques applied in industry today strictly speaking are AI technology. Still, they are part of innovative technology that will change workplaces and that is part of the transformation and the transformation processes we are talking about.

2.6 Artificial Intelligence and Sustainability

The connection between sustainability and artificial intelligence can be described in two ways: Firstly, AI can help in achieving sustainability and the SDGs. Using computers to achieve sustainability is also referred to as computational sustainability.

An overview on the range of applications can be found, for example, in Lässig et al. (2016). Computational methods in general and methods from artificial intelligence in particular can support finding solutions to sustainability problems in all three domains. For instance, in the case of ecological sustainability an algorithm could compute where to put up windmills for maximum efficiency or machine learning can help in tracking climate change (Rolnick et al. 2022). Other examples, with a severe focus on machine learning, are given in (Nishant et al. 2020). Similarly with economic sustainability, AI methods from the field of optimization, planning, or scheduling can be used to solve a particular problem or to improve on a given situation. Even addressing multiple domains is possible. Imagine an AI algorithm computing different solutions to solving a problem where each solution is associated with additional information on the projected ecological, economic and social consequences. The role that AI can play in achieving the SDGs also has to be explored from a regulatory perspective (Vinuesa et al. 2020). Secondly, AI needs to adhere to sustainability principles, and it should contribute to the SDGs itself. This means that the AI being used or developed needs to be sustainable in itself and that the methods need to adhere to and to deliver on achieving the SDGs. How such sustainable AI might look like is, for example, discussed in van Wynsberghe (2021). As a general example, algorithms should be economical in using computational and other resources. Also, AI methods need to be comprehensible and transparent in order to contribute to the SDGs, for example in striving for decent work or to enable responsible consumption.

An overview of the area of explainable AI (XAI) can be found in Hagras (2018). Gade et al. (2019) consider what explainable AI might mean in industrial settings. Another example is the European Union's General Data Protection Regulation. The potential impact of that regulation in terms of explainability of AI is discussed in Goodman and Flaxman (2017).

2.7 Work Design—MTO Approach

The object of work design is the work system. A current definition of this is provided, for example, by the VDI-VDE guideline 7100 "Work design conducive to learning" (VDI 2022 based on DIN EN ISO 6385, 2.2): "Work systems include the interaction of workers and work equipment to achieve a work result within a specific (possibly also virtual) space and a specific (possibly mobile and distributed over several work locations) environment, as well as the interaction of these components within a (possibly network-like) work organization". The work system is thus a sociotechnical system, i.e., an "action or work system in which human and material subsystems form an integral unit" (Ropohl 2009: 141). Rammert (2016: 29) speaks of "socio-technical constellations" that can change dynamically. Accordingly, in the understanding of this paper, work design is "the socio-technical process of planning, designing and realizing work systems according to technical, economic, ergonomic and human-scientific findings and target criteria" (Landau and Weißert-Horn 2007). The work design in WIRKsam therefore follows the MTO approach (see Sect. 2.2). In line with the conception of the sociotechnical system or the sociotechnical constellation, the MTO approach is based on the idea that there are interactions and interdependencies between these three domains (see also e.g., VDI 2022; Dworschak et al. 2021; Hirsch-Kreinsen 2020). It is therefore based on the principle of analyzing and designing aspects from these three areas simultaneously in order to take these interactions into account. To ensure that this succeeds, the affected employees and other relevant stakeholders are included in the analysis and design. The MTO approach offers conceptual framing as well as tools to design the interaction of people and technology in a way that considers both work design standards and economic goals. This offers scope for design that is not always fully exploited in digitization processes. What is more, we will explain later that this approach in particular appears conceptually suitable for achieving several sustainability goals, either directly or indirectly. To outline the added value which is generated by referring to the complete set of M, T and O and their interrelations, an example will help.

One of WIRKsam's corporate partners is a metal weaving mill in Düren, Germany. In this use case, an AI solution is being developed to improve the quality control of automotive filters, resulting in a reduction of manual quality controls and thus stressful, monotonous activities (Ferrein et al. 2022).

Human-Technology Interaction

How do humans influence technology?

In accordance with the participatory approach in WIRKsam, employees are involved in technology development. They contribute their expertise to the design of the AI system, for example, concerning the work process, the detection features of possible errors in the filter to be assessed, and the decision criteria whether the filter is considered "i. O." (in order) or "n. i. O." (not in order), i.e., whether it is to be sold or not. In addition to these functional aspects, the employees also co-design aspects of the human-technology interaction, such as the scope and presentation of the information provided, menu structures, etc. The human-technology interaction is also influenced by the design of the AI system itself (and not just the user interface). Sustainable—meaning long term here—use of the work system is dependent on the AI being designed in such a way that it is deemed useful by the employees. Initial experiences in WIRKsam show that this approach to IT development is not a matter of course, even 40 years after the "Humanization of Work" funding program (cf. Delamotte and Walker 1976).

How does technology influence people?

Conversely, technology influences people: from the very beginning of the participatory development, the existing technical possibilities influence employees, ranging from disappointment to positive surprise, and shape their perception of the "end product". If a positive attitude toward technology and its benefits is created through participation in the development of technology, employees can be expected to accept it later. In application, technology offers the possibility of spending less time on burdensome activities and, instead, of increasing one's own expertise or investing in more interesting and/or value-adding activities, all of which are essential elements of work design standards (e.g., Hacker 1995). To exploit these opportunities, work organization is called for (see below). With reference to Sträter (2022), this simultaneously pursues work-related sustainability goals, such as SDG 3: Health and well-being, SDG 4: Education, and SDG 8: Decent work and economic growth.

Technology-Organization Interaction

"Organization" should not be understood here in the sense of an entity, e.g., a company—but as the bundle of tasks related to organizational and operational structures in the work system. In principle, the MTO approach allows for a much broader interpretation up to larger contexts such as the market activity in a specific region or general networks that go beyond organizational boundaries. This interpretation can be found, e.g., in Wäfler (2022) but is not used here in order not to overload the complexity of the example.

How does technology influence the organization?

The technical system—in the case of our example, the intelligent quality control system—places various tasks in the work organization if the possibilities it opens are to be exploited in the design of work. On the one hand, this concerns the use of the freed-up time resources as explained above. An improved work organization can offer employees new learning opportunities, e.g., about production processes, and assign more varied and highly qualified tasks. More far-reaching organizational design measures, e.g., the transfer of additional responsibility or the formation of work groups with their own decision-making powers, are also possible based on the reduction in workload and the targeted use of human resources. This would correspond to a change in the division of tasks, but also to a decentralization of decisions in terms of the formal organizational structure. The use of mobile devices allows greater flexibility in terms of location and work scheduling, depending on the area of work.

How does the organization influence technology?

WIRKsam is based on the premise that technology should support people and not, conversely, that people should "serve" technology or even be replaced by it. This premise is in line with the opinion regarding the relationship between humans and AI recently published by the German Ethics Council (Deutscher Ethikrat 2023). The division of labor between humans and AI must be decided and designed. At the weaving mill we are looking at here, it is important that the employee ultimately retains decision-making authority and remains "in the loop". Filters classified as "not in order" continue to be reviewed manually. The functionality of the AI system is designed according to this goal. Organizational requirements concerning data protection are fed back into the technical system and incorporated into its design.

Human-Organization Interaction

How do people influence the organization?

Employees' qualifications and willingness to innovate are essential components of the foundation on which organizational change can be based. Within the framework of participative procedures, employees can influence not only the design of technology, but also issues of work organization such as decision-making authority, work forms (e.g., group work with partially delegated responsibility) or information flows. This presupposes a decision by management as to which issues employees should participate in and what degree of participation they should be granted (cf. e.g., Hucker 2008: 32ff.). But even in a "classic" manufacturing company, there are numerous factors through which employees have an impact on the organization, especially on processes. Simple examples are absenteeism or even resignation. In the work itself, for example, employees change process flows in an informal way, for example by modifying sequences or work equipment. Within the framework of actual analyses in WIRKsam, this was noticed by comparing the process documents of the respective companies with the actual processes during activity observations.

How does the organization influence people?

German industry is suffering from a shortage of skilled workers. At the same time, employees and applicants for skilled positions in industry have demands on their work and their employer as a result of social megatrends. One way of standing out in the employer market with positive employer branding and retaining employees in the company is the organizational design of attractive workplaces with innovative technology and an interesting portfolio of activities, so that employees can adequately use and enhance their qualifications and develop them for the benefit of sustainable employability. Employee participation is also an organizational measure that can have very different effects on employees, starting with the perception of increased attractiveness of the employer, increased motivation and identification with the company, but also excessive demands (Hucker 2008: 150). Forms of organization such as the group organizations already mentioned or newer forms such as the "swarm organization"—in which employees can be flexibly deployed at various positions in the company (VDI 2022: 24)—change the way in which employees work individually. The sustainability aspects in work design mentioned above can also be found here.

If, drawing on the above example, a technology is jointly developed and subsequently established to support collaboration in a semi-autonomous work group, we find ourselves at the intersection of all three areas of people, technology and organization. Corresponding examples, which also add the third field of action (e.g., organization when considering the human-technology interaction), can of course also be docked onto the other interactions described. The examples already show that, in reality, the connections between the fields of action (M-T, T-O and M–O) cannot be separated as cleanly as shown here. Interdependencies can have a chronological sequence, for example (see above). The participation of employees in management decisions (human influence on the organization) depends on how it is organized, for example whether employee suggestions are implemented or whether non-implementation is plausibly justified. However, the systematic breakdown aims to make the interdependencies clear by disentangling the interrelationships and thus to show why the use of technology alone cannot adequately shape a work system.

The following section brings together the strands of human-technology interaction and sustainability for the MTO areas of technology (artificial intelligence) and people (changes in work in conjunction with the use of AI) to form the perspective adopted in WIRKsam.

2.8 Artificial Intelligence and Transformation of Work

When dealing with data-driven technologies such as AI, transparency is a key issue. Under transparency we understand a concept which enables employees to understand how the AI develops its proposals and which data were used in this process. Transparency is not only necessary for the immediate use of AI, but also to win over employees in accepting, cooperating in, and contributing to changes in their work environment and processes. This is because sustainability also means prolonged and continued use. In this regard, AI can only be sustainable if the humans using it or working together with it are already considered in the development process. Some AI methods require training before use and for the decisions of the system to keep up with a changing environment retraining or even a continuous form of training will be necessary. Finally, any AI must be useful for the particular purpose it is being applied to. Humans will make use of AI methods more willingly if these methods are beneficial not only for the task at hand but also for the person working on this task. Moreover, the more critical the decisions that are proposed by an AI system get, the more crucial characteristics like trustworthiness are. The AI High-Level Expert Group on AI set up by the European Commission has issued a list for the self-assessment of trustworthiness (High-Level Expert Group on Artificial Intelligence 2020). Huchler (2022) emphasizes the opportunities of a complementary design of human-AI collaboration and presents criteria for using AI to make new forms of interaction and organization human-oriented. At the same time, he argues, this approach promotes new value creation concepts. In our terminology, this thesis also means that the two pillars of economic and social sustainability (or the corresponding SDGs) can be reconciled. With respect to the fact that not all companies are digitized to a level that allows the direct implementation of an AI-supported work system, Holmström (2022) proposes a framework to assess the readiness of an organization to adopt AI. The impact of integrating AI in work processes is considered in Braganza et al. (2021). For example, Galaz et al. (2021) discuss the potential that AI may have but also the risks that are associated with it. Altepost and Kurz (2023), for example, describe the concept of internal innovation labs as a concrete participation opportunity to involve the expertise and needs of employees, so that the design of a technical innovation is advanced in the context of a social innovation. In this context, they also provide some insights into the concrete opportunities and risks of working with AI, especially regarding the possibilities for works councils and employee representatives to participate.

Our perspective of how artificial intelligence should be deployed is clearly human-centered. This includes the notion that the design of AI-supported work is not dictated by technological goals or constraints. There is considerable scope for design in all MTO areas: user orientation and qualification (M), technology and its functionality (T) and organization (O), e.g., responsibility or the redesign of process flows. The following questions, among others, can be derived from these considerations:

- How can the analysis and design framework MTO be used to achieve an individually fitting design of the new work system based on common goals of companies and employees?
- How can conflicting goals, especially conflicts in the pillars of sustainability, be resolved to enable companies and their employees to jointly manage future transformations?
- How can the willingness and ability of employees and managers to innovate be awakened and, if necessary, increased?
- Which differences exist in the workforce and management levels regarding the effects of participatory measures?
- How can employees be prepared for their participatory tasks, e.g., testing technical prototypes in various iteration loops?
- What level of trust should employees have in the AI technology/the AI application to be developed? To what extent should they take a critical position?
- What level of trust do they develop in the participatory MTO process?

3 The Transformation of Work in the Context of Sustainable Innovation Processes in Companies Using the Example of WIRKsam

3.1 Procedure Model

As a common basis as well as a tool for future implementations of AI in companies, an overarching procedure model is currently being developed that interlinks procedures from work science, social sciences and AI development. Concerning the work-scientific aspects, the APRODI stage model (RKW 2020) chronologically structures the course of digitization projects in the phases of orientation, focusing, realization and stabilization. The MTO principle and stakeholder participation in the digital transformation of work are central to APRODI. However, while the model assigns suitable instruments and methods to the individual phases, it does not specify how these instruments and methods can be brought into a process flow. In particular, technical realization and its connection with work design require supplementation. Therefore, from the perspective of information technology, reference is made to the CRISP-DM model (Wirth and Hipp 2000), which offers points of contact in the sense of the MTO principle with its fundamental user orientation. A sociological approach of participative system development and analysis of human-technology interaction from the project SozioTex (Altepost et al. 2021) provides a methodology for the practical development of the technical system and linkage with work design. Thus,

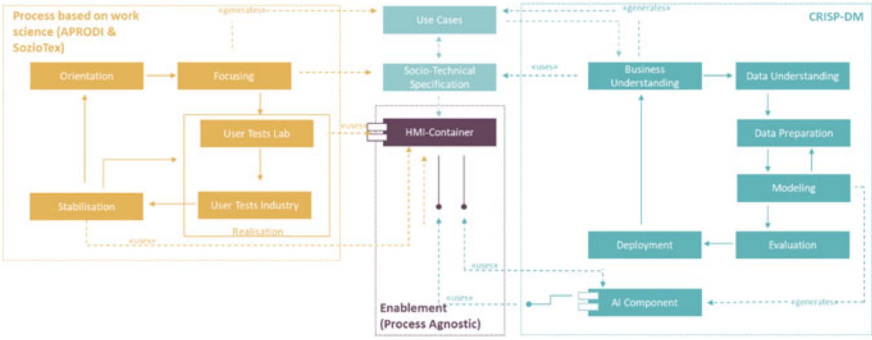

Fig. 2 Current status of the WIRKsam procedure model (Harlacher et al. 2023)

the sociotechnical constellation of the work system is mapped, and the approach of simultaneously addressing humans, technology and organization is considered.

Figure 2 shows on the left the parts of the overarching WIRKsam process which are based on SozioTex and APRODI. These two concepts, in turn, are based on work science and sociology of technology, among others, and explicitly allow iterative loops.

The work-scientific approach starts with the orientation phase in order to first identify the use case: Which problem is to be solved in the company with the help of artificial intelligence? The participation of employees in this initial phase is preferable since this ensures that the use case identified by management is actually useful on the shopfloor. The subsequent focusing phase includes analyses of the current situation, the requirements and, if applicable, the fears of the affected stakeholders by means of participatory instruments. The involvement of stakeholders at this early stage ensures the greatest possible sustainability in the sense that the necessary resources—finances, energy, working time, etc.—are used to achieve an operational problem solution that is also used by employees and serves both them and the company as a whole in the long term. Both economic, ecological and social sustainability goals are associated with this, and their potential conflicts become evident at this early stage. One possible instrument for negotiating conflict solutions is the "MTO workshop" in which all research partners as well as the relevant stakeholders from the company participate and jointly discuss the requirements for the sociotechnical solution from their respective perspectives. By including the expertise of the employees, it is now possible to realistically assess, among other things, whether the envisaged AI deployment actually appears to make sense. Otherwise, a new iteration based on the orientation will be necessary.

As the starting phase of the CRISP-DM model (right side of Fig. 2), business understanding serves to jointly define the goals of all MTO areas. At this juncture, the use case is further specified and confirmed with respect to both submodels. Requirements and goals from both models are incorporated into a common "socio-technical" specification. While data understanding and data preparation in the CRISP-DM model are being advanced by the information technology specialists, scientific tasks and preparations for the realization phase can be pursued in parallel. Modeling in our implementation of CRISP-DM does not directly lead to evaluation (of technical functionality) and deployment as in the original model, but is now branched off in the direction of enablement. In WIRKsam, enablement is mainly the responsibility of the aforementioned associated IT companies. A large part of enablement in each use case is developing the so-called HMI-Container according to the sociotechnical specifications identified in the work-scientific submodel, e.g., by means of MTO workshops. The HMI-Container can be understood as the human-technology interface (graphical or otherwise) in which the AI component, mainly developed by the AI specialists (MASKOR in the example of WIRKsam) in the CRISP-DM submodel, will be embedded as soon as it is ready. Since the HMI-Container is the means by which employees interact with the AI, it is important to participatively and iteratively develop and test it early on. This approach helps to create a work system which is deemed useful, avoids the not-invented-here syndrome (cf. Hannen et al. 2019; Katz and Allen 1982), and therefore is brought into actual use.

User tests, performed in the laboratory at first and in the respective company later on, form a separate iterative cycle in accordance with the SozioTex approach, in which prototypes are tested by future users according to work-related criteria and then passed on to enablement and, if necessary, to information technology for further development. Thus, a design of the human-AI interaction is achieved that contributes to humane work. In addition, from a work-scientific point of view, criteria such as learning support and transparency of the AI application are introduced. Here, the ergonomic criteria also coincide with SDG 4—Quality education.

Once a development stage has been reached that meets the requirements, APRODI enters the stabilization phase of deployment in the operational environment and CRISP-DM enters its deployment phase. Both models provide for a new orientation/focusing or business understanding, so that a further continuous development process of the sociotechnical constellation is also mapped. The completion of the procedure model is still in testing and progress.

3.2 WIRKsam Living Lab

Within WIRKsam, it is assumed that, from a sociological point of view, technical innovation cannot occur without social innovation and vice versa (Rammert 2010; Zapf 1989). Connecting both at first glance seemingly separate events—technical and social innovations—and recognizing the relations between them, it becomes apparent that what happens is sociotechnical innovation. This especially becomes apparent with regard to AI: it is not enough to develop AI as a “technological standalone project”, the social processes surrounding the development and implementation of AI have to be co-developed together with the technological aspects of the work system innovation. This is one of the sociological key perspectives concerning innovations and has been a point of discussion for many decades. Starting in the early twentieth century with Schumpeter and Ogburn who researched social relevance of technical innovations, the topic remains relevant to the present day (Häußling 2019). There are different examples of sociotechnical innovations, many of them connected to everyday life and showing their huge impact on society. The mobile phone is a prominent global example. Initially simply used as a telephone, mobile phones soon were given more functionality like text messaging, calculations, web browsing and video calls. With these added functions, mobile phones became very versatile which shifted the initial telephone usage toward the mobile phone becoming a technical everyday companion (Häußling 2019, p. 141). Based on this, when planning WIRKsam as a project, it became clear that sociotechnical innovation needs to be a part of the project's research goals. Hence a living lab was chosen as the setting to analyze sociotechnical innovation(s) in WIRKsam as well as the Rhenish mining area, WIRKsam's region of research interest. In doing so, the living lab becomes the center of WIRKsam's actions while at the same time making it possible to analyze and evaluate how WIRKsam's participants work together.

Living labs bring together science and society by enabling scientists, different stakeholders as well as people who are simply interested to participate in the scientific process based around the lab's main topic and/or object of research. The shared knowledge of the people involved usually leads to the development of new ideas concerning the living lab's object of research, its main topic, or both. Yet for a living lab's results to be fruitful, the sharing of ideas requires more factors, hence open innovation and sustainability are key factors in living labs (Böschen 2020). While open innovation allows a living lab's participants to present, discuss, choose, decide on and develop their ideas, one of the main goals of the living lab is that these ideas are sustainable. From a scientific point of view, the living lab's modus operandi is one of the objects of research, meaning that the procedures and the decision-making in a living lab are analyzed (Schäpke et al. 2017).

Based on a wide range and mix of scientific methods (Böschen 2020), living labs can be highly experimental, detailed with many small steps, and self-developing in a bottom-up way (for example participants deciding on the approaches of the living lab they are participating in) while keeping a strong focus both on the living lab's main topic and the object of research. To this end, each living lab has a very individual profile. Nevertheless, keeping a low threshold most possibly attracts public interest and therefore can enable a high degree of participation. Taking this into account, non-experts and laymen can take part in the lab and join the process by commenting and giving their perspectives, too. Despite these different aspects which have yet to be evaluated in a broad scope, the results of living labs have shown to be acknowledged in most cases by those who are affected.

The concept of living labs is a key element of WIRKsam. The aspects of transition, participation and open innovation within this project are especially driven by the ongoing structural change in the Rhenish mining area because of the approaching end of lignite mining which has been one of the main economic forces of the whole area (Böschen, Förster et al. 2021a, b). With this structural change affecting the whole area and hence the change being of major public importance, the idea of a living lab within WIRKsam is crucial to connect the scientific activities inside the project with the outside world in a way that offers a high degree of participation, not only by the project members, but also by the public itself (Böschen et al. 2021a, b). This also follows the goal of promoting WIRKsam's scientific results publicly.

The idea behind WIRKsam's living lab has two parts. Firstly, the living lab serves as a transdisciplinary collaborative space for all people directly involved in the competence center's research, namely from scientific, industrial and value partners and enablers. These groups can meet and work together in the lab online and offline at basically any time. Following the SozioTex approach, the collaborative space is used to jointly develop sociotechnical innovations with inputs from diverse stakeholder groups. This includes the aforementioned iterative user tests.

Secondly, the living lab serves as a public showroom of the project's results and demonstrators for a wider audience from outside of the project, becoming a public forum for WIRKsam. This is connected to the public role of the competence center and its necessarily public presentation of scientific results. The location where the living lab is based is shared by WIRKsam members and different scientific partners and projects outside of WIRKsam. This adds to the everyday exchange between all those people. The building's main floor sees different uses basically every day because of various conferences and meetings of all projects based here. In a metaphorical way, the open space reflects the idea of open innovation within WIRKsam. It is a space for collaboration and enables the people involved to analyze the collaborative aspects of their work, too.

Within WIRKsam's concept, the living lab is a crucial part of achieving sustainable and open innovation as well as transformation in science and society by enabling collaboration between and participation of people inside and outside of WIRKsam to the highest possible degree. Furthermore, this leads to similarly open research and development of new ideas to enable a transformation on all considered levels in the Rhenish mining area during its currently happening structural change. Both open research and collaborative idea development are two of the main goals of WIRKsam's living lab.

3.3 WIRKsam and Sustainable Innovation

In the understanding of the competence center WIRKsam, innovations are not "only" technical innovations such as an AI application. As described, this application is linked to new practices of work, qualification and organization, but above all to a participatory development of the entire work system. The level of novelty of these social innovations, according to our initial experience from WIRKsam, exceeds that of technology from the perspective of many a company. The textile industry, which is characterized by small and medium-sized enterprises (SMEs)—often traditionally grown family businesses—is probably already strongly oriented toward technical changes due to the structural change processes it has undergone, since it has always been a matter of setting high-tech products against competitors, e.g., from the Far East, and automating production processes. Jobs have tended to be cut over the decades. However, even as a high-tech industry with numerous "hidden champions", it is now confronted with a shortage of skilled workers due to demographic change. We summarize the sustainability aspects of this innovation situation below.

As in WIRKsam research partners, companies and employees jointly design customized work systems, this should not only strengthen the competitiveness and innovative capacity of regional companies, but also open up new opportunities in the working world of the future, e.g., relief from burdening work activities, further training and innovation. Established standards of work design (e.g., Hacker 1995; Hacker and Sachse 2014; Rohmert 1972), employees' interests and concerns and the preservation of their employability play central roles. In short, work system design in WIRKsam addresses various aspects of sustainability from the economic as well as the social pillar, which can be found, for example, in SDGs 3, 4 and 8 (Fig. 1) (see also Sträter 2022 on the contribution of work science to the UN Sustainable Development Goals). What is the relationship between these pillars, respectively, between the corresponding SDGs? And which role does classical ecological sustainability play in this context? First of all, SDG No. 8—economic growth and decent work—with its double claim already expresses in itself a possible line of conflict, which also shows up throughout WIRKsam. How economical are high-quality, innovative jobs? Higher qualifications usually correspond to higher wages, which some companies want to avoid. Can a company maintain its competitiveness if it loses highly qualified, experienced employees to more attractive employers? On the other hand, a company must be economically successful to be able to provide jobs at all. And in connection with SDG No. 5—Gender Equality, which includes the goal of self-determination in addition to gender equality—the question sometimes asked by companies as to whether they can actually afford participation can also be classified as a line of conflict between sustainability goals. Diving deeper, it seems crucial to ask what the sustainability of profitability itself means—is it about the preservation or growth of the company or also about other criteria? This is where concepts of extended profitability analysis come into play which, for example, can include acceptance of technologies or psychological stress of employees in ordinal scales as criteria (cf. e.g., Picot et al. 1985; Ney 2006). The time dimension of economic efficiency also becomes clear here, without which a sustainability concept cannot do, even beyond the mere availability of the means of production and the product (example Carl von Carlowitz). WIRKsam raises questions such as: is it really economically efficient if production goals are achieved in the short term, but are paid for with high sickness absence rates or high employee turnover? What is the underlying concept of economic efficiency? And what period of time would one have to consider for the "evaluation" of profitability? The WIRKsam approach will cover both the "original" understanding of sustainability as outlined by von Carlowitz as well as the "politicized" understanding of the three pillars of sustainability and the SDGs.

With help of WIRKsam's participative approach, companies can actively address such conflicts between the pillars of sustainability and underlying diverging interests. For example, the aim of the so-called MTO-Workshop is to gather all stakeholders associated with the AI-based innovation and, among other things, discuss the negative and positive effects of the innovation on the levels of technology, organization and individual people. In doing so, these different interests can be harmonized to a certain extent. The AI-assisted work systems to be created should (be accepted enough to) outlast the initial test and pilot phases by using participatory methods. In doing so, it is possible to trace how these conflicts play out in companies during the digital transformation. In this sense, the SDGs help to systematically highlight the specific areas of conflict due to their higher level of concretization. Through negotiation processes, every company must prioritize its sustainability goals for itself and re-produce or modify the prioritization as time unfolds and society changes. The prioritization of goals is dependent on the prospect of success concerning specific measures and strategies as well as on the organizational values and the willingness and capability to invest resources in order to live up to them. In summary, the following questions need to be addressed:

- (How) Can the introduction of AI lead to better working conditions (social sustainability), higher resource efficiency (environmental sustainability) and, through these and other effects, higher profitability (economic sustainability)?
- How are the tools of the participatory approach based on the MTO principle to be used to help companies link sustainable work design with the other sustainability goals and to find a prioritization that is jointly supported within the company? What other factors and design criteria must be considered?
- (How) Can successful sustainability profiles be identified for characteristics of companies and their workforces (e.g., corporate culture, industry, company size, degree of digitalization, socioeconomic characteristics of the workforce structure)?

3.4 WIRKsam and Transformations

"Work of the future" in the "future of work"—the titles of funding programs, books and websites, many of which can be found by asking Internet search engines, draw our attention to the imminent transformation processes pertaining work, some of which has already begun. This transformation is intertwined with other transformation processes, such as the economic transformation toward new business models in areas of structural change like the Rhenish mining area, the ecological transformation toward climate protection and the energy turnaround, and also the digital transformation, which has a great deal of overlap with the other transformation strands: support for work and increasing the resource efficiency of production processes through digitization are examples of this. The transformation of work is dependent on economic sustainability in terms of its shape and form. Companies can only provide jobs if they are economically viable. With this premise, however, there is room for maneuver: The automation scenario, for example, is based on a notion of economic sustainability that replaces human labor through automation. Other scenarios move toward using humans and technology in such a way that both do what they do best, thus jointly contributing to economic sustainability. To a certain extent, therefore, the transformation narratives also reflect ideas of sustainability and their conflicts: an economic transformation aims at sustainable corporate success, the ecological transformation at sustainable ecosystems and the transformation of work, as already described, at various aspects of sustainability, primarily the social pillar. The digital transformation plays an ambivalent role as a "cross-section", particularly regarding ecological sustainability aspects (e.g., own energy consumption vs. savings mediated by digitization) as well as the sustainability goals of work science. So, what can and should the work of the future look like, and how can companies and their employees help shape it? In WIRKsam, the participatory approach via the MTO principle is used to implement exemplary design options and research this process.

The following considerations refer to the Aachen Transformation Model, which defines research in the context of transformation according to three different levels:

- Transformation research,
- Transformational research,
- Research transformation.

WIRKsam aims to strengthen the innovativeness and competitiveness of companies and to secure innovative work in the context of AI-supported processes as a permanent competence center in the Rhenish mining area. As shown in the procedure model, the implementation of an integrated sociotechnical specification for work system design leads to the development of prototypical systems in several iterations involving employees and further stakeholders of the companies. In a further step consulting and training services will be developed that support and drive the transformation in the companies. This also includes the development of an innovation-promoting mindset. This is important in order to not only be able to cope well with the changes currently taking place within the framework of the project goals and structural change for the benefit of companies and employees, but rather to be able to actively and innovatively shape the challenges of a world that is also characterized by change beyond this. The joint development, testing and learning takes place in the living lab setting described in Sect. 3.2. Thus, WIRKsam—in relation to the three levels of the Aachen Transformation Model—is essentially a transformative project(transformative research). This formative branch of the project is continuously flanked by an analytical branch of interdisciplinary scientific analysis, in which theoretical and methodological concepts from different disciplines are integrated and empirical analysis methods are developed for researching sustainable innovation processes in companies in the context of the transformation processes described (Fig. 3). The analysis of various research questions and evaluations provides a basis for further iterations of system development.

It is not quite easy to assess now to what extent "research transformation", i.e., a change in research in and through WIRKsam, will take place. When can we speak of a transformation of research? Is this synonymous with a paradigm shift or does it refer more to the framework and goals/less to the content of research? Does the consideration of sustainability aspects mean a further departure from the freedom of value judgment of research (Weber 1968)? Is this even a crucial transformative aspect?

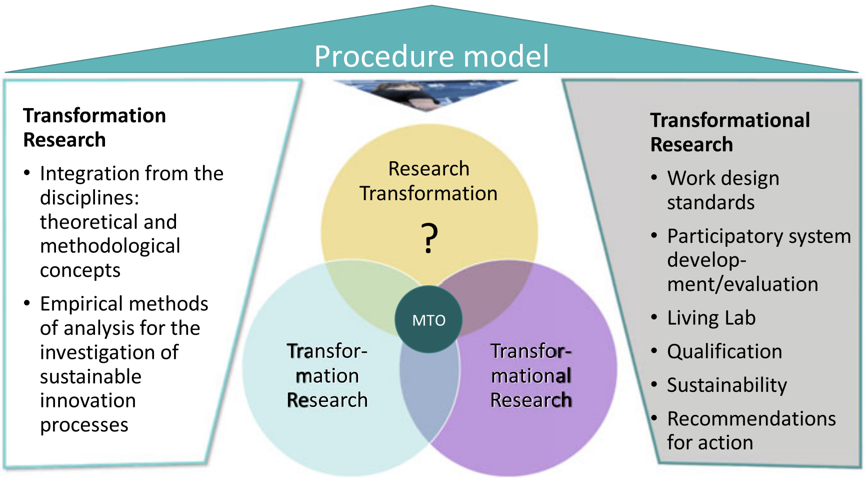

Fig. 3 Aspects of the three levels of transformation of the Aachen Transformation Model in WIRKsam

4 Collection of Questions

Because of the large scientific scope of WIRKsam, the following is a collection of questions resulting from the contents of the previous chapters which will be addressed and answered in the future.

2.2 Competence Center WIRKsam

How exactly is work changing in the context of AI technologies? What scope is there for using the opportunities offered by technologies to achieve economic and work-related goals without relinquishing control over possible risks? Which AI methods are suitable for problem solving, but also for work design that does not degrade employees to “operators”?

What role do innovation networks play in a sustainable corporate culture and in strengthening both human-centered work and the competitiveness of companies?

How do the changes affect different social groups in the company, how can these groups be involved?

2.3 WIRKsam in the Context of Transformation tasks

How are the drivers of structural change and shortage of skilled workers, (AI) digitization and work design interlinked? (This question is to be considered exploratively during WIRKsam based on the application examples.)

How do structural change activities in mining areas as an overall transformation link the different transformation strands in specific ways? What are the specific characteristics of structural transformation that provide for a particular type of linkage?

What role does the participatory approach play in revealing these linkages?

2.7 Work Design—MTO Approach

How can the MTO analysis framework be used to achieve an individually appropriate design of the new work system based on common goals of companies and employees?

How can conflicting goals, especially conflicts in the pillars of sustainability, be resolved to enable companies and their employees to cope with future transformations as well?

How can the willingness and ability of employees and managers to innovate be awakened and, if necessary, increased?

Which differences exist in the workforce and management levels regarding the prospects for success, but also the appropriate characteristics of participatory measures?

How can employees be prepared for their participatory tasks, e.g., participation in requirements identification or testing of technical prototypes?

What level of trust should employees have in the AI technology/AI application being developed? What level of trust do they develop in the participatory MTO process that their interests will be adequately considered and will lead to a design of the work system that is acceptable to them?

3.2 WIRKsam Living Lab

What is the impact of a regional living lab when its area of interest is affected by structural change?

Which aspects of the sociotechnical work system can be developed and tested in the physical space of the WIRKsam Living Lab, which can only be developed and tested at the respective companies?

3.3 WIRKsam and Sustainable Innovation

What is the relationship between these pillars, respectively, between the corresponding SDGs? And which role does classical ecological sustainability play in this context?

Is it really economically efficient if production goals are achieved in the short term, but are paid for with high sickness absence rates or high employee turnover? What is the underlying concept of economic efficiency? And what period of time would one have to consider for the “evaluation” of profitability?

(How) Can the introduction of AI lead to better working conditions (social sustainability), higher resource efficiency (environmental sustainability) and, through these and other effects, higher profitability (economic sustainability)?

How are the tools of the participatory approach based on the MTO principle to be used to help companies link sustainable work design with the other sustainability goals and to find a prioritization that is jointly supported within the company? What other factors and design criteria must be considered?

(How) Can successful sustainability profiles be identified for characteristics of companies and their workforces (e.g., corporate culture, industry, company size, degree of digitalization, socioeconomic characteristics of the workforce structure)?

WIRKsam and Transformations

What can and should the work of the future look like, and how can companies and their employees help shape it?

What does this mean for the value judgment in the context of scientific theory?

When can we speak of a transformation of research? Is this synonymous with a paradigm shift or does it refer more to the framework and goals/less to the content of research? Does the consideration of sustainability aspects mean a further departure from the freedom of value judgment of research (Weber 1968)? Is this even a crucial transformative aspect?

5 Summary and Outlook

The perspectives shown in the course of this paper highlight the transformation of work within companies of the textile industry in the Rhenish mining area, which is currently undergoing a structural change in a time of global challenges concerning environment, economy and politics. As we point out, these challenges are mirrored in the way conflicts between the three pillars of sustainability play out on the level of individual companies in the mentioned region. These conflicts form some of the focal points of our ongoing research. With the help of AI, WIRKsam aims to create work environments which at the same time are socially acceptable, ecological and which ensure the economic survivability of our partner companies. All of the aforementioned aspects require new and innovative ways of work, but not only in the practical sense of day-to-day work on the shop floor of companies. The use of AI within the textile industry changes work to improve the quality of the jobs while also making a higher qualification possible as well as changing corporate culture while trying to achieve a high degree of user participation in the process. This aspect is expanded by introducing a living lab within the project. Using a living lab as a way of enabling open and sustainable sociotechnical innovation offers the possibility of bringing science and society together by different means of participation and, by that, taking the project's results to the public as it happens and starting the transformation right there. Innovation processes are not only meant technically, but also social innovations, e.g., a participation culture as well as changed practices in the company regarding organization, division of labor, use of technology, or various aspects of sustainability, are included. They enable companies and their employees to co-develop and support technical innovations, especially under consideration of sustainability. In this way, different transformation and sustainability aspects can be coordinated with each other and conflicts can be resolved.

With WIRKsam being a recently started research project and competence center, in this article we collected some questions raised by the ongoing transformations and the corresponding WIRKsam approach, resulting in the need to address and analyze these aspects further soon. Especially the aspects of research transformation and transformational research require a closer look. These will be focused during the upcoming phases of the WIRKsam model which is being developed further and fine-tuned as WIRKsam progresses as a whole. To what extent this will actually lead to a transformation of research remains to be seen. Against the background of the MTO approach, the "competence" of the competence center as a unified entity requires the interlocking of perspectives. If the researchers take the chance to reflect their disciplinary perspective to this extent, at least a creative and goal-oriented combination of methods and theoretical basis can succeed. The competence center WIRKsam will thus fulfill the claim of a holistic analysis and design of innovative work with AI in the Rhenish mining area. These activities are always oriented toward the state of research and practice and thus, to a certain extent, offer a dynamic constancy in and for change.

Acknowledgements /Funding: WIRKsam Competence Center receives funding from the Federal Ministry of Education and Research (BMBF) in the program "Regionale Kompetenzzentren der Arbeitsforschung" under grant number 02L19C601 administered by Project Management Agency Karlsruhe (PTKA). We would like to thank our scientific partners, the Institute of Applied Industrial Engineering and Ergonomics (ifaa) and the Mobile Autonomous Systems and Cognitive Robotics Institute (MASCOR) at FH Aachen University of Applied Sciences Aachen, and our industry partners in this project.

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Transformation of the Built and Lived Environment

Frank Kemper and Frank Lohrberg

Abstract The built environment is like a reason and solution for different ongoing societal and environmental change processes. On the one hand, it may enable societal progress, ensure people's health, and is a precondition for our modern society's working and productivity environment. On the other hand, the built environment is a crucial driver of carbon emissions, and a significant driver of climate change improvements in manufacturing processes, (re)use of structures, and reduction of energy consumption are requirements. Obviously, researching possible solution paths for changing boundaries requires a variety of interdisciplinary resources and expertise. Everything mentioned interferes and significantly depends on the economic opportunities the different societies can spend for the transition and how willing they regard the expected changes. The growth area "Built and Lived Environment" (BLE) of RWTH Aachen University aims to provide such kind of interdisciplinary research playground. Different ongoing methods and examples emerging from the growth area BLE and specific solutions of transformative research in the described field are presented.

Keywords Built environment · Lived environment · Transformative research

1 Introduction

The societal challenges the world community faces due to global warming, the necessary energy transition, geo-political system rivalries, and the associated economic tensions could hardly be more significant. There is also no question that, on the one hand, rapid and targeted technical innovations are required to deal with these pressing questions of the future. On the other hand, society actively supports the necessary

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P. Letmathe et al. (eds.), *Transformation Towards Sustainability*,
https://doi.org/10.1007/978-3-031-54700-3_13

change and the inevitable hardships. The creation and implementation of new technologies, the evolution of habits in the light of changing conditions over a period—“it is nothing less than a new moral revolution that humanity must successfully complete if it does not want to seal its own end” (Appiah 2011).

The patterns of such significant societal change follow a routine that stems from ignorance via recognition of action. After a successful transformation, former societies looked back in disbelief and questioned why action was not taken sooner. Examples of such historical changes in Western societies are the abolition of slavery and the introduction of women’s suffrage (Schneidewind 2018). Concerning environmental and demographic challenges, the Club of Rome report in 1972 (Meadows 1972) is the first, primarily ignored warning call. After numerous climate protection conferences and increasing climate protection commitments, humanity is heading towards a phase of action—but we are still at the very beginning. Today, it is scientifically undisputed that the challenges mentioned at the front are so urgent due to the limitations of resources and the expected consequences of climate change and that the warning of 1972 is manifesting in the climate change crisis we face. Most people can already feel that hesitant changes are no longer justifiable and demand corresponding political measures. The transformative achievement that political decision-makers need to demand from society and the economy cannot be distributed over several decades in doses. Instead, the immediate implementation will affect the current and future generations with exceptionally high intensity.

The built environment, which has always been intended to protect people from natural phenomena and external dangers, is of direct importance for the well-being of humankind. The residential development provides such protection and is essential for physical and mental health. The built infrastructure represents the basis for our current economic activity, without which the prosperity achieved and the opportunities for technical innovation would hardly be possible. One example is the successful invention and mass production of vaccines in the wake of the corona pandemic, which was ultimately only possible, thanks to the available research and infrastructure resources. At the same time, however, the construction sector is also significantly involved in artificial climate change. The manufacture and operation of buildings are responsible for around 40% of global CO_2 emissions (Chen 2015, Moran et al. 2018) . It thus becomes clear that the moral revolution must take place to a considerable extent within the construction sector—but at the same time, the aspects of well-being cannot be neglected so that the socio-ecological change can also be accepted and supported.

In this context, the “double decoupling” (Weizsäcker et al. 1996) should be mentioned, a fundamental principle of sustainable management. It expresses that, due to technological advances, there is a decoupling of the economy and environmental consumption (green economy), which takes place in the existing economic order. According to the principle cited, however, this alone is no longer sufficient (among other things, due to rebound effects), so the quality of life must also be decoupled from economic growth. This means it is also particular about the definition of prosperity and quality of life—ultimately, a social issue primarily about justice.

And not only climate change and its risks to natural hazards require an interdisciplinary confrontation about the usage, materialization, construction forms, and compositions of buildings, quarters, and cities in the future. People are nowadays much more aware of the interference between living spaces and human health. The exterior air quality is mainly affected by industrial and traffic pollution; however, the built environment can positively influence the micro-climate by planting, green facades, and a meaningful building arrangement. The interior air quality can be further improved based on restorative materials, ventilation, and building technology. In the context of increasing heat, aspects like urban heat cells, drought, and microparticles will also be more relevant in the future. The corresponding trends require a reflection of sustainability ambitions and suitable solutions, such as labour market, mobility of residents, and their desired prospective way of life—likewise in modern urban centres, in suburbs of developing countries, and in rural areas. Predictions, analyses, and recommendations need manifold expertise, including profound knowledge of specific local boundary conditions.

In Fig. 1, the interfering aspects of transformation are visualized. It is believed that different trends, such as climate change, digitization, mobility, and the higher expectations of people towards individualization and health are inducing stress into the built and lived environment, demanding adjusted solutions. The interdisciplinary group Build and Lived Environment (BLE) at RWTH Aachen University has declared its goal to advance thematic research in the context of these tendencies. All those involved are aware that the solution approaches also involve interactions at different levels of the built and lived environment (mutual adaptive solutions). For this reason, the development of research projects is organized in thematically appropriate research groups, with a significant focus on the inclusion of young scientists. As a side effect of this joint research work, it is expected that the individual disciplinary research of the actors involved will also benefit, as there should be a coordinated exchange of methods, data, and approaches (cross-cutting issues).

The uniqueness of BLE lies in the interweaving of different perspectives. For instance, when it comes to the prediction of flood events and the implementation of construction measures for their containment in civil engineering, architecture can develop an assessment scale for the preservation or protection of culturally significant buildings. Economics can conduct cost–benefit analyses to assess the macroeconomic impacts, while the science of transformation can facilitate necessary changes through communication with policymakers and the general public. This example illustrates that an isolated handling of the complex issue can completely disregard the overall interests of society. That is why collaborative work on thematic aspects is now being pursued.

Like flooding (aggravated by climate change), all trends illustrated in Fig. 1 benefit from joined effort. The disciplinary research of the respective fields remains unaffected and provides necessary expertise and methods to tackle the multifaceted research questions.

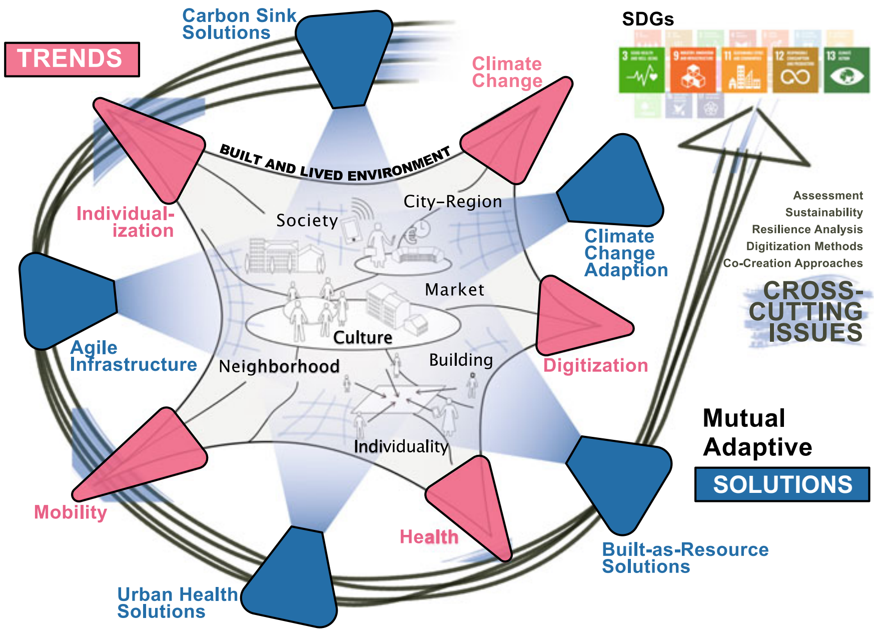

Fig. 1 Built and lived environment (BLE) is exposed to trends—a successful transformation towards the SDGs needs mutual adaptive solutions in various fields with overarching impacts

2 Inter- and Transdisciplinary Methodology

Regarding the built environment and our future life within it, these considerations result in very concrete starting points, which are intended in this sense regarding technological advances and social and societal aspects. The "future art" that is now necessary, with which the Wuppertal Institute describes "the understanding of the character, the course and the rhythm of social change processes", can only succeed in an interdisciplinary manner given the challenges mentioned above—there can hardly be any doubt about that either. This future art must be paired with accompanying technical innovations that cushion the effects of technological change on society as far as possible. For future buildings, people's well-being needs to be the main focus. Regarding the materials used, the manufacturing processes, the durability, and versatility, as well as their operating expenses, they must succeed in such a way that suitable concepts are made possible for the needs of affluent societies as well as for growth and poor communities.

Interdisciplinarity is also to be underpinned by spatial knowledge. In this regard, space is not only seen as a resource, offering materials and areas for building. Space is also integral to the built environment, setting a robust framework for implementing new technologies more systematically (Seto et al. 2014). This means taking ecological issues into account, but also economic and societal ones. Moreover, the successful development of living labs in the last years has underpinned the idea of space as a medium for transdisciplinary research and space as a method to engage stakeholders by co-design or co-production of a built environment.

Technologically innovative ability and social art of the future are the challenges that the growth area "Built and Lived Environment [BLE]" of the RWTH Aachen University is taking on. It is primarily about transformative research to support change actively. This contribution focuses primarily on the interdisciplinary approach and the addressed focus levels and provides examples of successful ongoing projects within that framework. BLE gathers multidisciplinary knowledge from different fields: mainly architecture, civil engineering, economics, socio-technical sciences and medicine.

RWTH Aachen University acknowledges BLE as a "growth area", incorporating the field within its excellence strategy. The university supports its profiling towards interdisciplinary cooperation in core areas with this format. Notably, BLE will be the first RWTH core research area that does not focus on producing new technologies in a narrower sense (hardware, software) but takes a broader approach with also "orgware solutions". This approach is based on the hypothesis that sustainable solutions—especially in the built environment—will also be found on changing mindsets and behaviours and cultural sufficiency practices. The related influence domains and fields of action are shown in Fig. 2. The BLE initiative addresses the multidimensionality of the topics by considering the various scales inherent to building-specific issues, as the solution approaches inherently span across different scales. Particularly, questions related to individuality, mobility, and health are primarily addressed at the neighbourhood, district, or superregional scales. Regarding decarbonization, material research is required, and construction processes must be adapted or questioned. But the necessary transitions will also need to be discussed in the context of urban planning and the overall utilization of landscapes. Other overarching and spatially related issues, such as mobility or digitization, similarly extend across the entire range of scales. This is another distinctive feature of the BLE initiative: it encompasses expertise across all the aforementioned scales.

Following such an actor-oriented research approach, BLE makes its research effective by setting up living laboratories. Hypotheses, methods, and products will be developed, tested, and verified in cooperation with actors and user groups (a triad of co-design, co-production, and co-evaluation). Many existing initiatives and experiences can be built on here, such as the Living Labs of the RWTH ("RRI Hub" and "Living Labs Incubator"), the dialogue platform ("REVIERa") developed by the RWTH as part of the structural change in the Rhenish Revier. and the "ACademie for collaborative urban development". The living laboratories are designed as a network so that heterogeneous actors can get involved in the research process in the sense of "open science", and socio-technical innovations can be developed problem-oriented. At the same time, living laboratories—in addition to classic formats such as conferences, publications, and digital media—serve bidirectional scientific communication.

The living laboratories will also nurture the interdisciplinary research of the scientist involved as they reveal the need for new methods and analysis for complex and interfering systems. Involved researchers reflect and iterate datasets, procedures,

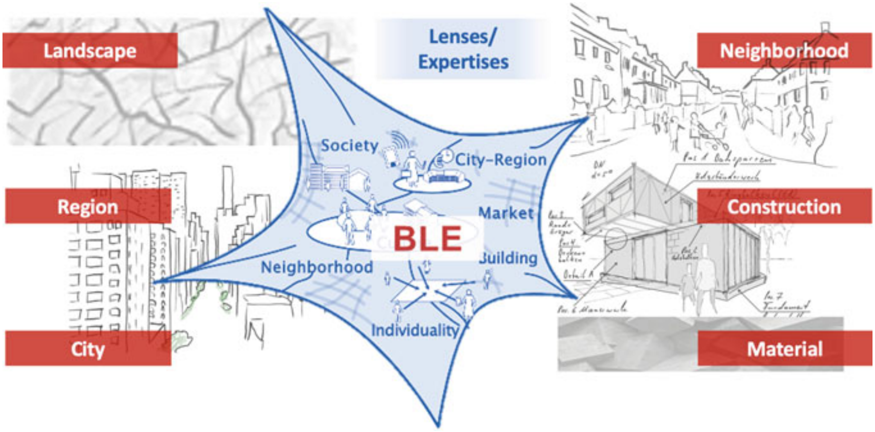

Fig. 2 Influence domains and levels expertise in different scales (lenses) for the growth-area "Built and Lived Environment" (BLE)

and criteria to find well-balanced solutions. Likewise, such scientific substantiation provides a base for political decisions and social participation.

3 Core Areas of Research

The transformation of the built environment is related to a necessary adaptation (climate change and natural hazards), mitigation of climate change effects (fewer carbon emissions, more efficiency, usage of building stock), and sustaining a healthy living environment. As these aspects are interdependent, scientific efforts must focus more on the overall consequences leading to the main reason for the drafted inter- and transdisciplinary approach. In the following sections, we describe the core research areas and some superordinate aspects to illustrate the thematic cross-relevance.

3.1 Decarbonized Buildings

The reduction of harmful greenhouse gases is a global challenge for society. The operation of buildings and the construction industry causes almost 40% of global CO_2 emissions. BLE is dedicated to this problem and researches socio-technical solutions on different levels. Central to this is the design and technical development of long-lasting, adaptable, and recyclable supporting structures made from naturally renewable and artificial building materials and a holistic implementation based on life cycle assessment instruments (Svirejeva-Hopkins et al. 2004). On the manufacturer side, the controlled use of materials, research into new composite materials and the use of additive and energy-saving manufacturing processes are addressed. Regarding the sustainable operation of buildings, the focus is on decarbonization, resilient energy supply, and security of supply (e.g. through improved energy efficiency and direct use of renewable energy), which both new technologies as well as standards and usage practices, as well as the consideration of district-related solutions, for example regarding municipal heating networks.

11% of the carbon emissions of the construction sector is directly attributed to the manufacturing of building materials, e.g. cement, steel, etc. The growing world population and increasing global demand for comfortable living spaces further magnify the problem. The current demand for housing and infrastructural development consumes more than 40 billion tonnes of material annually, mainly primary ones. On the other side, ~ 33 billion tonnes of waste result annually, out of which the majority is handled by landfilling and incineration (Creutzig et al. 2015). There must be more innovative ways to close these circularity and carbon gaps. We must search for material solutions that utilize co instead of emitting even more. Improved design principles enable material-minimized structures. Alternative material streams, novel co-processing pathways, and new construction technologies may pave the way towards net-zero or climate-positive construction strategies. In any case, individual silo approaches are not an option for the future. Only a collective synthesis of integrated interdisciplinary viewpoints will provide more circularity, less materiality, and novel carbon sink solutions. Specifically, the following aspects require deeper consideration and implementation:

- New materials as enablers for a decreased resource and carbon footprint in the construction
- Circularity in construction (less primary, more secondary materials)
- Novel design principles and manufacturing technologies for material-minimized structures
- New approaches to assessing sustainability and materiality of construction
- Treatment and utilization of wastes, e.g. from dumps and landfills.

3.2 *Preservation and Activation of the Building Stock*

The excessive amounts of energy invested in existing buildings and the bound sociocultural values, on the one hand, and the high consumption of materials and energies in new buildings, on the other, render existing building stock the most precious resource. Therefore, it is important to focus on built-as-resource solutions and establish and profile them as an interdisciplinary field of research and practice. Planning and construction solutions must be developed to protect, redevelop, and/or adapt existing buildings to promote socio-ecological transformation in our cities and regions. These solutions should consider historical, cultural, social, and design practices, which enable and condition new forms of careful use, as well as considering engineering, economic, and environmental science issues.

An essential aspect in this regard is the preservation and activation of the current building stock: Instead of "building with resources", it is, therefore, necessary to understand "what is built as a resource". BLE is consequently looking for planning, structural, and procedural solutions for how the existing building can be valued and adapted given the enormous socio-ecological and economic transformation requirements and which cultural points of contact and practices allow and promote new forms of use. In doing so, the limits of stock development must be explored from an energetic-ecological, economic, and normative-cultural point of view. It is crucial to develop an interdisciplinary, indicator- and value-based model for measuring the building stock as a resource while testing new planning instruments with which the supply is sustainable, and future proof can be designed. Handling and weighing of all mentioned aspects require analytical tools to evaluate and enable optimization. For this aim, a concept of values and correlative dependencies needs to be established, which objectifies individual building situations.

The confrontation with the existing settlements and urban fabrics is central here, as these require causally integrated, i.e. inter and transdisciplinary approaches. Current debates point at the built and lived neighbourhoods as the vital arena, where measures for shaping sustainability and resilience transitions are assumed particularly effective. Built and lived communities also comprise multiple forms of cultural heritage, constituting a valuable yet often side-lined resource in resilience and sustainability debates. At the same time, however, considering built and lived districts as urban heritage still poses manifold and essential conceptual, methodological, and practical (instrumental and procedural) challenges, how integrated transitions towards sustainability and resilience could be informed, initiated, and steered.

3.3 Climate Change and Crisis Adaptation

Climate change requires the rapid adaptation of spatial structures, infrastructure, and buildings, but also of socio-cultural structures (usage behaviour) and individual transformations (physical and psychological, acceptance of measures restricting use). The rapid succession of crises in recent times (pandemic, floods, heat waves, energy supply) raises additional questions as to how agile the built structures can react and how they can be set up in the future. These aspects must be mutually analyzed and operationalized, which requires, e.g. integrated approaches to climate impact modelling and the identification of suitable climate adaptation measures as well as the consideration of health-related aspects. BLE investigates how construction can be linked more closely to the functionality of ecosystems and the ecosystem services they produce. While traditional building defines natural processes as a risk of damage, BLE takes up the potential of "nature-based solutions", for example, to regenerate material flows, cool air, regulate floods, cope with dry phases, but also to create socio-cultural added value (well-being, identity, …).

The consequences of climate change can be observed worldwide in similar patterns: slower variations of weather events cause more prolonged phases of rain and heat, leading to more frequent occurrences of flooding and drought, respectively. Extreme events of precipitation, windstorms, and heat waves tend to occur with shorter return periods and locally with higher amplitudes. In brief, the natural equilibrium and the ability to balance weather phenomena tend more and more to reach and exceed their limits.

For instance, in July 2021, a flood disaster occurred in the western part of Germany. The flooding incident was caused and aggravated by multiple factors: prolonged and intense heavy rain, topography, soil saturation, and soil conditions in the areas of rainfall—but also by interventions in natural river courses and peripheral buildings. Unexpectedly, buildings that were supposed to offer protection were in flooded areas. More than 180 citizens lost their lives. Besides extreme precipitation, severe wind events can also cause significant damage to the built environment and put humans at risk. This year, a tornado hit the city of Paderborn, with 43 people injured. Examples like these can be observed worldwide and with increasing frequency of occurrence.

While it is still not clear to what extent such severe events might increase in frequency or severeness due to climate change—it is likely that both features will be affected in an unfavourable way in the future, and the mentioned examples painfully demonstrate the possible impact of climate change to us. Therefore, climate change adaptation is a key topic for planning our future living environment and infrastructure. The construction sector is relevant, as it contributes significantly to carbon emissions (and thus offers potential for savings). Still, it also promises to provide opportunities for adaptation and solutions to gain resilience. Both aspects are closely interwoven with social, economic, and cultural issues. Due to this complexity, the topic demands us to bring together knowledge from different disciplines to stimulate new scientific interactions. The threat of natural disasters, the resilience of the built infrastructure, and the weighing up of security requirements and life risks in the areas of society, economy and culture should, therefore, also be included in future planning processes and receive more awareness among decision-makers. Some specific questions that need to be addressed in this context are:

- How can we predict and guarantee structural and infrastructural safety in the future?
- How must we adapt our built environment to climate change tendencies?
- How can reliable infrastructure consider reduced carbon emission goals?
- How do we need to modify planning processes?
- How can we moderate transformation processes and gain the support of politics and society?
- How must we develop higher education to raise the right experts?

Hence, technical, planning, and societal aspects require an outbalanced discussion of safety, reliability, and material efficiency.

3.4 Healthy Environments

Much of the building sector's contribution to global warming comes from providing healthy and comfortable thermal, visual, olfactory, and acoustic conditions indoors, where we humans spend 90% or more of our time. At the same time, people living indoors and in urban areas are among those most affected by climate change, as this is where the adverse impacts of climate change are exacerbated (e.g. synergistic interactions between heat waves and urban heat island effects). Climate change, demographic change, and scarcity of resources are therefore increasingly challenging health and well-being—in addition to this, there are the consequences of the COVID-19 pandemic. Given the continuing urbanization, the city as a living space has a decisive role to play. Since the built stock characterizes European cities, solutions are needed for a sustainable and healthy transformation. Due to the complex interactions between people and space, solutions to increase the resilience of urban spaces, interiors, and their occupants require multidisciplinary and multiscale approaches. BLE focuses on the multidimensionality of existing cause-effect relationships. For this purpose, in addition to social and creative aspects, medical-physical (e.g. thermal, visual, electromagnetic, and acoustic exposures) and health-psychological aspects are increasingly being examined.

Urban spaces and buildings are among the most important contributors to greenhouse gas emissions. Research suggests that energy-intensive solutions accelerate climate change (and further degrade outdoor environmental quality), harm human health, and reduce human resilience. Therefore, Urban Health Solutions (UHS) addresses the core of BLE: the interactions between space and people—between the "built" and the "lived" environment. Due to the complex interactions between people and space, solutions to increase the resilience of urban spaces, indoor environments, and their inhabitants require multidisciplinary and multi-scalar approaches. UHS stakeholders present their work related to one or more of the following four scales:

- component and interior
- house & ensemble
- site & neighbourhood, and
- city & region. Altogether, these contributions consider: (I) multiple modalities, (I) interactions between environment and user, and (III) quality and value.

Multimodality includes consideration of multiple sensory modes (e.g. thermal, acoustic) and disciplinary backgrounds and targets (e.g. architecture and medicine; aesthetics; and health). Interaction and role of the user consider people in the urban context as active designers: indoors through their interactions to ensure comfortable environmental conditions and in the urban context for the co-design of transformation processes towards health-promoting urban districts. Quality and value represent the objectives of research and action defined on different scales and differentiated according to the disciplines. Good research questions include the effect of physical stimuli on human behaviour and health and the relation to energy use and sustainability. Methodologies reflect the diversity of approaches and have (a) new/mixed methods within laboratory environments, real buildings, and the urban context, including thoughts on understanding health in line with the salutogenic model and (b) theoretical approaches to healthy cities and regions.

4 Specific Approaches Towards the Support of Transformation

As the alert reader may have noticed, the general programme of BLE encompasses multiple issues related to transforming the built environment. Such an approach must depict all relevant interrelations and challenges when starting interdisciplinary cooperation. Therefore, BLE has elaborated several focus projects as test beds for collaboration among the scientist involved. This serves as a kind of starting point to subsequently explore the complex field of topics in a step-by-step manner. The projects presented below are all based on specific collaborations with local and regional stakeholders, thus addressing questions that have an immediate prospect of realization. Furthermore, they offer the opportunity to establish regional and cross-regional networks, which not only support the concept of thematic research but actually demand it.

4.1 Competence Network Space-Water-Construction

The flood disaster of July 2021 demonstrated society's dependence on flood and disaster control, land use, and infrastructure and settlement development. Sustainable solutions must be anchored in actor-oriented processes much more than in the past, beyond technical flood protection. To this end, BLE will bundle expertise from various specialist areas of the network (e.g. climatology, hydraulic engineering, urban water management, urban planning, and urban development) and combine a wide range of methods, e.g. safeguarding cultural heritage, climate impact modelling, land use planning, and process design. The aim is to set up the previous advice to public institutions (e.g. politics, administration, and associations) more concertedly and to bundle it with other partners from science and administration to form a competence network.

4.2 Cooperation Area Net Zero City Aachen Living Laboratory

The city of Aachen has been given special access to national and European funding by being named a "Net Zero City" by the EU. The goal formulated therein ("a happy, just, healthy, climate-neutral city") coincides with the research ambitions of BLE. In this respect, it was agreed to set up a joint living laboratory even more: to understand the entire city as a "real city of research" and to work together intensively in application-oriented research. Common events are planned for autumn 2022, at which the urban planning is to be compared with the BLE expertise and the EU funding agendas, and a roadmap for further action is to be developed from this. The aim is to research innovative methods and technologies for climate protection and climate adaptation in the city, also with the involvement of the RWTH campus development, and to implement them in pilot projects. Quality of life, health, and social balance are essential criteria.

4.3 Human-Building-Quarter Experimental Space

While the relevance of indoor spaces for health and well-being has already been recognized, the interactions between people, buildings, and the outdoor areas of the neighbourhood have yet to be researched. However, the pandemic has clearly shown how much health is being challenged by changes in living, working, and leisure behaviour and the associated socio-spatial behaviour. Likewise, climate change and the associated overheating of inner cities and rooms in summer cannot only be countered by technical adaptations of internal rooms. Holistic approaches are required here that consider the district's climatic interdependencies and behavioural patterns. For this purpose, BLE is building the experimental space Man-Building-Quartier, an interdisciplinary and transdisciplinary platform for researching the interaction between man and space using real (existing and experimental buildings), virtual and modelled spaces. This leads various BLE expertise together, including building technology, occupational and environmental medicine, climate impact modelling, district research, urban development, and open space planning. In addition to generating health-related knowledge, methodological questions are answered, such as the replicability of reality and its transferability to laboratory and simulation environments, especially regarding the inclusion of individual and social behaviour.

4.4 "Growth" Strategy

In addition to this research strategy, BLE has also developed a strategy of dissemination and engagement of further experts and stakeholders, e.g. a yearly conference is scheduled to show the BLE approach and expertise to a broader audience. To this end, in 2021, an online conference highlighted the summer flooding crises around Aachen. By showcasing the link to climate change and the multiple reasons for this disaster, BLE could shed light on its approach and engage further stakeholders in its work. In 2022 a follow-up will focus on the critical issue of RWTH campus energy supply—again to sensitize for the BLE approach but also to find hands-on answers through interdisciplinary discussions among RWTH researchers. According to the strategy, in 2023 the dissemination of BLE's work will address a national and international audience. Within a unique RWTH format—the Kármán-Conference—it is planned to gather experts from all over the world in Aachen to discuss the subject of "built-as-resource". The conference should facilitate knowledge exchange and discussion in this field and enhance the visibility of BLE in general.

As a "growth area" BLE is trying to engage Junior Principal Investigators (JPIs). To this end, several funding schemes are applied for, among them a call on "Profilbildung" launched by the federal state of NRW. The aim is to form a post-doc group that can boost BLE by its own research, support the work in focus projects, and engage PhD students across the faculties involved. JPIs have also been the focus of a BLE Science Day that was conducted in June 2021. Taking place in an inspiring environment—a so-called pop-up Campus funded by the BBSR—many JPIs can allocate their research to BLE core arenas, present their work, and exchange with peers. As a follow-up of the BLE Science Day (Day 2022), more than 20 JPIs gathered recently in two science workshops conducted by the RWTH excellence initiative. The workshops focus on successfully writing research proposals but also serve as a unique opportunity to team up for further interdisciplinary BLE research.

4.5 Perspective

A sustainable anchoring of the initiative at RWTH Aachen University seems promising. Funding from the state of North Rhine-Westphalia was approved as part of the Profil.2022 programme, which enables structured development. In particular, scientific employees (post-doc level) are funded for the core areas presented in Sect. 3, so that the research questions can be worked out in the form of concrete sub-projects. It is expected that this will allow other young scientists to be integrated into the core areas at short notice via project plans. The principal investigators of the participating faculties, who previously acted as the nucleus for the growth area, will continue to support the initiative and the sub-projects to be developed in an advisory capacity and by contributing their own resources. The timeframe for funding is from 2023 to 2026. After that, the initiative should be so deeply rooted that it can support itself through thematic funding.

5 Collaborative Teaching

Interdisciplinary teaching is part of the strategic development of RWTH Aachen University in the context of the "Exzellenzinitiative". Concerning buildings and the lived environment, different formats have been established in recent years, especially between the faculties of architecture and civil engineering. I might sound a bit offbeat to term such collaboration as "interdisciplinary",—but in fact, it is. The way of teaching, research, methods, and solutions differs significantly between architecture's more art-oriented discipline and civil engineering's more analysis-oriented discipline. While architects primarily work on a project base, civil engineers enjoy a traditional, fundamentally oriented education. Nevertheless, graduates from both disciplines need to work together and find standard solutions for factual project-oriented work in professional careers. Bringing together the fields in early stages and facing the contrast of education, responsibility, and the areas of influence are suitable to widen the view towards future problems and the openness for interdisciplinary collaboration.

In the framework of BLE, education can also significantly benefit from the other involved disciplines. It is aimed at establishing interdisciplinary projects with student groups of all parties which address topics of the BLE agenda. Student interviews underline that the young generation is very interested in such project work. Furthermore, a significant acceptance or rather an expectation for such ways of education can be especially observed for female prospective students. This could be a pivotal solution to increase the interest in technical study programmes for women.

The faculty of civil engineering (supported by the architecture faculty) is currently planning a new international master's programme, "Resilient Civil Engineering". This study programme tries to combine analytical, method-oriented teaching with specific projects. Lectures from both faculties plan the curriculum and will be part of the curriculum. Within the framework of the jointly designed projects, the scientific-technical approaches of engineering are combined with planning methods. The necessary intersections for joint research should also arise from this collaboration, and students should be introduced to thematic research in the field of BLE and its core areas. Student work in the master's programme can also be specifically integrated into project initiation or execution. Such collaborations are an essential starting point for a potential future study programme, "BLE".

6 Conclusion

A transformation in the built and lived environments is necessary due to various changing boundary conditions to reach sustainability development goals (SDG). Due to complex interactions, this process needs interdisciplinary efforts, methods, and expertise. The challenges and opportunities have led to establishing of a multi-disciplinary platform at RWTH Aachen University—the growth area "Built and lived environment" BLE. An essential part of the inter and transdisciplinary methodology is the cooperation in core areas aiming towards sustainable solutions alongside changing mindsets and behaviours and cultural practices of sufficiency. The needed transformation of the built and lived environment is a significant demand to our society, and it needs support by research and transformative moderation to guide as direct as possible towards SDG goals.

The core areas of BLE (decarbonized buildings, preservation and activation of the building stock, climate change and crisis adaptation and healthy environments) are essential to reach societal and economic goals in the longer run. In each of these areas, transdisciplinary research is ongoing and further strived in the future. Specific approaches based on living labs, competence networks, and experimental spaces give an insight into the transformative process of the growth area BLE and its growth strategy. Finally, transdisciplinary capacities are visible in the collaborative teaching approach, where new generations of students and lecturers learn based on interdisciplinary cases.

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Exploring Transformation in and Across Clusters of Excellence

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Abstract At the RWTH Aachen University, there are two Clusters of Excellence: The Fuel Science Centre (FSC) and the Internet of Production (IoP). Due to their complex structures, long-term funding, broad variety of disciplines involved and other exclusive characteristics, they provide high chances of change and might, thus, be seen as levers for transformation. In this article, the focus is put on the potential transformation on the content-level and the structures as well as the implications of transformation on the team and work processes are described since the Clusters of Excellence do not only underlie external influences fostering transformation (e.g. political decisions or environmental conditions) but also internal ones due to, for instance, staff turnover or new research findings influencing the future visions and operating of the clusters.

Keywords Cluster of Excellence · Transformation · Fuel Science Centre · Internet of Production

1 Introduction

"Nothing is so constant as change." (Heraklit of Ephesus, 535–475 BC).

In a world characterised by megatrends such as globalisation, demographic change or digitalisation on the one hand and by global crises such as climate change, the COVID19-pandemic, war in Ukraine, and resulting further crises and shortages e.g. in energy on the other hand, various respective challenges to science and society arise. Thus, actors across all levels of society, politics, research, and economy have to face the consequences resulting from these trends and crises in order to ensure

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P. Letmathe et al. (eds.), *Transformation Towards Sustainability*,
https://doi.org/10.1007/978-3-031-54700-3_14

future viability of, e.g. resources, production, and mobility. Consequently, processes and strategies need to constantly be reflected, adapted, and transformed in order to be able to foster this challenge of viability.

Major branches of both economy and research in Germany, which underlie those trends and the challenge of constant adaptation presented, are production and (renewable) resources. In order to tackle such overarching and complex topics, the Excellence Strategy of the Federal Government and the Federal States was launched in Germany. With this strategy, Clusters of Excellence (CoE) have been created in order to conduct scientifically excellent research on central topics of today's time, sustainably strengthen Germany as science location, and further improve its international competitiveness (https://www.dfg.de/foerderung/programme/exzellenzstrategie/). Due to the CoE's long-term funding, the adaptation of contents and structures is inherent in their nature, resulting in various chances and often needs for transformation as well. Since the CoE are of interdisciplinary nature, the aim is to foster the complex research questions. This nature also results in further implications with respect to the chances the CoE provide, not only on the technological and scientific levels, but also on the structural and social levels. Therefore, CoE might also be levers of transformation with respect to scientific output and solutions to the trends and challenges, but also regarding structural developments in the German research landscape and how research is conducted in the future. In this article, two CoE are put under investigation in order to describe the (ongoing) transformation in these organisational research units: the Internet of Production (IoP) and the Fuel Science Centre (FSC), which both are currently in their second funding phase. These two clusters will be described in more detail in the following paragraphs for laying the basis of identifying aspects of transformation and providing insights into the hypothesis of CoE being levers of transformation.

The **IoP**, on the one hand, has its origins in the CoE "Integrative Production Technology for High-Wage Countries", which was funded from 2006 to 2017 during the first funding phase of the Strategy of Excellence. It worked on the development of innovative solutions to ensure the future viability and competitiveness of the local manufacturing sector. Success includes, for example, developments of new intelligent production systems, solutions for the efficient production of customised components, end-to-end product life cycle management (PLM) and increasing networking and collaboration. Production technology makes an important contribution to prosperity and social stability in high-wage countries. Manufacturing is one of the core sectors of the European labour market. Confronted with increasingly intense global cost pressures, however, it finds itself caught between the conflicting demands of economies of scale, planning accuracy and forecasting ability, and is exposed to a rapid and value-oriented need for adaptation. The focal points of the cluster's internal research projects were in the areas of individualisation, virtualisation, as well as integration and self-optimisation of production. In the research area of individualised production, the tension between manufacturing customised products as cheaply and efficiently as possible was researched. The goal was to produce economically competitive products from batch size one. The focus was therefore on radically shortening the product development process in order to get from the idea to the individual product as quickly and cheaply as possible. To increase development productivity, the research projects pursued different approaches.

The Internet—in its meaning of a worldwide socio-technical network—has revolutionised accessibility of data and knowledge. This idea has been transferred to the physical world with the concept of the Internet of Things (IoT). A direct application of the IoT approach to production is currently not sufficiently feasible, as there are many more parameters, but much less available data compared with other big data application domains. Modern production is characterised by vast amounts of data. However, this data is neither easily accessible, interpretable, nor connected to gain knowledge. The IoP's vision is to enable a new level of cross-domain collaboration by providing semantically adequate and context-aware data from production, development and usage in real-time on an appropriate level of granularity. The central scientific approach is the introduction of Digital Shadows as purpose-driven, aggregated, multi-perspective and persistent datasets. The IoP will design and implement a conceptual reference infrastructure for the Internet of Production that enables the generation and application of Digital Shadows (https://gepris.dfg.de/gepris/projekt/390621612?language=en).

For the realisation of the IoP, Aachen's highly renown researchers in production engineering, computer science, materials engineering and further necessary disciplines team-up to solve interdisciplinary challenges, like the integration of reduced production engineering models into data-driven machine learning for cross-domain knowledge generation and context-adaptive action. The IoP will be leveraged by the production engineers in order to support a new way of more holistic working on—and with—systems by developing and advancing engineering tools, methods and processes. Therefore, an integrated development for the entire production technology is required. Aachen—as the starting point for the IoP—is characterised by an extraordinary range and outstanding reputation in production research as the results of the previous CoE "Integrative Production Technology for High-Wage Countries" clearly illustrate. The RWTH Aachen Campus offers a unique infrastructural environment including a broad range of research institutes and industrial companies allowing for an integrative development and validation of the IoP. Interdisciplinary collaboration is fostered by an environment that, among others, includes the support of early career researchers by a Research School (https://gepris.dfg.de/gepris/projekt/390621612?language=en).

Big and visionary goals always carry risk both in conception and in the implementation and achievement of research outcomes. Within the IoP, one faces unpredictable challenges—especially in the context of disruptive changes due to new technologies or digitalisation in all areas of society. Future breakthroughs, for example in network technologies (5G networks) or computing power (quantum computing), might enable new alternative approaches to achieving our overall goals, which in turn also promise enormous opportunities. Therefore, the IoP pursues an agile research management approach that allows for continuous adaptation and further development of the planned approach.

For this purpose, the RWTH Aachen Campus offers unique infrastructural conditions with diverse research institutes and industrial partners for the integrative development and validation of the IoP. The balanced composition of participating researchers from five RWTH faculties and six non-university research institutions offers a unique opportunity to realise the vision of the IoP. The setup brings together outstanding researchers from the required disciplines. The participating institutions offer—in addition to principal investigators and associated researchers—more than 11 junior professorships (or equivalent) at the respective institutes. In addition, more than 85 postdoctoral researchers and 500 doctoral students complement the supporting resources. To ensure a significant impact of the Internet of Production, the cluster has access to a unique technical environment. The widespread pool of test benches, real production machines as well as laboratories of the participating institutes offers a first-class infrastructure and the developed and networked digital infrastructure of all participating institutes complements the technical infrastructure to lay the foundation for the IoP (https://www.iop.rwth-aachen.de/cms/Produktionstechnik/Forschung/~rgqp/Struktur-des-Forschungsprogramms/).

The **FSC**, on the other hand, derives from the CoE "Tailor-Made Fuels from Biomass" of the first funding phase of the Strategy of Excellence and continues its work by capitalising on its achievements to act as a structuring element at RWTH Aachen University and its partner institutions. Together with the Forschungszentrum Jülich and the two Max Planck Institutes at the Campus Mülheim, a world-class research environment will be established, which is embedded in a network of strategic partnerships with globally leading research institutions and companies. Joint appointment models for junior research groups, tenure track and lighthouse professorships will create attractive career paths within the German academic landscape.

The increasing availability of non-fossil energy technologies opens unprecedented possibilities to re-design the interface of energy and material value chains towards a sustainable future. The fundamental research in the FSC aims to integrate renewable electricity with the joint utilisation of bio-based carbon feedstock and CO_2 to provide high-density liquid energy carriers ("bio-hybrid fuels"), which enable innovative engine concepts for highly efficient and clean combustion. FSC will generate fundamental knowledge as well as novel scientific methodologies to replace today's fossil fuel-based static scenario by adaptive production and propulsion systems that are based on renewable energy and carbon resources under dynamic system boundaries.

The FSC "Adaptive Conversion Systems for Renewable Energy and Carbon Sources" aims at the generation of fundamental knowledge and novel scientific methods for the development of sustainable technical solutions to valorise renewable electricity and alternative carbon feedstock into liquid energy carriers for CO_2-neutral and near-to-zero pollutant emission propulsion systems. Current research on renewable fuels is focused on fuel replacements for present-day engine technology that are either biofuels from non-food biomass or e-fuels from CO_2 capture and utilisation. FSC goes far beyond this approach by defining the scientific basis for the development of bio-hybrid fuels through integrated design of production and propulsion systems. The targeted technologies are adaptive to anticipate the increasing diversification of energy supply and carbon feedstock availability for a mobility sector in transformation. The (electro-) catalytic production of fuels as well as chemicals is envisaged as an important enabler for flexible and economic value chains. Molecularly controlled combustion systems are targeted to maximise efficiency and minimise emissions during the recovery of the chemically stored renewable energy. Methodological approaches will be developed to assess and ultimately predict the environmental impact, economic viability, and societal relevance of the technical developments. The FSC strengthens disciplinary competences in natural sciences, engineering sciences, and social sciences and converges them in a dynamic team science approach. Forward-integration occurs from fundamental science to the complex systems of fuel production, mobility, and transportation. Simultaneously, system-level information is propagated back by inverse methodologies to enable an integrated molecular and machine design (https://www.fuelcenter.rwth-aachen.de/cms/Fuelcenter/Der-Exzellenzcluster/~smxo/Vision-und-Mission/).

Due to characteristics such as this complexity and long-term funding of the CoE, it can be assumed that they have many starting points and opportunities for transformation. In order to gain more insights into this assumption, the two CoE—IoP and FSC—are described in more detail with specific respect to their contents, structure, and implications on team and work processes within this article. Following this introduction to the clusters IoP and FSC, Chapter "An Actor in the Transformation Triad: The Platform Approach "REVIERa"" presents aspects of transformation within these CoE with regard to the derivation and changes in the contents their research focuses. Analogously, Chapter "Sustainability, the Green Transition, and Greenwashing: An Overview for Research and Practice" describes transformation of these clusters on their structural levels. Chapter "Infrastructures and Transformation: Between Path Dependency and Opening-Up for Experimental Change", then, supplements these levels by deriving the impact of transformation in the CoE with respect to the work and the team processes taking place within the clusters before providing an outlook to possible future onsets of further transformation.

2 Transformation on the Content-Level

Inherent to both CoE under investigation in this article with respect to transformation on the content-level is the adaptation towards new technologies, methods, and processes. This transformation in both IoP and FSC also reflects in the change of the CoE's names from the first to the second funding phase: while the FSC has transformed from "Tailor-Made Fuels from Biomass" to "Fuel Science Centre", the change in the IoP is represented by the names "Integrative Production Technology for High-Wage Countries" to "Internet of Production".

With respect to the latter, content-driven transformation has evolved from the expansion towards a focus on data and the amplified integration of data-oriented and -processing disciplines such as computer and data science on the one hand. On the other hand, the contents of the IoP have also transformed with respect to the processes and research subject since it shows a change from black to green production. With respect to the FSC, transformation on the content-level has mostly derived from the finite nature of fossil fuels and the national strategy for the elimination of combustion engines in the (private) mobility sector.

This content-based transformation of the two CoE derives from environmental and political changes as well as scientific findings that have evolved both outside and inside the CoE since the start of the funding. Due to the major influences such as the climate crisis and finite fossil fuels, for instance, politics and science have reacted by transforming their contents to more sustainable and green solutions to enabling the life as we know it in terms of economy, production, and mobility. Thus, a content-based transformation also shows in both CoE: while the IoP changes its contents from black to green production, the FSC has increasingly oriented itself towards researching forms of fuels from various origins. This pressure to act in both CoE has various reasons: for the IoP, the reasons mainly derive from supply bottlenecks and shortages, energy transition, and a scarcity of resources; for the FSC, the changes predominantly result from political discussions and decisions with respect to the future handling of combustion engines and drive types. As has been shown in a study with 32 experts on the research field of the FSC—i.e. the European alternative fuels market such as politicians, non-profit organisations, and industries like chemistry, aviation, and automotive—the transformation of the fuels market and research is heavily under influence of legal framework conditions as well as the political discussions and goals (Jungnickel et al. 2022). The study also shows that there might be a policy-driven market development resembling an ongoing transition from fossil fuels to alternative ones with the aim of sustainability in those resources (Jungnickel et al. 2022). This transformation,appears to be particularly driven by the European Union Renewable Energy Directive (RED) as well as players such as the mass media and hydrogen-producing companies from Africa, and developments concerning the Northeast Passage as a region for alternative fuels transportation (Jungnickel et al. 2022). Moreover, the FSC's research is also influenced by political decisions and directives, which are made during the respective funding phases. The policy initiative "fit for 55" of the European Green Deal resembles an example for such political decisions with an impact on the FSC as it translates the EU's targets on handling alternative and fossil fuels into legal acts until 2030 (European Commission 2021).

These transformed contents the CoE work on are also reflected when investigating the outputs such as scientific publications. As far as the publications within the CoE are concerned, the topics they cover and are tagged with in, for instance, scientific journals or at conferences and their proceedings have transformed accordingly. Due to the changes in research domains or the orientation of the research focus, the scientific publications refer to these transformed topics as well, since they are a direct output of the CoE's research and reflect the respective processes within them. Across the different funding phases of the FSC, for instance, the main topics, i.e. "chemistry" and "engineering" have remained, but the variety of further topics has transformed (see Fig. 3). Besides the variety of topics (displayed by the differently coloured blocks in Fig. 3, each colour resembling a specific topic), the frequency of mentions within publications (displayed by the number in each coloured block in Fig. 3) has varied as well. During the funding periods, the topic of "energy fuels", for instance, has gained in frequency of mentioning which might derive from the increase of political discussions on the way fuel needs to be realised and (further) developed in order to be or become sustainable. Moreover, material-oriented topics such as "materials science" and "microbiology" in general—in addition to the established topics "biotechnology applied microbiology" and "biochemical molecular biology"—have emerged. This transformation on the content-level of publications as output of the FSC might result from the perceived pressure to act mentioned above as the way fuels are used and produced or developed and is subject to political and environmental debates and transformation themselves.

With respect to the IoP, in comparison, the transformation on the content-level shows in the design and conduct of the regular meetings such as the IoP Conference and Research Summits which both have taken place twice a year since the start of the funding. When considering the agendas for investigating the transformation of this CoE's contents, it shows that topics have changed here as well. A content analysis of the topics displaying in the agendas provides insights into a transformation towards more ecological and social topics over the course of the funding phases. Social aspects, however, have always been present in the regular meetings such as the Research Summit, the CoE-Conference or different workshops and trainings, which might derive from the existence of a Research School as a means for fostering interdisciplinary collaboration and the (further) development of soft skills. The Research School promotes the development of researchers at different scientific stages (Bachelor and Master Students, Doctoral Students and Postdoctoral Researchers). This includes the promotion of individual careers as well

Fig. 1 Central visual characterisation of the IoP Cluster of Excellence (https://www.iop.rwth-aachen.de/cms/Produktionstechnik/Forschung/~rgqp/Struktur-des-Forschungsprogramms/)

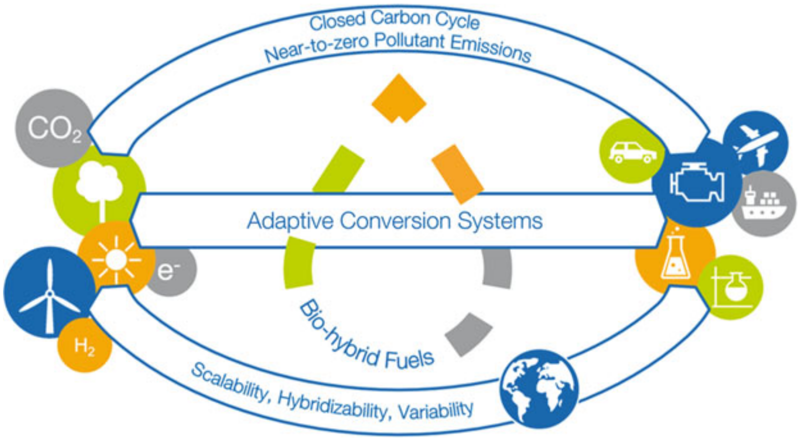

Fig. 2 Central aspects of the FSC cluster of excellence (https://www.fuelcenter.rwth-aachen.de/cms/Fuelcenter/Der-Exzellenzcluster/~smxo/Vision-und-Mission/)

as a systematic training programme that supports new topics and dynamics. Furthermore, researchers have the opportunity to participate in workshops, methodological trainings and micro trainings. The interdisciplinary exchange within the Research School fosters a cross-disciplinary, cluster-relevant learning environment. The main goals are to support academic excellence, promote interdisciplinary collaboration, and strengthen methodological, social, and personal skills. The target groups of the Research School are students, PhD students, and PostDocs.

Regarding the course of meetings, though, the agendas increasingly contain topics from the field of computer science, which complies with the observation that the overall contents of the IoP have transformed across the two funding phases so far. The agendas show a higher frequency of topics such as "digital shadow" and "intelligent production" resembling terms from the interface of engineering and computer sciences (see Table 1). Moreover, the content analysis displays a pursuit for ecological and collaborative topics such as "sustainability" or "cross-linkage to FSC" which might also result from the perceived pressure to act on environmental effects or influences of production.

This transformation on the content-level also brings a need to transform the structural level of the CoE as well which are put under investigation in the following chapter.

3 Structural Transformation

Analogous to the content-based transformation in the CoE, the necessity of transforming the structural level has evolved and increased over the past two funding phases as well. With the broadening of topics that are put under investigation within

Fig. 3 Transformation of topic areas in scientific publications across the funding phases of the FSC (from TMFB 1 to TMFB 2 to FSC)

Table 1 Overview of agenda topics of the IoP (2011–2022)

2014	2015	2016	2017	2018	2019	2020	2021	2022
(Self-) optimisation	Forming technology	Metrology	(Self-) optimisation	Virtual reality	Virtual reality	Internet of production	Networking with FSC	Interdisciplinarity
Automation and robotics	Material sciences	Material sciences	Virtual reality	Data protection	Machine learning	Cybersecurity	Virtual reality	Collaboration
Metrology	Requirements analysis and product development	Interdisciplinarity	Software development and simulation	Machine learning	Usability	Data infrastructure	Machine learning	Interdisciplinary publications
Forming technology	Human factors	Forming technology	Usability	(Self-) optimisation	Interdisciplinarity	Digital shadow'	Machine tools	Vision for next proposal
Optics	(Self-) optimisation	Laser cutting	Metrology	Forming technology	PhD process		Forming technology	Machine learning
Differences to World 4.0	Software development and simulation	Automation and robotics	Material sciences	Metrology	Digital shadow'		Good scientific practice	Internet of production
Machine learning	Machine tools	(Self-) optimisation	Forming technology	Optics			Metrology	Digital shadow'
Meta-research (on research projects)	Optics	Meta-research (on research projects)	Machine tools	Material sciences			(Self-) optimisation	Research data management
Machine tools	Metrology	Optics	Optics	Human factors			eMobility	
Requirements analysis and product development	Automation and robotics	Requirements analysis and product development	Requirements analysis and product development	Creativity and innovation			Requirements analysis and product development	

(continued)

Table 1 (continued)

2014	2015	2016	2017	2018	2019	2020	2021	2022
Laser cutting	Additive manufacturing	Gamification	Machine learning	Business model innovation			Material sciences	
Software development and simulation	Diversity management	Software development and simulation	Production theory	Ethics			Supply chain law’	
Organisational development	Production theoiy	Human robot interaction	Interdisciplinarity				Digital shadow	
Empirical methods	Entrepreneurship	Virtual reality	Additive manufacturing				Digital process chain	
Production theory	Organisational development	Machine tools	Automation and robotics				Intelligent production	

the two CoE and the corresponding increase in complexity of research, there has been a need for fostering and expanding interdisciplinarity, which constantly gains importance. Interdisciplinary collaboration is a challenging task that can lead to new knowledge and solutions. A successful interdisciplinary collaboration of different disciplines does not only refer to the cognitive level but also includes social, communicative, and organisational levels. On the structural level, thus, there is a transformation with respect to the amount of disciplines involved and, correspondingly, the scientific backgrounds of the clusters' employees, particularly the research associates and professors. In the case of the IoP, for instance, the expansion of the contents towards the enhanced inclusion of data science results in the integration of further disciplines such as computer science and data science itself, since it is not sufficient anymore to merely include different fields of engineering sciences which are directly connected to production technology.

This structural transformation is, however, not only dependent on the (further) development of the contents which the CoE's research is focused on. It also results from the overarching, general demand from the labour market and scientific community for educating T-shaped researchers rather than I-shaped ones. Due to the rising complexity of topics and problems to be solved, it is necessary to have people who have a broad as well as deep knowledge on their scientific contexts. Thus, researchers need to be educated deeply in their respective disciplinary field gaining corresponding expertise and deep methodological and factual skills of their discipline, by being simultaneously trained in broad transfer skills for being able to apply their knowledge in another field of expertise and cooperate efficiently and effectively with other disciplines or domains. It, thus, refers to combining hard and soft skills in a single researcher.

The two CoE under investigation in this article represent respective levers to fostering this transformation towards this trend or rather necessity for T-shaped researchers. This characteristic as lever results from their complex contents and structures: on the one hand, they provide the need and offer for (further) developing and applying one's own deep disciplinary expertise with respect to the problems to be solved within the IoP and FSC; on the other hand, they foster the (further) development of broad, transfer expertise as researchers in the CoE need to collaborate with other disciplines, make themselves understood, adapt methods and expertise, as well as integrate theories and results in interdisciplinary teams. For integrating the deep expertise on the disciplinary level, the contents of the FSC and IoP require a respective specified knowledge, methods, and processes in order to conduct the basic research their funding is oriented towards. For facilitating the development of broad expertise, the two CoE provide respective measures and events.

These measures include, for instance, regular meetings to give room for interdisciplinary exchange and foster the communication and discussion across the disciplines involved in the CoE. Thus, such meetings include workshops for strengthening collaboration across both disciplines and use cases or working groups (e.g. CA3 workshops in the FSC) on the one hand, and common meetings for all cluster employees (e.g. Research Summits in the IoP) on the other hand. These measures provide time and space for both disciplinary and interdisciplinary exchange, integrating ideas and perspective in order to form new ways of collaborating and researching within the clusters as well as disseminate insights and results of the research conducted so far. For particularly fostering the interdisciplinary exchange and collaboration, the nature of most of these meetings is moderated and interactive in order to integrate all employees accordingly as well as supporting the chance for transforming the clusters and their research continuously across all hierarchical levels and organisational structures.

The **IoP** includes various working groups, which are divided into Expert Groups and Demonstrators. The four Expert Groups consist of employees from different departments and faculties who are pushing different topics for the Internet of Production. The Expert Group Kubernetes "Cluster4aCluster" is based on an open source software. The Ontology Group addresses ontologies and semantics for the IoP. The Group Artificial Intelligence combines methods of AI research with targeted use cases with the goal of advancing the state of AI research in the IoP. The last group, Future of Work, bundles the competencies of the Future of Work and also focuses on the integration of humans into socio-technical production systems. The demonstrators are divided into electric vehicles, machine tools, and turbomachines.

As a result, an investigation of the potential to transformation on the structural level shows that transformation within such complex and interdisciplinary CoE such as the FSC and IoP requires a specific designation of communication. In order to successfully develop and transform, it is necessary to include and expand existing communicative measures and elements to successfully collaborate in interdisciplinary fundamental research. Moreover, respective communicative skills and measures also provide the chance for successful and effective knowledge management across all employees of the CoE. In order to undergo the structural and content-based transformations presented in Chapters "An Actor in the Transformation Triad: The Platform Approach "REVIERa"" and "Sustainability, the Green Transition, and Greenwashing: An Overview for Research and Practice", the knowledge across all those included in the CoE needs to be managed in terms of knowing about the included disciplines' methods, procedures, and theories, but most importantly the results and insights gained so far for further developing the visions of the CoE.

Another aspect of transformation on the structural level with respect to the CoE under investigation is the development of partner institutions. As has been shown in Chapter "An Actor in the Transformation Triad: The Platform Approach "REVIERa"", the scientific publications as output of the research processes within the IoP and FSC show signs of transformation with respect to the contents and topics the authors have written about. When not only considering the topics but also the structural data of publications, such as authors and affiliations involved, this scientific output can also provide insights into aspects of transformation. As for the FSC, for instance, an investigation of the publications across the two funding phases with special respect to affiliations shows an increase in university collaborates who have jointly published with FSC employees (see Fig. 4). In comparison to Fig. 3, the differently coloured blocks in this figure represent the different affiliations the collaborators come from while the numbers within these blocks resemble the number of persons collaborating with the FSC from the respective affiliation. Moreover, the transformation on the structural level represented by Fig. 4 might suggest a strengthening of the collaboration with German (university) partners, as the most frequent affiliations resemble institutions from the German research community such as "DWI Leibniz Institute for Interactive Materials", "Helmholtz Association", "Ruhr-Universität Bochum", or "Research Centre Jülich".

Resulting from the structural and content-based transformations presented above, it is also assumed to have affected the social level of the CoE under investigation. Thus, the impact and implications of those transformational aspects on the contents and structures of the FSC and IoP are discussed in the following chapter.

4 Impact on the Work and Team Processes

As has been shown in the previous chapters, the two clusters FSC and IoP have undergone transformations on various levels for the past decade since they are levers for transformation due to their complex, long-term, and interdisciplinary natures. The particular transformations of contents and structures also results in effects on the employees who actively shape the CoE and conduct the research processes within them. These implications, however, do not only affect the CoE internally with respect to their team and work processes, but also have impact on the IoP and FSC's environment, such as the research community nationally and internationally.

Deriving from the insights on structural and content-based transformations within the IoP and FSC (see Chapters "An Actor in the Transformation Triad: The Platform Approach "REVIERa"" and "Sustainability, the Green Transition, and Greenwashing: An Overview for Research and Practice") it is assumed to be necessary to foster knowledge management across all those involved. Due to changing structures and the continuous developments in methods to use and contents to research on, the researchers who are active in the CoE under investigation need to be supported in terms of sharing their knowledge during the transformational process. Since the IoP and FSC are university-based clusters, they underlie a certain employee turnover, e.g. due to limited time spans of PhD processes which results in continuous potential loss of knowledge and information. However, these pieces of information can be essential during the transformational processes in order to foster their successful conduct. Thus, a cluster-internal implication of transformation is the need for supportive measure considering knowledge management in particular.

As for the CoE under investigation, such measures have been developed and implemented. On the one hand, one supportive measure is the creation of a Research School, which is a group of cluster employees with special focus on providing supportive structures and skills for all those involved in the CoE in order to foster successful interdisciplinary collaboration and exchange as well as the (further) development of soft skills besides the disciplinary research. On the other hand, another supportive measure is the creation of web-based platforms. Both the FSC and IoP have created online platforms for knowledge securing and transfer across their working groups, use

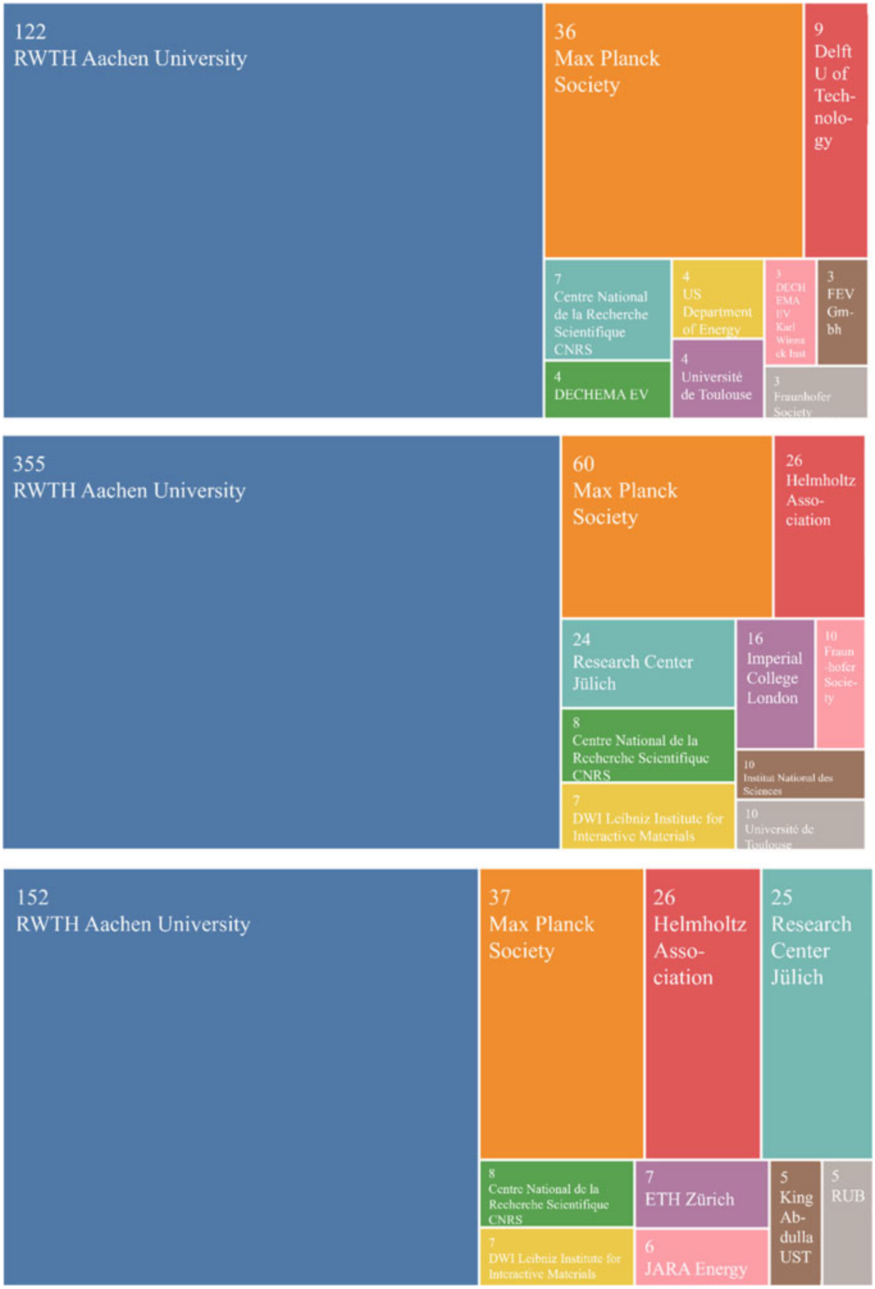

Fig. 4 Transformation of affiliations in scientific publications across the funding phases of the FSC (from TMFB 1 to TMFB 2 to FSC)

cases, events, methodologies, and employees in general. As for the FSC, for instance, the platform currently shows 190 users from 30 different institutes involved in the CoE. It is used for an overview over the CoE in general and its projects included as well as review its findings and processes as it involves more than 40 interdisciplinary projects that are put under investigation within the context of the FSC. Moreover, it supports the knowledge management as it provides crucial information on the processes in the FSC with respect to the nature and contents of the projects, the people who work on them, and the most important results. With these pieces of information, it is assumed to foster transformation by means of facilitating the identification of interfaces between different working groups, employees or institutes involved and the needs for further investigation. Also, the platform provides detailed information on each molecule the FSC researches on by displaying characteristics such as its structure and the need for further improvement or examination. These pieces of information are directly linked to the text description of each project by connecting it to the main results section.

With such measures like the platforms in both CoE under investigation, it is not merely possible to share, manage, and exchange knowledge on the current status of the transformation process, but also to provide insights into possible future interfaces. The implications of the content-based transformation of the CoE also concern the institutes involved in the IoP and FSC and their respective research outside of it. Analogous to the transformation of authorships and affiliations when considering the publications as scientific output of the CoE, the institutes involved have transformed with respect to their cluster-external projects and research as a transformation can be observed that constantly develops away from classic DFG individual proposals towards collaborative projects. Thus, CoE might be considered levers of transformation towards an increase in interdisciplinary collaborative projects due to their interdisciplinary nature that is characterised by close collaboration of employees across different disciplines and institutes.

Correspondingly, the CoE provide both a good visibility inside and outside the scope of the RWTH Aachen University. Due to the high number of people, disciplines, and institutes involved, there is a high chance of expanding the scope of the IoP and FSC's research and impacts. With all these employees and continuously transforming structures, contents, and staff, the CoE represent levers for transformation as they are characterised by a high number of contacts that derive from the partners involved. Thus, these contacts from cluster employees can benefit the CoE in general with respect to meeting the challenges of transformations on the content-level by getting in touch with further experts in the respective fields. Also, the transformations which the IoP and FSC undergo themselves continuously have impact on these contacts and their respective subject areas.

5 Summary and Outlook

As has been shown over the course of this article, CoE represent levers of transformation on different levels. With respect to the contents, they underlie external entities and circumstances fostering or sometimes forcing transformation since the clusters need to adapt their research according to their own findings but also to environmental situations and requirements. As for transformations on the structural level, the IoP and FSC have presented examples of the need to also internally change corresponding to the contents as well. Due to increasingly complex problems and methodologies for solving them, it has become more and more important to network with other institutions outside the CoE as well as foster interdisciplinary collaboration more closely within the CoE themselves.

Thus, the CoE provide chances for transformation due to their interdisciplinary and collaborative nature for fostering future problems and adapting themselves continuously towards future requirements. With their large size and long-term funding, they provide good examples of how transformation is practised and handled in terms of research processes. However, the transformations on the structural and content-based level in particular also raise further questions on the both cluster-internal and -external implications for the employees involved: it might be put under further investigation in the future, thus, if the kinds of jobs have changed that, on the one hand, the clusters look for when searching for new employees and, on the other hand, that the labour market provides.

The IoP has been able to gather various knowledge and research data in the past years. The future goals are to link this collected knowledge and data with each other. In addition, the IoP strives to integrate elementary cross-sectional tasks such as research data management, sustainability in production and structure as well as gender and diversity more strongly into the cluster. Thus, the interdisciplinary of the project becomes clear once again. Another challenge is to continue to promote interdisciplinary cooperation and communication between the various disciplines despite the high fluctuation of employees.

Acknowledgements Funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany's Excellence Strategy—EXC-2023 Internet of Production—ID: 390621612 and Cluster of Excellence 2186 "The Fuel Science Centre"—ID: 390919832.

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Research Transformation

Academia as a Key Factor in Fostering Responsible Research and Innovation with and for Society: The Case of the RRI Hub at RWTH Aachen University

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Abstract Nowadays, society faces challenges like climate change and inequality that are addressed by the Sustainable Development Goals. Academia plays a central role as a driver for innovation through research, teaching, and transfer to develop answers to these challenges. Responsible Research and Innovation (RRI) provides a framework for aligning research and innovation with societal needs. The technical university RWTH Aachen University considers RRI to be one of its main principles and established the RRI Hub as part of its excellence strategy in 2019. The RRI Hub is supposed to strengthen RRI in research, teaching, and transfer, with a focus on sustainable and responsible development, social innovation, and sustainable and inclusive artificial intelligence. This article describes the importance of academia to foster RRI and to structurally integrate it into universities using the example of the RRI Hub at the technical university RWTH Aachen. As a case, a participatory research project in the area of RRI is presented additionally.

Keywords Higher education · RRI · Sustainability · Transformation · Technical university

1 Introduction

In light of the interconnectedness of various societal challenges such as the COVID-19 pandemic or climate change, the United Nations 17 Sustainable Development Goals (SDGs) (United Nations 2015) show that sustainable solutions require the collaboration of different stakeholders and disciplines (Annan-Diab and Molinari 2017; Miller et al. 2014). Thus, a framework for addressing these challenges has been introduced by Responsible Research and Innovation (RRI), calling for socially responsible solutions to consider the needs of all societal stakeholders.

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P. Letmathe et al. (eds.), *Transformation Towards Sustainability*,
https://doi.org/10.1007/978-3-031-54700-3_15

In the European Union, Responsible Research and Innovation has gained increasing attention as a cross-cutting issue within Horizon 2020 (Owen et al. 2021). In short, RRI aims to align research and innovation with societal needs (Schomberg 2013) and envisions the collaboration of civil society, business and industry, policy-makers, the research community, and the education community to find solutions for global challenges. As part of the research and education community, Higher Education Institutions (HEIs) can be important actors in promoting RRI (Margherita and Bernd 2018; Tassone et al. 2018). HEIs can contribute significantly to finding solutions to global challenges through the socially responsible orientation of research, teaching, and transfer (Owens 2017). In particular, universities of technology have the responsibility of educating future engineers, as they are the ones to develop technical innovations (Crawley et al. 2014). Nevertheless, to achieve collaboration of different stakeholders in research and innovation, universities need to open up and conduct research with and for society (Tassone et al. 2018; Ritzen 2020). Thus, universities need to address RRI at different levels. However, prior studies show a lack of research on implementing RRI in higher education institutions (Tassone et al. 2018).

RWTH Aachen University in Germany, one of Europe's leading technical universities, has already created structures to strengthen RRI at the university level (RWTH 2019). With the establishment of the RRI Hub in 2019, a structure for pursuing responsible research and innovation on the three tasks research, teaching, and transfer, was established. The RRI Hub sees the assumption of social responsibility as the objective and the foundation of an excellent university and envisions becoming a nucleus for the socially responsible orientation of the university. Therefore, the RRI Hub conducts several activities interlinking research, teaching, and transfer and to strengthen cooperation of research and innovation within industry, society, government, and academia. We present the goals and activities of the RRI Hub in this article. Further, we present the results of a research-based teaching project, highlighting the relevance of the integration of RRI in research, teaching, and transfer and underlining the statement that interconnecting these three tasks can contribute to a successful implementation of RRI at universities.

Thus, this paper contributes to closing the research gap on implementing RRI in HEIs by pursuing the research question "What role do universities have in implementing RRI with and for society, and how can they succeed?". In section two, RRI will be defined, and the role of RRI in an institution of Higher Education will be explained, taking the specific case of a technical university. Here the current status of RRI at RWTH Aachen University will be deployed. Subsequently, section three presents the RRI Hub in detail by addressing its research, teaching, and transfer activities that aim to promote RRI systematically to serve as an example of how RRI can be implemented in universities. In section four, study results indicate the importance of RRI in technical HEIs and show that applying RRI to all three tasks, which the RRI Hub is implementing and has implemented so far, can be seen as a promising approach.

2 Responsible Research and Innovation

Within the 8th European Framework Program Horizon 2020, Responsible Research and Innovation gained increasing attention as a cross-cutting concept. RRI is a political concept that fosters "(ethical) acceptability, sustainability and societal desirability" (Schomberg 2013, p. 63) of research and innovation by putting society at the center of today's research processes and by aligning research and innovation more closely with society's values, needs, and expectations (Owen et al. 2012). Thus, research and innovation shall be sustainable and morally defensible, and societal interests should be involved in science and innovation to distribute responsibilities equitably among all.

2.1 Definition

The idea of RRI dates back to the early twentieth century and a discussion about the responsibility of science and technology (Owen et al. 2012), leading to an increasing need to link innovation and responsibility (Genus and Iskandarova 2018; Ribeiro et al. 2017). The European Commission has primarily shaped the recognition of the concept of RRI within the European Union during the last decade, with RRI then being a cross-cutting theme within Horizon 2020, the major funding program by the European Union (Owen et al. 2012; Geoghegan-Quinn 2014). Anticipating the impact of research and innovation on society and highlighting the importance of research and innovation in solving global challenges (Owen et al. 2012), the goals of Horizon 2020 include, for example, that actors such as scientists, citizens or organizations work together on research and innovation that fulfill the values and needs of society as a whole in the process and the subsequent result.

Even though different accounts have subsequently approached a formal characterization of RRI (Geoghegan-Quinn 2014; Stilgoe et al. 2013; Jeroen van den Hoven 2013), the most often used definition of RRI (Ribeiro et al. 2017) by von Schomberg (2013) states that RRI…

> "is a transparent, interactive process by which societal actors and innovators become mutually responsive to each other with a view on the (ethical) acceptability, sustainability and societal desirability of the innovation process and its marketable products (in order to allow a proper embedding of scientific and technological advances in our society)" (Schomberg 2013, p. 63).

The definition emphasizes the role of and in service of society and highlights the need for collaboration among business and industry, the education community, the research community, policymakers, and engaged citizens (Owen et al. 2012) (see Fig. 1) to achieve alignment of research with society's needs, as well as to find collaborative solutions to societal challenges and create societal benefit (Schomberg 2013; Tassone et al. 2018; European Commission n.d.).

In an attempt to unify discourses, the EU-funded project 'RRI Tools' (RRI Tools 2016) defined four process dimensions of RRI as a framework for the constant

Fig. 1 RRI concept based on RRI Tools (RRI Tools 2016)

exchange between society, politics, the education and research sector, and industry and business (see Fig. 1): diverse and inclusive, open and transparent, anticipative and reflexive, and responsive and adaptive. Diverse and inclusive refers to the diverse involvement of a broad spectrum of actors in research and innovation. This integration of everyone in the respective processes is intended to strengthen the democracy of society and make knowledge more usable. Under the claim to be open and transparent, findings of methods, results, conclusions, and impacts should be communicated openly and transparently. The third point is to look at research and innovation in an anticipative and reflective way to foresee essential insights into possible consequences and thus be more able to act in case of doubt. The last process dimension, responsive and adaptive (in the face of change), sets the goal of being able to adapt research processes and the required structural conditions to changing conditions, needs, or new scientific findings.

In 2014, the European Commission further highlighted six dimensions of RRI: engagement, science education, ethics, gender, open access, and governance (Italian Presidency of the Council of the European Union 2014). However, later, governance was no longer considered a key dimension as it was considered too challenging to implement in the work program and, moreover, it should be considered an underlying dimension of the other aspects (Owen 2013). Therefore, the European Commission addresses the five dimensions within the Science and Society work program (Owen et al. 2021). The first is to focus on research integrity/ethics and the acceptance of scientific and technological developments in science and society (RRI Tools 2016). The second dimension, gender equality, means that equal gender participation in teams and decision-making bodies should be promoted, and gender dimensions in research and innovation should be taken into account to improve the quality and social relevance of the results (RRI Tools 2016). The third point, open access, is about making scientific information accessible to all. This means making scientific work freely and directly available to improve and accelerate scientific research. In addition, this should facilitate cooperation between individual actors and promote a productive exchange with civil society (RRI Tools 2016). Fourth, public engagement aims to increase society's involvement in research and innovation processes, which are collaborative and depend on the cooperation of a wide range of actors. The intention is to involve all stakeholders throughout the processes and always align with all interests (RRI Tools 2016). The fifth point, science education, focuses on improving current educational processes, empowering citizens to participate in research and innovation debates, fostering new scientific talent, and increasing the overall number of researchers (RRI Tools 2016).

2.2 Responsible Research and Innovation at HEIs

As part of the education and research community, HEIs are supposed to be important stakeholders in RRI (Margherita and Bernd 2018). Education for and with society is a central principle of RRI regarding teaching at HEIs (Tassone et al. 2018). HEIs can address 'education for society' by addressing societal challenges in teaching using appropriate pedagogical concepts where students are active learners (Margherita and Bernd 2018; Tassone et al. 2018). 'Education with society' means integrating different actors in teaching and learning processes. Universities should offer interdisciplinary and transdisciplinary teaching formats by creating opportunities for exchange between students and scientists, government, civil society, or businesses (Tassone et al. 2018). Furthermore, HEIs can foster RRI in research and teaching processes, e.g., by offering inquiry-based teaching formats. By doing so, RRI helps in interweaving research and teaching activities. In research, RRI calls for integrating external stakeholders, like societal actors, in research starting from the beginning of a research process, and considering them as equal research partners (Levikov et al. 2020).

The policy level has already recognized the role of higher education in promoting RRI and has established funding mechanisms for integrating RRI in HEIs, e.g., on EU level through Horizon 2020. The likelihood of RRI being implemented within organizations increases when they actively participate in Horizon 2020 programs (Ryan et al. 2021). Besides, Ryan et al. (2021) show that HEIs are more likely to address RRI if they are characterized by a high level of research intensity and multidisciplinary orientation. However, few HEIs have addressed RRI in their policy frameworks (Tassone et al. 2018) and previous studies show a research gap on how

RRI can strategically be implemented in HEIs (Tassone et al. 2018). Tassone et al. (2017) state that "[f]ostering RRI in higher education curricula is about equipping learners to care for the future by means of responsive stewardship of research and innovation practices that address the grand challenges of our time in a collaborative, ethical and sustainable way." (Tassone et al. 2018, p. 343).

Technical universities could have an essential role in promoting RRI. Including RRI in STEM education trains responsible innovators who, in turn, take RRI into account in later research and development processes. However, to the best of our knowledge, no studies or articles consider the particular role of technical universities in promoting RRI. Therefore, this article also demonstrates how technical universities, using RWTH Aachen University as an example, can successfully implement RRI in research, teaching, and transfer.

We argue that RRI should be implemented holistically in all institutional structures. At the institutional level, RRI should be addressed as a framework. Furthermore, as proposed by the concept of RRI, universities should consider RRI in all three tasks, research, teaching, and transfer, as cross-cutting concept. Following Ribeiro et al. (2017), multiple actors like civil society, industry, and researchers from different disciplines must all contribute to responsible research and innovation. Based on this, HEIs must open up to societal demands and stakeholders to foster RRI.

3 The Responsible Research and Innovation (RRI) Hub at RWTH Aachen University

In the following sections, we show how RWTH Aachen University addresses RRI in research, teaching, and transfer, exemplified by the Responsible Research and Innovation Hub.

3.1 Implementing RRI at RWTH Aachen University—The RRI Hub

RWTH Aachen University started actively assuming the role of initiator and structure provider for socially responsible and sustainable innovation by integrating RRI into its Excellence Strategy in 2019. As part of the Excellence Strategy of the German Federal and State Governments, RWTH was successfully named one of Germany's Universities of Excellence in 2019. Under the heading 'The Integrated Interdisciplinary University of Science and Technology. Knowledge. Impact. Networks.' (RWTH Aachen University 2019), RWTH Aachen University strives to become one of the central national players in the science system that provides sustainable solutions for current and future global challenges. RWTH's vision is "to further grow beyond a unique integrated, interdisciplinary university by embracing the convergence of knowledge, approaches and insights from the humanities, economics, engineering, natural and life sciences, i.e. biology and medicine" (RWTH Aachen University 2019, p. 1).

Within the Excellence Strategy, RRI is explicitly addressed and called for as "one of the guiding principles" (RWTH Aachen University 2019, p. 47). This integrative approach served as the basis for developing the RRI Hub.[1] As part of the Excellence Strategy's measure 5, 'Collaborate in Living Labs', the RRI Hub was installed with the goal of "foster[ing] the cooperation between science and civil society in order to find meaningful solutions to complex challenges" (RWTH Aachen University 2019, p. 47). The RRI Hub aims to anchor responsible research and innovation as one of the central guiding ideas in research, teaching, and transfer, and become a nucleus for a socially responsible orientation of the university.

The RRI Hub sees the assumption of social responsibility as the objective and the foundation of an excellent university. It is guided by the image of an integrated and interdisciplinary university that is responsible for developing technical solutions to global challenges in its research programs and, at the same time, training future experts (students) who contribute to the sustainable implementation of these solutions in different areas like civil society or business and industry. The RRI Hub aims to strengthen cooperation in research and innovation within industry, society, government, and academia (as part of the research and education community in the RRI concept), following the idea of the quadruple helix (Carayannis and Campbell 2012, 2009; Afonso et al. 2012).

3.2 The Conceptual Framework and Ecosystem of the RRI Hub

The RRI Hub's vision is to become a nucleus for a socially responsible orientation within the three guiding tasks of universities: research, teaching, and transfer (see Fig. 2). The overall mission of the RRI Hub is to foster sustainable and socially responsible research and innovation that meets societal needs. Therefore, the RRI Hub pursues two goals: (1) to foster cooperation between science and civil society to find meaningful solutions to complex challenges in research, teaching, and transfer and (2) to promote and foster the recognition of social commitment through research and transfer. To create opportunities for cooperation, the RRI Hub aims to network, bundle, and concretize competencies through a reciprocal relationship between RWTH Aachen University and other actors, such as civil society. In particular, the RRI Hub focuses on educating students to be responsible innovators of tomorrow to find solutions for global challenges as they are addressed by the 17 SDGs within its teaching activities. To achieve its goals, the RRI Hub incorporates inter- and transdisciplinary perspectives by integrating different disciplines and actors in its teaching and research activities.

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[1] www.hub.rwth-aachen.de.

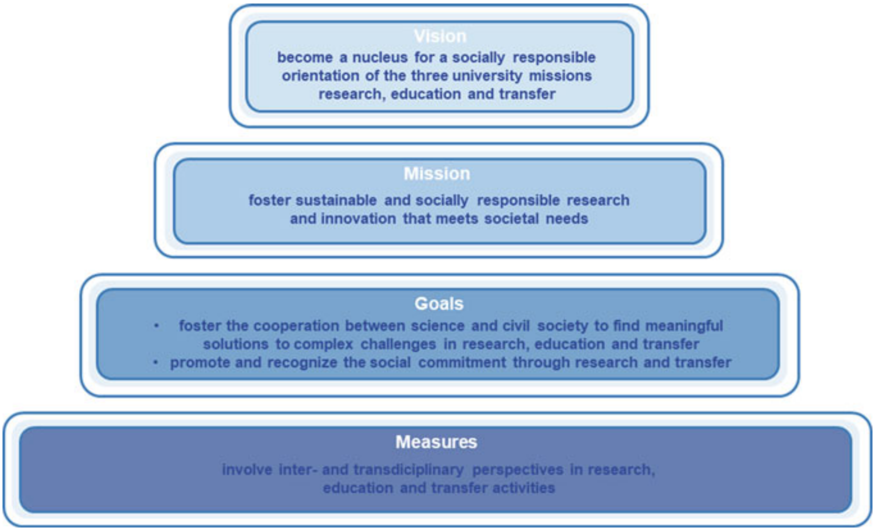

Fig. 2 Vision, mission, goals, and measures of the RRI Hub

All of the activities of the RRI Hub are framed by the Sustainable Development Goals. As an academic actor, the RRI Hub operates in research, teaching, and transfer with different actors of the quadruple helix (Afonso et al. 2012) and has already established successful collaborations based on a community-building approach characterized by reciprocity, interaction, and mutual respect (Berg et al. 2020). In **society**, the RRI Hub works together with, for example, Nongovernmental Organizations (NGOs) to promote civic engagement. Furthermore, the RRI Hub collaboratively works with other partners from **academia** (e.g., other HEIs in Aachen, Germany and worldwide). Here, joint teaching activities and research projects are conducted on topics related to the 17 SDGs. Further, collaboration with **governmental actors**, like the municipality of Aachen, is part of the transfer activities of the RRI Hub, aiming to sensitize for RRI and strengthening joint activities between academia and other actors. Lastly, collaborations with **industry** are, for example, established within teaching such that industry partners are invited to give talks in courses and seminars.

3.3 The Focus Areas of the RRI Hub

The RRI Hub's activities within research, teaching, and transfer are located within three focus areas (see Fig. 3). The focus area of sustainability and responsible development forms the overarching thematic focus of the RRI Hub. All activities aim to promote a socially responsible and sustainable orientation of research, innovation, and education. Based on this, the focus areas social innovation and social entrepreneurship, and sustainable and inclusive artificial intelligence are derived.

Promoting social innovation and social entrepreneurship is one practical way HEIs can actively implement and support RRI and contribute to achieving the SDGs. Furthermore, despite the demand at the EU level, social innovations are not yet systematically promoted at universities (Cinar and Benneworth 2021). Artificial intelligence as general purpose technology (Cockburn et al. 2018) has become a driver for innovation and technological change (Littman et al. 2022) in various application fields with highly influential power and therefore radiates into many disciplinary domains. Besides, AI is known to equally transform science and society (Harari 2017).

Sustainability and Responsible Development

As the overarching thematic focus, all of the RRI Hub's activities are aligned with the SDGs and have sustainability and responsible development as their starting point and main focus. For example, various SDGs are addressed in all courses and seminars offered with the aim of addressing a holistic understanding of sustainability, demonstrating the importance of all dimensions, and enabling students to act responsibly. Furthermore, all of the RRI Hub's research activities aim to contribute to the achievement of a sustainable and responsible future. Science with and for society,

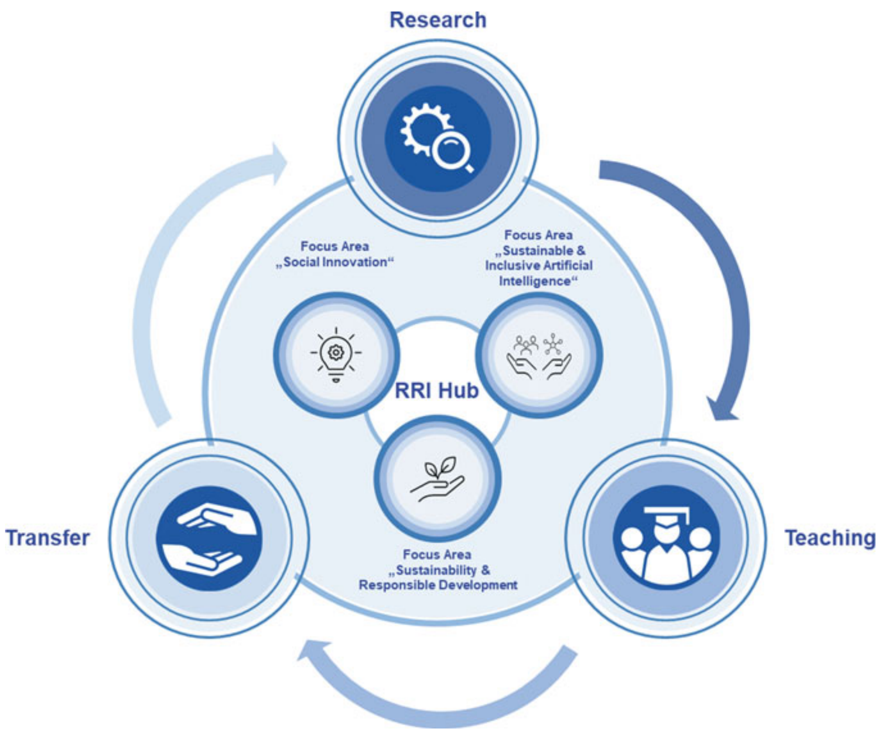

Fig. 3 Relational diagram of the activities of the RRI Hub

as addressed in the RRI concept, forms the conceptual framework of the RRI Hub's research activities.

Social Innovation

Current global challenges, as they are, for example, addressed by the 17 SDGs, show that innovative solutions are needed that go beyond technical innovations (Bayuo et al. 2020). The importance of social innovation and social entrepreneurship in addressing global challenges has been increasingly discussed in the literature in recent years (Cinar and Benneworth 2021; Bayuo et al. 2020; Benneworth and Cunha 2015; Cinar 2019; Cunha and Benneworth 2020; Kumari et al. 2020). Connected to RRI, social innovations are often characterized by collaboration between different actors so that, in the sense of the quadruple helix, industry, civil society, government, and academia are all involved in the innovation process. In particular, the role of academia and universities has been increasingly discussed in recent years (Bayuo et al. 2020). Within its report 'A European Ecosystem for Social Innovation', the European Commission highlights universities' role as a driver for social change by promoting social innovation and states that universities and social organizations should create opportunities for dialogue between different stakeholders (European Commission, Directorate-General for Research and Innovation, Georghiou L 2018). By promoting RRI, HEIs could highlight the need for collaboration between science and society or government, which could foster HEIs' role in social innovation. However, studies show that universities have not yet established supporting conditions for social innovation and social entrepreneurship on all university levels (Bayuo et al. 2020). Besides, there is still a lack of research on the role of universities, particularly technical universities, in social innovation processes (Cinar and Benneworth 2021; Bayuo et al. 2020; Berg and Leicht-Scholten 2021). With a growing interest and relevance of social-tech entrepreneurship (Calderini et al. 2021), technical universities can contribute to finding solutions to global challenges by promoting and connecting social innovation and technical innovation.

Based on the intersection of social innovation and RRI, the RRI Hub works on topics such as social innovation and social entrepreneurship in research, teaching, and transfer. In particular, the RRI Hub explores the role of technical universities in fostering social innovation and social entrepreneurship. The RRI Hub's research also addresses the extent to which students at technical universities already understand social innovation and the extent to which they can envisage a professional future as founders or employees in a social enterprise. The aim is to close the research gap on the role of universities in social innovation and to derive recommendations for action for technical universities.

Sustainable and Inclusive Artificial Intelligence

Current developments show that digitalization and AI reach a diverse field of application areas with highly influential power. Digitalization and AI have become drivers for transformation and technological change and will have a long-term influence on society and communities (Littman et al. 2022), productivity, equality, and the environment (Vinuesa et al. 2020). Consequentially, AI impacts sustainability as defined by the UN SDGs in its many dimensions. For example, AI may help to reach the basic provisions of clean potable water, green energy, and food security (Mondejar et al. 2021).

Yet, it is not a straightforward task to analyze the transformative outcomes of digitalization and AI with regard to its positive or negative impacts. While AI may have a negative impact on 59 targets of the SDGs, more than three-quarters (134 targets) may benefit from the use of AI (Vinuesa et al. 2020). By focusing on sustainability's economic pillar, AI is estimated to add around 14% to the global economy by 2030 (Mondejar et al. 2021). However, using AI will also lead to significant changes in the work environment and introduce new risks for the labor market (Rajnai and Kocsis 2017). In the pillar environment, it is important to recognize the ongoing discourse between AI for sustainability and the sustainability of AI. The latter is less often addressed in current research, although the technology itself has huge environmental costs (Vinuesa et al. 2020; Wynsberghe 2021). To gain a meaningful overview, the whole socio-technical system needs to be considered (Wynsberghe 2021). The positive impact of AI on the (societal) infrastructure, such as transportation, energy, and education will also create new dependencies and must be addressed in the early stages of integration and development (Robbins and Wynsberghe 2022). Perhaps the most difficult influences to predict and relate to the third pillar of sustainability: society. Taking the World Wide Web as an example, we see that digitalization has the potential to distribute access to knowledge, information, and skills, and may also be an enabler for political participation. However, in many countries, the web lacks clear practices to protect privacy or act against discrimination, and it is currently controlled by large companies and states with the possibility to limit freedom of speech. Furthermore, many poor areas still do not have any access—thus, the web may even increase inequalities (Foundation 2015). Moreover, the discussed transformations exhibit a clear deficit with regard to SDG 5 'Gender Equality' (Vinuesa et al. 2020). A digital gender gap can be observed online (Initative D21 e.V. 2020), and beyond, examples of discriminatory AI with respect to gender or race accumulate [e.g. (Barocas et al. 2017)]. Meanwhile, more and more initiatives address AI for social good (Cowls et al. 2021) as AI has become an important means to identify problems (e.g., poor areas (Jean et al. 2016); discrimination (Heinrichs 2021)) and thus can generate actionable knowledge.

This actionable knowledge may bridge gaps between society, technology, and academia and may enhance adequate strategies for governance. In particular, as a cross-cutting topic, a fair, sustainable, and inclusive use of AI radiates into all other focus areas. Looking ahead to the field of social innovations and entrepreneurship, AI-applications are seen as both: a general purpose technology which can be used for various applications in various fields (Cockburn et al. 2018), but also as an invention as a method of invention (Cockburn et al. 2018), so it can, for example, be used to address urgent environmental challenges with novel methods (George et al. 2021). It is a straightforward conclusion that RRI initiatives must address the impacts of AI and digitalization. Taking AI and digitalization as the focus of RRI will help to analyze and address societal impacts from a long-term perspective. Therefore, the RRI Hub conducts research on how to integrate sustainability and diversity perspectives in AI systems for ethical and responsible use.

3.4 *Research—Teaching—Transfer: The Three Tasks Addressed by the RRI Hub*

An overall goal of the Excellence Strategy (RWTH Aachen University 2019) is to "create a unique education, research, and transfer hub with dynamic research networks crossing disciplinary and organizational borders" (RWTH Aachen University 2019, p. 1). The RRI Hub therefore fosters engagement across the three tasks: research, teaching, and transfer. In line with RWTH's Excellence Strategy, transfer is "the continuous and mutual exchange of ideas, knowledge, technologies and people within RWTH, with partner organizations, societal groups and industry." (RWTH Aachen University 2019, p. 20). This means to drive collaboration between academia and society as well as industry and government. However, to have a holistic effect in all university areas, the combination of the three tasks is essential.

Research

The Excellence Strategy formulated the research mission of the RRI Hub as follows: "An essential component of the RRI Hub is to integrate students in interdisciplinary research teams working on solutions to real problems with non-profit organizations" (RWTH Aachen University 2019, p. 47). Therefore, the RRI Hub conducts research in RRI and integrates students' and societal perspectives through a responsible and sustainable design of research and development processes. The goal of the RRI Hub's research is a better alignment of scientific results and societal needs through open participation. Integration of citizens in research processes ranges from a passive consumption of science to a high engagement, for example, in data collection and analysis (see ladder of participation, Arnstein 1969). The RRI Hub conducts research projects using methods such as citizen science and living labs. Living labs are to be understood here as temporally and spatially limited test spaces where innovative technologies and models can be tested under real-life conditions as an appropriate, concrete way to involve citizens in the design and experimentation of new innovations (Wagner and Grunwald 2015).

Examples of Research Activities

One example of research activities of the RRI Hub is the Living Lab Templergraben (Templergraben 2023), a collaborative project with partners from different sectors, for example, the student initiative Uni.Urban.Mobil, the NGOs VCD and ADFC, the city of Aachen, and the AStA (student representation) of the RWTH Aachen University. The goal was to evaluate mobility concepts by closing a particular road in the main campus area to individual motorized traffic and, at the same time, evaluate the use of the resulting newly created spaces. The RRI Hub supported this project and, in particular, conducted quantitative research, evaluating the acceptance and success of the project.

Furthermore, international cooperation can enhance the quality and impact of research. Currently, two projects are planned with international partners on the focus topics of ‘social innovation’ and ‘sustainable and inclusive artificial intelligence’. Thus, the RRI Hub works on research projects together with other European universities. In the field of social innovation and social entrepreneurship, the RRI Hub conducts research with partners of the ENHANCE Alliance. Through a survey among students at the ENHANCE universities, the research project aims to examine how social entrepreneurial structures impact STEM students’ social entrepreneurial intention. The study will also contribute to explaining how perceived social norms could affect STEM students’ social entrepreneurial intention. Thus, the results could contribute to discovering how technical universities can strengthen and support social innovation processes. Accordingly, a journal paper on the role of European technical universities in social innovation processes will be published in 2024.

To assess algorithmic bias and unfairness in the context of ‘Sustainable and Inclusive Artificial Intelligence’ (Decker 2021), research on participatory approaches for fair Explainable AI (XAI) is planned. Giving credit to the fact that perceived fairness of AI heavily depends on several factors, such as the circumstances under which a decision is presented (Grgic-Hlaca et al. 2018), explanations must be understandable and well-interpretable for laypersons who are affected by a decision but do not have any background knowledge on AI (Decker 2022). Therefore, non-experts, and in particular those who are often not involved in decision-making processes, shall be involved in the development of fair and inclusive AI.

Education and Teaching

As a university with a focus on the technical sciences, RWTH Aachen University sees itself not only with the responsibility to develop technical solutions for global challenges but also to train excellent experts who will contribute to the development of solutions and their implementation in science, industry, and society (Leicht-Scholten and Krieg 2019). As future decision-makers, students have a decisive multiplier role in implementing sustainable development as described by the Sustainable Development Goals (United Nations 2017). This means a mutual exchange of ideas, knowledge, technology, and people within the university, with partner organizations as well as with business and society. Active learning approaches, such as problem-based, project-oriented, and case-based learning have been proven to be the most appropriate methods for providing meaningful education for sustainable development (United Nations 2017; Beagon et al. 2022). These approaches empower students to explicitly take action instead of remaining simple ‘observers’ of the world around them. The RWTH Aachen University has developed its strategy for a competence-oriented, research-led, and practice-related education of highly qualified and responsible graduates where social responsibility forms the foundation for excellent research (Hochschulrektorenkonferenz 2017; RWTH Aachen University 2009; Steuer-Dankert et al. 2019; Leicht-Scholten et al. 2020) and “[e]lements of social responsibility and sustainability will be gradually integrated in the educational framework of all curricula." (RWTH Aachen University 2019, p. 47). A strong opening of the HEI in the direction of civil society and active participation of the students in social issues can move social commitment specifically into institutional focus. Problem-based learning and project work are a means to strengthen RRI and science education in educational institutions (Hazelkorn et al. 2015).

To train responsible innovators for sustainable development, the RRI Hub offers teaching formats in cooperation with various internal and external university actors. The goal here is to teach students to acknowledge their own social responsibility and to empower them to take action towards achieving the SDGs. The RRI Hub pursues competence-oriented teaching in all basic and advanced modules and offers interdisciplinary and cross-cutting modules to convey intercultural competencies and global perspectives.

Examples of Teaching Activities

Examples of the RRI Hub's teaching activities include interdisciplinary courses within Project Leonardo, a project at RWTH Aachen for interdisciplinary courses on social challenges in which lecturers from different disciplines contribute their expertise. The RRI Hub offers, together with the FH Aachen and the Catholic University of Applied Sciences Aachen, the course 'Sustainability and Transformation as an Opportunity and Challenge for Society'. In this course, the various dimensions of sustainability are considered and discussed. Building on keynote speeches, current problems are worked on in cross-university and cross-disciplinary groups, and proposed solutions are developed. Based on the concept of citizen science, the course invites speakers from all sectors: experts from various scientific fields, (social) start-ups, civil societal actors like NGOs, and governmental actors. This approach allows students to consider sustainability holistically and to learn about it from the perspective of different experts. On the other hand, the experts can explore the students' points of view during the discussions (Hub 2022).

Furthermore, two significant projects will be implemented in 2023. Promoting responsible societal transformation is one goal of the European university alliance 'ENHANCE'. The alliance, consisting of different technical universities in Europe, has been funded by the European Commission since the end of 2020. Within ENHANCE, the RRI Hub has developed the Massive Open Online Course (MOOC) 'Responsible Innovators of Tomorrow' in collaboration with colleagues from other ENHANCE universities. Based on the OECD Learning Compass (OECD 2019), the MOOC covers topics related to responsible innovation, with a focus on science and technology studies. Embedded in this European project, students will not only learn more about topics like RRI and social responsibility but will also get the chance to exchange with international experts (https://enhanceuniversity.eu/about-us/). Furthermore, the RRI Hub integrates project-based learning in different teaching formats, for example, in a seminar on current challenges in the context of RRI and in a Winter School on RRI, which was offered in March 2023.

Transfer

As already mentioned, the RRI Hub pursues the goal of strengthening the transfer to society and the involvement of non-academic stakeholders in research and innovation processes to find solutions for global challenges. To this end, various projects are implemented with regional, national, and international actors. Furthermore, at the university level, the RRI Hub collaborates with diverse actors such as, for example, with the Staff Unit for Sustainability and University Governance (see Höhl et al. 2024), rectors delegates for sustainability in teaching and research, and with the student representation (AStA) of RWTH Aachen University.

Examples of Transfer Activities

The RRI Hub works together with the city of Aachen, the civic foundation Lebensraum Aachen, and the AStA of RWTH Aachen University in a project called 'Engagierte Stadt' ('Engaged City'). In Germany, there are more than 100 cities that have received the 'Engagierte Stadt' label and thus promote civic engagement (Engagierte Stadt 2022). The difference in Aachen, compared to other cities, is the cooperation of different actors from civil society, academia, student body, and government within the framework of the 'Engagierte Stadt'. The aim of the project is to create a democratic, diverse, and solidarity-based society in which engagement is actively lived. Besides, bundling resources, networking and exchange, and making engagement visible are the main goals of the project. For this purpose, among other things, a regular exchange of the actors takes place and joint projects are implemented.

Furthermore, the RRI Hub is a co-initiator of the network 'Social Entrepreneurship Euregio (SEEu)'. SEEu is committed to building an ecosystem for social and sustainable innovation in Aachen and the Meuse–Rhine Euroregion (Social Entrepreneurship Euregio 2022). The network was initiated by Aachen's universities and other organizations from Aachen's business community and civil society. The target groups are students, start-up entrepreneurs, social entrepreneurs, and all those interested in sustainable and social innovation. SEEu organizes events, e.g., on the topic of impact investment and offers networking and exchange of experience to founders, start-ups, and all those interested in social entrepreneurship.

4 How to Practically Interconnect RRI in Research, Teaching, and Transfer?

"When it comes to the connection between research and education, as suggested by Healey (2005 p. 68), students are likely to gain most benefits from research when they are actively engaged in it, through for example inquiry-based processes" (Tassone et al. 2018, p. 342). Based on this assumption, the RRI Hub integrates students in research projects in the context of RRI and thus links research and teaching. The example project presented in this chapter underlines with its results the importance of doing so.

The course ‘Engineer meets User’ at the Faculty for Civil Engineering at RWTH Aachen University uses a research-based teaching and learning format in which more than 100 engineering students actively engage in research on topics in the context of RRI. The RRI Hub provides a general broad course topic based on current technological developments. The students are first familiarized with social science research methods during the course. They, for example, learn the basics of questionnaire construction for quantitative research. Afterward, the RRI Hub and the students jointly develop a questionnaire which the students distribute. At the end of the semester, the students discuss the results in groups and present their evaluation in a scientific paper, a scientific poster, and a video including recommendations for stakeholders of the quadruple helix. The students are accordingly involved in different phases of the research process. The collaborative work between the RRI Hub and the students ensures that their knowledge and interests are included within the questionnaire and that they can engage with the RRI Hub’s topics. By actively being involved and following the research process, the students will be enabled to independently identify research questions, describe and reproduce the main stations in the research process, develop an appropriate research design for the research questions, and apply social science research methods.

The course topic of the summer semester 2022 was ‘The Responsible City of the Future – Visions for Aachen’. Based on the transformation of cities due to, for example, climate change or demographic change, the survey aimed to determine to what extent citizens of Aachen, especially students, envision a city of the future and how universities can foster cooperation between different stakeholders such as civil society, industry, academia, and government. To explore the citizen’s understanding of responsibility and the importance of participation, items to explore the interlinkages between innovation, artificial intelligence, and responsibility in the urban environment were added. By participating in all stages of the research process, students could identify the current challenges of their city and assess a broader public’s view on these topics.

4.1 Methodology

The quantitative online questionnaire co-developed by members of the RRI Hub and the students consisted primarily of closed multiple-choice questions with additional free text fields. The questionnaire was distributed online within four weeks in May and June 2022 without any restrictions. It took the participants 10–12 min to complete the questionnaire, and the framing of the questions addressed students in particular.

In total, over 951 people, mainly residents of Aachen, took part in the survey over four weeks. Of these, 47.5% of participants reported to be female, 46.7% were male, and the remainder were either diverse or did not specify their gender. Most respondents reported being between the ages of 19–22 (41.0%) or 23–26 (39.2%). A total of 3.3% were younger than 19 years, and 12.0% were over 26 years of age. Accordingly, 72.4% of the respondents stated that they were students, 13.9% were employed, and the rest were pupils, in training, or retired. For the project, a direct connection of the participants to the city of Aachen or its immediate surroundings was useful. 77.2% of the participants had such a connection to the Aachen city region. At just over 62.7%, the vast majority also resided in the surrounding area. Another 14.5% were regularly in the area due to their professional or academic activities.

4.2 Subject

To support students in understanding the importance of involving different stakeholders and perspectives in sustainable transformation and development processes like formulated within the RRI concept, the questionnaire addressed five focus areas: society and participation processes, economy, infrastructure, academia, and individual aspects. During the course, the relevance of the five areas or actors in the context of sustainability and responsible development was discussed with the students. Based on this, the RRI Hub and the students jointly developed survey questions in all five focus areas.

The area of society and participation processes addressed citizens' desire to contribute to Aachen's development. For example, questions were asked about the extent to which citizens take advantage of participation formats such as living labs and would like to get involved in public decision-making processes. In addition, the participants were asked to what extent they would like cooperation formats between science and society. Based on our research question, the aim with this area was to find out specifically how exactly HEIs can engage society in the area of RRI. In the economy part of the survey, the role of local companies in the city of the future was emphasized, and respondents were asked to give their opinion on the influence they attribute to different local stakeholders. The infrastructural questions aimed at the current mobility behavior of Aachen's citizens, their perception of public spaces in this context, and the general cityscape and soft location factors. Questions revolving around the field and role of academia were, for example, intended to provide information about the participants' perceptions of the extent to which they believe they, as citizens of Aachen, can participate in current research projects of the local HEIs. This aimed at exploring the role of technical universities in strengthening RRI. Further, participants were asked how well-informed they feel about current research topics by the RWTH Aachen University and researchers. The two other focus areas of the RRI Hub (sustainable and inclusive AI and social innovation) were also addressed in the questionnaire to explore the connection of these topics to sustainable transformation and development processes, so respondents were asked individual questions on both topics. Individual aspects in the questionnaire included particular questions about the respondents' lifestyle to explore their attitudes to life, e.g., whether a sustainable lifestyle is essential for them or whether respondents are actively involved in climate protection.

4.3 Results and Discussion

In the following, some study results will be exemplarily presented and discussed in the context of RRI. Further, it will be derived which role citizens assign to universities in implementing RRI with and for society.

Society and Participation Processes

The participation of different stakeholders in research and innovation processes is one of the core ideas of RRI (Schomberg 2013). HEIs, in particular, can play an important role here by actively addressing and involving citizens in research and teaching projects. The extent to which this is desired and perceived by citizens was asked in the questionnaire**.** Most of the survey participants generally agreed that citizens should actively engage in research processes (cf. Figure 4a). 65% of the participants agreed or strongly agreed with the statement, "Citizens should be actively involved in research processes at appropriate points". This result supports the call for HEIs to create opportunities for the involvement of citizens in research processes.

One example of fostering participation processes among citizens—one of the key components of the RRI concept—is by using so-called living labs (German 'Reallabore'), a concept that the RRI Hub has addressed, for example, in the Living Lab Templergraben (see above, Sect 3.2). 57% of the participants in the survey saw potential in living labs as they agreed or strongly agreed with the statement, "I positively assess the potential of living labs as an opportunity for citizen participation". However, as 28% answered to that same statement, "I don't know" (and the remainder disagreed or strongly disagreed), it could be assumed that citizens are not familiar with the concept of a living lab. This assumption can be supported by literature as research has suggested that citizens are not always aware of the possibility of contributing to research projects via citizen science (Kam et al. 2021), thus showing the need for the interconnectedness of research, teaching, and transfer.

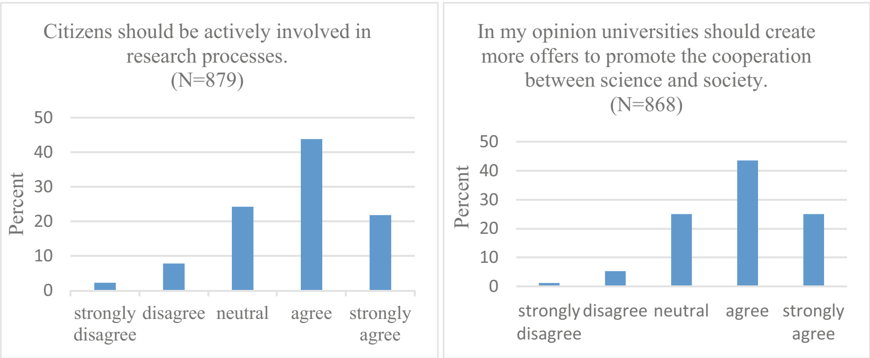

Fig. 4 Results of the statements **a** "Citizens should be actively involved in research processes" and **b** "In my opinion universities should create more offers to promote the cooperation between science and society"

At the same time, participants see universities as having a responsibility to provide more support for this process. 63% agreed or strongly agreed with the statement, "In my opinion, universities should create more offerings to promote collaboration between science and society". (cf. Figure 4b). The results thus show a clear desire among respondents for more collaboration. Collaboration opportunities could range from active involvement in research and innovation processes to discussion events on scientific topics or poetry slams. 'Science for and with society' as a critical principle of RRI (Owen et al. 2012) highlights the need for collaboration opportunities. For the scientific community to conduct 'science for society', the views and interests of societal stakeholders must be understood. This results in the relevance of exchange formats between stakeholders to implement the principle of 'science with and for society' from the university side.

Academia

Academia as an essential stakeholder in RRI processes can contribute to a responsible and sustainable future through, among other things, socially responsible research and education. To address this, issues in the context of RRI can, for example, be discussed in university courses. The questionnaire asked participants to what extent they would like ethical issues, as one dimension of RRI, to be included in their study programs. Participants generally thought ethics is a cross-cutting topic and should be included in all study programs. 57% of the participants agreed or strongly agreed with the statement, "I think ethical issues should be discussed in every study program" (cf. Figure 5).

The questionnaire also addressed the role of innovation and AI for a responsible and sustainable future. Social innovations, in particular, can contribute to achieving the SDGs. The results show that 43% of respondents would support the promotion of such innovations that contribute to the achievement of the SDGs. However, 35% were neutral toward the statement, and 20% disagreed or strongly disagreed. The European Union and individual state governments have recognized the importance of social and sustainable innovation to achieve the SDGs and established special support

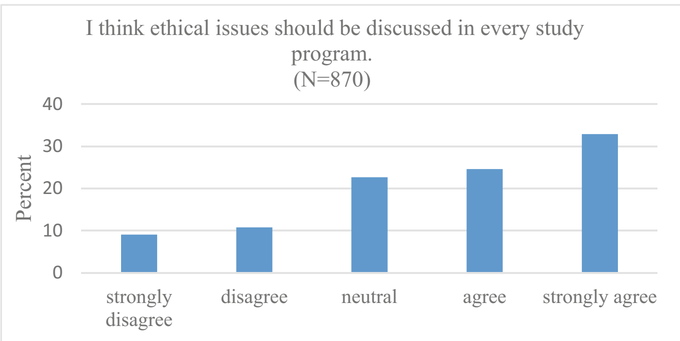

Fig. 5 Results of the statement, "I think ethical issues should be discussed in every study program"

measures like funding for social enterprises (Borzaga et al. 2020). In Germany, the federal government has also set itself the goal of developing a strategy to promote social innovation in the coalition agreement of 2021 (SPD, Bündnis 90, Die Grünen und FDP 2021).

Aachen's citizens were further asked about their opinion regarding several aspects of AI, which, as a cross-cutting topic, is and will be especially relevant in the context of sustainable city development. In light of the rapid growth of AI technologies (Cheung 2022) and its inherent risks (Tsamados et al. 2020), participants were first asked whether they felt positively inclined toward using AI. Ultimately, participants saw a huge potential in AI because 54% agreed or strongly agreed with the statement, "I fundamentally see the use of artificial intelligence as an opportunity for society" (cf. Figure 6a). However, growing in their impact on life-influencing decisions based on predictions and classifications (Hildebrandt and Gutwirth 2008), AI systems show tendencies to reinforce already existing biases (Zhao et al. 2017), produce unfair or discriminatory outcomes, or to systematically reinforce stereotypes and inequalities (Bozdag 2013). Results showed that participants were well-aware of these risks. 36% of the participants agreed or strongly agreed with the statement, "I think the use of artificial intelligence poses significant risks to society" (cf. Fig. 6b). Overall, more people saw AI as an opportunity than as a risk. A Pearson correlation shows that participants of the study, who generally saw the use of AI as an opportunity for society, also thought that its use entailed considerable risks for society ($r = 0.825$, level of significance 0.01, $N = 951$).

Consequently, ethical perspectives must be included in the development and usage of AI to ensure inclusive and sustainable use. This approach has been addressed by many policy papers lately (Hacker 2018; Jobin et al. 2019). This is supported by the survey in which 54% of the participants agreed or strongly agreed to the statement "I think ethical perspectives are paramount in the development and use of artificial intelligence" (30% were neutral toward the statement and 15% disagreed or strongly

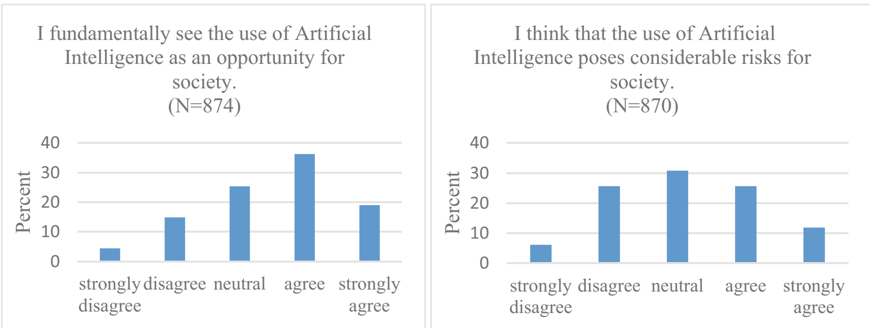

Fig. 6 Results of the statements **a** "I fundamentally see the use of artificial intelligence as an opportunity for society" and **b** "I think that the use of artificial intelligence poses considerable risks for society"

disagreed). This statement supports the RRI Hub's research in the area of sustainable and inclusive AI.

Overall, the survey showed that many respondents, mainly students, considered topics in the context of RRI to be highly relevant. In particular, the survey results indicate that universities are highly responsible for actively involving citizens in research and development processes to foster 'science for society'. Furthermore, regarding transfer to and from society, the results show a need for universities to establish possibilities for collaborations between science and other stakeholders in the context of RRI. This is possible, for example, through implementing projects or events with societal stakeholders, such as those organized by the RRI Hub as part of the 'Engagierte Stadt' project. There are various examples of the successful involvement of different stakeholders in the research process. These examples include citizen science projects or living labs, and the results show that citizens desire participation in research processes. To successfully implement RRI at HEIs, this means creating opportunities for science and society to work together on research projects. In particular, promoting citizen science or living labs can play a role here. In terms of teaching, the necessity of including RRI and knowledge about its process dimensions, such as ethics, in all study programs becomes evident. The relevance of cross-cutting, interdisciplinary topics such as AI must be recognized, and ethical perspectives integrated into all study programs. To summarize, this case highlighted the need for a holistic view of RRI at the university level. The results show that a consideration of RRI in all three tasks—research, teaching, and transfer—is necessary and desired by citizens as well as students. In order to achieve integration of all tasks, the example of the RRI Hub shows that the structural anchoring of RRI at the university level is also essential.

5 Outlook

This article explored the role of universities, especially technical universities, in implementing RRI with and for society and some approaches in succeeding to do so. Using the concrete example of the RRI Hub at RWTH Aachen University, this paper showed how RRI as a framework for aligning research and innovation with societal needs and achieving the SDGs could be anchored at HEIs. This article showed further, how RRI can be addressed in the contexts of research, teaching, and transfer at a technical university. Despite taking into account the facts that the results of the presented study are limited due to the number of participants (approximately 900 citizens of Aachen) and that the results may be biased due to the high percentage of students, the case nevertheless demonstrates the relevance of integrating RRI across all university areas. Nevertheless, the anchoring of topics in the context of RRI in teaching and collaboration opportunities between different stakeholders are desired by citizens and students. It is therefore important to not only remain theoretical, but also to become active within the opportunities that one has as academic actor in research and teaching. The relevance of taking RRI into account at a strategic level is evident. It further stresses the necessity to consider RRI a strategically important topic to be integrated into research and innovation, as well as into the educational strategies of technical universities and HEIs in general. In line with Margherita and Bernd (2018), we argue that all employees should be sensitized to RRI. Projects like the RRI Hub can be one possibility for HEIs to provide an impetus for responsible research, innovation, and the education of responsible innovators. Strategies for implementing RRI at all levels of universities remain to be explored, and more research must be conducted to develop recommendations on implementing RRI sustainably. Through its activities in the three fields of research, teaching, and transfer, the RRI Hub can address the topic of RRI not only within the university but also outside it.

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Toward Antifragile Manufacturing: Concepts from Nature and Complex Human-Made Systems to Gain from Stressors and Volatility

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Abstract Taleb coined the term "antifragility" to describe systems that benefit from stressors and volatility. While nature provides several examples of systems with antifragile behavior, manufacturing has so far only aimed to avoid or absorb stressors and volatility. This article surveys existing examples of antifragile system behavior in biology, biotechnology, software engineering, risk management, and manufacturing. From these examples, components of antifragile systems and principles to implement these components are derived and organized in a framework. The framework intends to serve as guidance for practitioners as well as starting point for future research on the design of antifragile systems in manufacturing.

Keywords Antifragility · Biologization of manufacturing · Resilience · Complex systems · Volatility · Uncertainty · Disturbances

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P. Letmathe et al. (eds.), *Transformation Towards Sustainability*,
https://doi.org/10.1007/978-3-031-54700-3_16

1 Introduction

In complex systems, small local deviations can emerge to unforeseeable critical disturbances (Ribeiro et al. 2011). With increasing complexity, high-impact events happen more frequently while predictions become more difficult, if not impossible (Taleb et al. 2009). In our globalized interconnected world, most companies did not anticipate the financial crisis 2007–2008 or the COVID-19 pandemic for example. In manufacturing, complex systems are common. Manufacturing systems and processes rely on the complex interplay of multiple factors related to material properties, process parameters, machines, human workforce (Herrera Vidal and Coronado Hernández 2021) as well as wear and environmental conditions (Bergs et al. 2020). Even for processes such as fine blanking, which is in practice for nearly 100 years, the theoretical understanding of the interdependencies between tool, material, and process is still limited (Aravind et al. 2021). At the same time, most manufacturing companies operate in interconnected, global manufacturing networks (Lanza et al. 2019). Hence, companies are subject to numerous interdependencies with partners and uncertainties of external events, which renders them susceptible to unpredictable disruptions (Peukert et al. 2020).

While complexity and uncertainties pose major challenges for manufacturing systems (Lanza et al. 2019), (complex) biological systems thrive in volatile environments and benefit from external stressors. The biological evolution represents an illustrative example. Evolution benefits from volatility in the form of mutations and from stressors through natural selection. Bacteria, for example, develop resistances to human-made drugs in only a few months and even adapted to benefit from industrial by-products in wastewater from polymer manufacturing (Danchin et al. 2011; Negoro et al. 1983). Biological systems have mechanisms that go beyond concepts such as resilience or robustness. A resilient system returns to its initial state as quickly as possible after the occurrence of stressors (Equihua et al. 2020). Robust systems preserve their initial state despite being exposed to stressors and volatility. In contrast, biological systems even benefit from stressors and volatility—without having to rely on predictions. As unpredictable events are inevitable in complex, technological systems present in manufacturing, it seems logical to adopt this trait from biology and to consider unpredictable events as a potential source for improvement rather than something strictly negative. Coming from research in risk management and applied probability, Taleb coined the term "antifragility" to describe this phenomenon (see Fig. 1) (Taleb 2013). Adapting the concept of antifragility promises a potential solution to address complexity and uncertainties present in manufacturing.

The idea of applying mechanisms found in biology to complex technical systems is not new. However, most of the existing manufacturing literature focuses on survivability and fault prevention. Antifragility goes further by emphasizing how to gain from stressors and how to "love" errors. Hence, it provides a strategy to thrive in a complex, unpredictable environment (Taleb 2013). With the intent to find inspiration for the development of antifragile manufacturing systems, this article surveys existing examples, which are or may be considered antifragile, from multiple research fields.

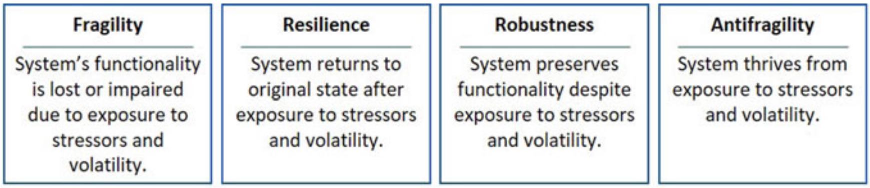

Fig. 1 Definition of fragility, resilience, robustness and antifragility

More concretely, the survey is focused on publications from biology, biotechnology, risk management as well as software engineering representing another domain with complex, technological systems. Besides, examples indicating antifragile-like traits from the field of manufacturing itself are presented. Furthermore, a framework for antifragile manufacturing is derived.

We favor the concept of antifragility over resilience, because antifragility exceeds the resilient ability to respond to a stress by resisting damage and recovering, i.e., reverting to the previous state. Antifragility, in contrast, learns from stressors and improves. Antifragile systems are designed, such that the use of unexpected events as a source of information for a targeted transformation is facilitated. Thus, we want to contribute our ideas of antifragility to an advanced Aachen Model for Transformation Research as an original contribution to transformation.

The remainder of this article is organized as follows: Sect. 2 introduces concepts that manufacturing already adapted from biological systems to overcome challenges associated with complexity and uncertainty. Section 3 highlights existing examples of antifragility from the aforementioned domains of biology, biotechnology, software engineering, risk management, and manufacturing. In Sect. 4, the framework to establish antifragility in manufacturing is proposed. Section 5 addresses challenges of antifragile manufacturing for future research, followed by a conclusion in Sect. 6.

2 Biologically Inspired Approaches Addressing Uncertainty and Unforeseeable Disturbances in Manufacturing

Resilience is frequently discussed in different academic fields as a desirable property for complex systems to deal with unforeseeable shocks and disturbances. Asokan et al. (2017) suggest that resilience is enabled through flexibility. Many-to-one and one-to-many mappings between components and functions facilitate flexibility in biological systems. Asokan et al. note that multi-functionality and overlapping functions of components likewise facilitate flexibility and resilience of manufacturing systems. However, in engineering resilience typically aims at returning to a state. In contrast, biological evolution emphasizes a more transformative form of resilience (Asokan et al. 2017).

Self-organization is another concept that is common in biological systems (Camazine et al. 2001) and that many researchers discussed as a solution to complexity and uncertainty in manufacturing. In a self-organizing system, the global behavior solely emerges from interactions of lower-level components, which act based on local information and a set of rules. Zhang et al. (2017) introduce two concepts, which are prevalent in the literature dealing with self-organization in manufacturing: holons and multi-agent systems. The philosopher Arthur Koestler coined the term "holon" to describe the organization of biological and social systems. A holon represents a basic unit of a system, which is in itself an autonomous whole, but also part of something, for instance another holon (Babiceanu and Chen 2006). Multi-agent systems aim to implement a distributed intelligence that is composed of multiple autonomous (software) agents. Zhang et al. propose to use agents as representations of physical entities, such as products, workers or machines, and subsequently aggregate different agents to functional modules, for instance for job scheduling or material transportation, based on the philosophy of a holonic organization (Zhang et al. 2017).

Bionic manufacturing systems (BMS) represent an alternative concept which is similar to holonic manufacturing systems (Tang et al. 2020), sharing the idea of decentralized, autonomous units and a focus on adaptivity. BMS have a hierarchical structure inspired by life forms being ordered in a hierarchy of cells, organs, lives and populations. Single autonomous production units correspond to cells. Based on the "DNA" of tasks, cells are combined through self-organization to provide the required manufacturing functions. In order to prevent conflicts between cells, the system is extended by coordinating units (analogous to enzymes in biological systems) (Tharumarajah 1996).

Lee et al. (2011) introduce the idea of *engineering immune systems*. Inspired by biological immune systems and the human nervous system, the concept envisions endowing manufacturing systems with self-maintenance capabilities allowing to survive in complex and uncertain environments. Lee et al. propose multi-agent systems to model the required functionalities of the engineering immune system, which comprise health assessment and prognosis, (maintenance) task planning and task execution. Darmoul et al. (2013) also present a framework inspired by biological immune systems to deal with disruptions in manufacturing. In analogy to biological immune systems, their blueprint for an artificial immune system is composed of artificial counterparts of cells, tissue, immune cells, pathogens, antigen presenting cells, B-Cells, Th-cells and memory cells (again implemented through multi-agent systems). These different components mirror mechanisms of biological immune systems to detect and classify abnormalities, assess consequences, derive and coordinate counter-measures and memorize successful reaction strategies in a decentralized way. Tang et al. (2020) propose a control model, which is inspired by the interplay of nervous system, endocrine system and immune system in nature. A main difference to related approaches is that it acknowledges the central nervous system as a centralized control unit. Hence, the model from Tang et al. includes a centralized shop floor controller mimicking the nervous system, which supervises and imposes constraints to distributed, cooperative and autonomous units.

Barbosa et al. (2011) hypothesize that mechanisms found in biological systems provide further inspiration to optimize multi-agent systems in manufacturing. More precisely, they discuss swarm optimization algorithms as well as mimicking pheromone-based communication of social insects (called stigmergy). In another paper Leitão and Barbosa (2010) survey bioinspired methods, such as self-organization as well as optimization algorithms, inspired by swarm intelligence and evolutionary theory, and their applications to engineering problems in complex, adaptive manufacturing systems.

Neves and Barata discuss *evolvable production systems* (EPS) as an approach to cope with unpredictable events, particularly in the context of assembly companies (Neves and Barata 2009). EPS are related to holonic manufacturing systems and bionic manufacturing systems and also based on hierarchically organized, autonomous modules (Ribeiro et al. 2011). However, according to Neves and Barata, EPS have a more dynamic notion (Neves and Barata 2009). Evolvable production systems are capable of adaption as a short-term response to opportunities or disturbances, but also of evolution in the long term. While a system adapts for instance by changing its behavior (e.g., through self-organization capabilities), evolution comprises a gradual introduction of new features (Ribeiro et al. 2011). The evolvability of complex parts (e.g., a production line or cell) is enabled through high flexibility on low-complexity levels (e.g., single devices within the system) (Neves and Barata 2009). Sufficient descriptions of modules in terms of required space, mechanical aspects, electrical specifications, control aspects, communication interfaces, etc., are prerequisites to replace, re-configure or expand modules (Hofmann 2010). From a technical perspective, ontologies (Parreiras 2012) and software agents provide tools to facilitate module interoperability (Neves and Barata 2009) and hence system reconfigurability.

In conclusion, the existing literature offers many examples of biologically inspired approaches to deal with unforeseeable disturbances in complex manufacturing environments. Typically, publications focus on recovery from shocks. Evolvable production systems are a notable exception as they also lay a foundation to gradually improve rather than just recover. As elaborated in the following section, the philosophy of antifragility goes beyond these concepts. Antifragile systems do not only benefit from volatility and disturbances, "the antifragile loves randomness and uncertainty, which also means—crucially—a love of errors" (Taleb 2013). This *love of errors*, i.e., the emphasis on exploiting errors and stressors constitutes the difference to existing approaches, which emphasize avoidance or compensation of errors.

3 Antifragility

As mentioned before, antifragile systems go beyond resilience and robustness, in that they benefit from volatility and stressors. In manufacturing, volatility may for instance arise in the form of fluctuations in material properties that occur despite unchanged material specifications (Harsch et al. 2018). A stressor is a source of harm, e.g., a disturbance in the supply chain in consequence of the Suez Canal blockage in 2021 (Yee and Glanz 2021). Mathematically, antifragility can be described by the probability distribution of positive ("gains") and negative effects ("losses") on the system resulting from volatility or undesirable events. In a robust system, the effects of stressors are very likely to be small. Even in the presence of unlikely, unforeseeable events, a robust system remains mainly unchanged. This results in a narrow probability distribution of effects on the system (see Fig. 2c). Similarly, a resilient system behavior leads to a narrow probability distribution as resilient systems return to their original state after being exposed to stressors. A system that returns to its original state neither improves (gains) nor deteriorates (loses). In fragile systems, the consequences of most events that occur have small effects, however some rare events can lead to extreme negative effects, possibly resulting in an irreversible loss of function of the system. Therefore, the distribution of effects on the system has a "heavy left tail", i.e., there is a certain (low) probability of events leading to a high loss for the system. While fragile systems may by chance improve from unforeseen events, they are always characterized by this "heavy left tail" (see Fig. 2a, b). In contrast, negative effects in antifragile systems are limited (thin left tail of the distribution), while positive effects can potentially be large (fat right tail) (Equihua et al. 2020; Taleb 2013).

The bottom row of Fig. 2 depicts an alternative way of describing antifragility mathematically. In fragile systems, varying the size of a stressor or event (denoted as x in the bottom row of Fig. 2) may lead to high, potentially fatal losses. Mathematically

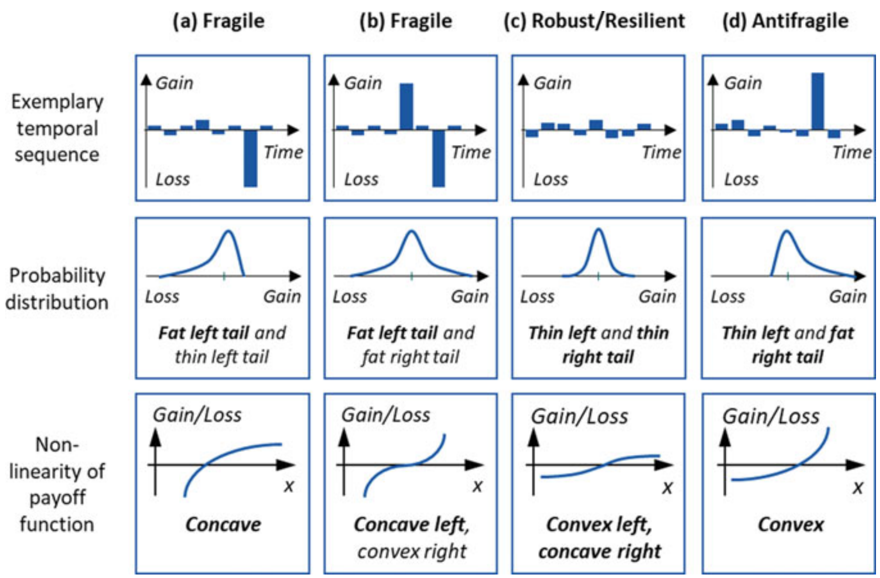

Fig. 2 Exemplary temporal sequence, probability distribution of positive and negative effects and asymmetries in payoff functions in fragile, robust and antifragile systems, respectively [based on (Taleb and Douady 2012; Aven 2015)]

this corresponds to the "payoff" of the system responding concavely in the loss domain because of variations of x (see Fig. 2a, b). Here, the term "payoff" denotes the gains or losses a system experiences, when x is varied. In case of a convex payoff function (see Fig. 2d), losses are limited and higher advantages are to be expected, if x is volatile. Accordingly, antifragility is defined as a convex response to volatility or disturbance variables (for a defined range of variation). Robust systems (see Fig. 2c) remain almost unchanged to variations in x.

Very unlikely or unexpected critical events cannot be predicted (reliably). However, the previously described distinction of fragility and antifragility based on convexity or concavity respectively allows to (heuristically) detect the fragility or antifragility of a system (Taleb and Douady 2012). If a system reacts convexly to volatility, predictions become obsolete, since downsides are limited while there is chance that upsides will significantly outweigh the downsides.

To detect whether the payoff of a system is convex, a more specific and system-dependent definition of "gains" and "losses" as well as the stressor is required. For example, in the financial markets, "gains" might be actual monetary returns while the market volatility represents the stressor. In that example, a small stock investment could be considered antifragile, since the loss is limited to the initial investment, while the stock price could surge significantly higher than the potential losses. In the case of a manufacturing process, "gains" could, e.g., be expressed in terms of reduced costs, reduced makespan or improved quality, while varying material properties represent a stressor.

The mathematical perspectives on fragility, robustness, resilience and antifragility illustrated in Fig. 2 are idealized and will typically not hold outside of a certain scope. For instance, the muscular system of a human might benefit from external stress (e.g., through exercising) and hence could be considered antifragile. However, if the stress exceeds a certain limit, it will result in injuries (i.e., fragility) rather than muscle growth.

In the following subsections examples of antifragile behavior are surveyed. The examples are divided into four different domains. First, examples from biology are presented (Sect. 3.1). Following, already existing examples of antifragility in human-made systems from the domains of software engineering (Sect. 3.2) and risk management (Sect. 3.3) are discussed. Finally, examples from manufacturing, which demonstrate antifragile behavior, are described in Sect. 3.4.

3.1 Antifragility in Biological Systems

Many examples of (potentially) antifragile systems are present in nature. Biological evolution is a result of novelty creation in response to various stress factors. Living beings and ecosystems experience diversity generation by relatively low impact incidents that yield tremendous benefits in case of extreme events by improving the chance of survival (Negoro et al. 1983). Organisms can adapt to environmental changes by modification of metabolic pathways, down- or up-regulation of particular functions. In general, living organisms are characterized by an excess of functional diversity and genetic variation. *Polyextremophiles* are especially successful in surviving broad range of environmental conditions. The term polyextremophiles denotes organisms that thrive in the face of more than one extreme (e.g., extreme temperature and radiation). They are characterized by a high degree of phenotypic plasticity. One example of such polyextremotolerant organisms is black fungi *Aureobasidium pullulans*. These organisms evolved to develop numerous protective pathways (i.e., production of melanin or polyphosphates) that help to endure different environmental events mostly unbearable for other species. Capable to survive catastrophic events, they take an advantage of the availability of resources freed after the elimination of other organisms that could not survive. Even in the very stable and uniform laboratory conditions, the morphology of black fungi significantly differs. In addition, they can form facultative associations with other species to benefit from oligotrophic conditions. These features of black fungi as well as the given examples of tinkering allows Grube et al. to call them antifragile (Grube et al. 2013).

Here it is important to mention the term evolvability—the ability of biological systems to produce phenotypic diversity which is both heritable and adaptive (Kirschner and Gerhart 1998; Payne and Wagner 2019). Evolvability and its delicate interplay with robustness are important prerequisites of evolution and natural antifragility (Kim et al. 2020). In recent years, much progress is achieved in understanding the molecular basis of evolvability, such as mechanisms of phenotypic diversity generation, robustness in genetic systems and adaptive landscape topography. Phenotypic variation is caused by stochastic gene expression, errors in protein synthesis, protein promiscuity and epigenetic modifications. Recent review from Payne and Wagner elaborates on this topic in detail (Kirschner and Gerhart 1998). The development of antibiotic resistance in bacteria is an example of antifragility provided by stochastic gene expression and complex regulatory mechanisms involved in stress-response reactions and smart genetic information management (Levin-Reisman et al. 2017; Lewis and Shan 2017; Wencewicz 2019). The same principles are applied when bacteria evolve to catabolize xenobiotic substrates. In this case, the presence of unknown substances activates a stress-response resulting in release of reactive oxygen species provoking mutations that can potentially lead to acquiring of novel functions (Akkaya et al. 2018; Händel et al. 2015; Lorenzo 2014). Evolutionary principles are also used for *directed evolution*, a method used for protein engineering (Bornscheuer et al. 2019).

Antifragile dynamics are present in all the levels of organization of life. Thus, on the molecular level the antifragility of biological systems is provided by redundancy of genetic code and highly resilient natural protein sequence space that allows evolvability and sufficient functional stability to ensure the heredity of beneficial changes. On the cell level, complex metabolic pathways regulate the response of individual cells to changes in the environment by tuning the expression of enzymes, defining cell differentiation routes and influencing the cell cycle. Cells that evolved in environments with more perturbations demonstrate antifragile dynamics. Here, *CD4 + T-cells* may serve as good example of highly-dynamic antifragile systems that react to presence of pathogens in the body and send the signal to other immune cells to initiate the immune response in accordance with the nature of infection agents. Subpopulation of CD4 + T-cells differentiates into memory cell that contribute significantly to antifragile behavior of immune system. Muscle tissue is a very illustrative example of antifragility on a tissue level. In response to stress caused by excessive exercise muscles are growing and becoming more enduring. Muscle development is regulated by a complex cell signaling network that reacts on molecular level to type and intensity of training. For instance, resistance exercises result in growth of muscle mass, whereas endurance exercise promotes the increase of capillary density, mitochondrial protein, oxidation enzymes, and more metabolically efficient forms of actin and myosin (Keller et al. 2011; Nader 2006). Similarly, antifragility is observed on organ and system level. Staying with the case of physical training as stress-event, heart and cardiovascular system can serve as further antifragility examples on organ and system level. Thus, aerobic exercises lead to the enlargement in heart dimensions, increase in blood volume, number of microcirculatory vessels and oxygen delivery to muscles. Such changes lead to improvement of the health of the individual organism in general (Hellsten and Nyberg 2011). Furthermore, antifragility can be easily observed on population level, where it is mostly ensured by the diversity. Next are the ecosystem and biosphere levels, the most complex and diverse systems that benefit from environmental variability and go beyond robustness and resilience (Equihua et al. 2020). In such hierarchical organization of life, antifragility on higher levels of organization is ensured by shared set of underlying processes and phenomena of the lower levels.

3.2 Antifragility in Software Engineering

In software engineering, it is well-known that bugs lead to errors. To avoid that, debugging is a steady task for software engineers. But while software systems have become too complex to fix bugs in a satisfactory way, so-called "failure self-injections" are used to test the "error-recovery capabilities" of software systems (Monperrus 2017). Following that, software engineers operate antifragile and not resilient since the steady exposure to errors should help to improve the software performance of Internet-based and distributed systems (Monperrus 2017; Basiri et al. 2016). Hence, programmers highlight the design and execution of such stress tests over the building of the software. A famous example here is Netflix' "Simian army", a group of self-injected failures that harm the software to train its running-capability despite the ongoing occurrence of errors (Tseitlin 2013). Since these errors are neither known nor foreseeable in their impact, software designers refer to this method as "chaos engineering" (Basiri et al. 2016). In the context of monitoring such systems, this double non-knowledge is also called "unknown unknowns" (Fighel 2017; Kim 2012). Especially with the aid of machine learning, engineers hope to gain new insights into the behavior of complex systems. De Florio (2014) argues in this context that the combination of elasticity in testing options and resilience in counterbalancing shocks defines antifragility in machine learning. Baruwal Chhetri et al. (2019) hypothesize that reinforcement learning offers a potential solution to reduce unknown unknowns through the exploration of (yet unseen) variations to known events. Additionally, there is a psychological aspect in antifragility for software engineers. Following Russo and Ciancarini (2016) in their "antifragile software manifesto", programmers should not look for bugs anymore but develop an "error-loving" attitude since errors are the "primary source" in antifragility.

3.3 Antifragility in Risk Management

Contrary to risk assessment in economics, antifragile systems do not imply a concept of risk that depends on psychological notions such as subjective preferences or risk aversions (Rothschild and Stiglitz 1971). Instead, in a mathematical sense, risk can be applied to all systems as a "heuristic" to detect the fragility of systems described in nonlinear functions (Taleb and Douady 2012). This "detection heuristic", as Taleb and Douady phrased it, should help to map so-called threshold-values in the function from where the loss stays low, but the profit can grow exponentially (Taleb and Douady 2012; Derbyshire and Wright 2014) (see also the convex function in Fig. 2). In consequence, this notion of risk neither refers to a known value of probability distribution nor to a moderate risk value based on scenario techniques with its emphasis on causation (Derbyshire and Wright 2014; Knight 1921). Instead, risk is defined as a steady exposure to unknown events until the system withstands the external stressors and starts to improve its performance. Aven (2015) argues that there are no antifragile systems, only antifragile heels in a system's behavior. Risk assessment should therefore focus more on the description of key concepts like resilience and antifragility than on probability numbers of rare events (ibid.). However, Johnson and Georghe (Hespanhol 2017) used antifragility as an empirical category next to robustness and fragility to measure the performance of a simulated American smart grid power system. In their simulation, they examine ten categories of antifragility on a scale of -10 to $+10$. Risk is here proportional to efficiency in the analysis, since the more redundant procedures the system develops the less efficient it is, but also the less fragile in the long run. Additionally, more efficiency requires more resources which increases the risk probability (Johnson and Gheorghe 2013). Also, regarding emergency scenarios for urban planning, Hesphanol describes risk as a factor that can be minimized over time due to "cultivating redundancy of resources" (Mothes 2015). Using digital technologies like smartphone-apps and public campaigns for the preparedness of citizens, unforeseeable shocks lose their impact and become iterative risks of small shocks to the community. Antifragile risk management does not refer to psychological categories nor to methods of probability calculation. It contains a strategy to expose a system to harmful events while developing a redundancy in the way the system uses its resources to overcome the shocks and improve in the long run.

3.4 Antifragility in Manufacturing

Within the field of manufacturing, antifragility is yet largely unexplored. One potential explanation could be that in manufacturing it is more difficult to cap downsides—e.g., compared with software engineering (cf. Sect. 3.2), where it is possible to rollback to a backup of the software if a critical failure occurs. This allows software engineers to embrace stressors in order to test and advance their systems while keeping risks limited. If a machine on a shopfloor is damaged or scrap is produced, a manufacturing company cannot load a backup to return to a previous state. Thus, the hurdles to investigate the concept of antifragility in manufacturing seem to be higher. Moreover, the manufacturing domain has put a strong emphasis on efficiency and reducing volatility (see, e.g., lean manufacturing). In contrast, antifragility embraces volatility and accepts short-term inefficiency, for example in form of redundancies allowing to absorb shocks before learning from them to benefit in the long run.

So far, only a few production-related publications explicitly address the subject of antifragility. For example, Mothes (2015) acknowledges potential benefits of antifragility for manufacturing companies. He proposes modular production systems enabling flexible reactions to market fluctuations. However, as Mothes notes himself, antifragility is more than just flexibility. Derbyshire and Wright (2014) argue that excess stock inventory is antifragile to market volatility. If a crisis causes a shortage of an important material, its price will surge. Thus, manufacturers that held a buffer for that material will gain from the stressor (i.e., the crisis).

The literature additionally provides examples, which are at least related to antifragility in manufacturing. Although evolvable production systems (see Sect. 2) do not emphasize stressors or randomness as being desirable, the concept of (biological) evolution is inherently antifragile (see Sect. 3.1). Strain hardening describes the increasing strength and hardness of polymers and metals caused by distortion of the material or more precisely of its crystalline structure (Gooch and Gooch 2007; Manutchehr-Danai and Manutchehr-Danai 2009) and can be seen as antifragile reaction to distortion. Moreover, the semiconductor industry found ways to benefit from uncontrollable random variations in manufacturing. For instance, so-called physical unclonable functions (PUF) exploit (physical) variations in semiconductors to generate cryptographic keys (Shen et al. 2016; Yanambaka et al. 2018). The security of PUF gains from the randomness of the manufacturing process. Raghunathan et al. (2013) propose an algorithm, which exploits core-to-core variations in multi-core chips. Their algorithm cherry picks the ideal subset of cores from a chip based on the characteristics of a given application. The semiconductor industry has created options from variations.

The so-called pulsed laser-assisted wire-based laser metal deposition (LMD-w) is a manufacturing process showing potentially antifragile behavior. LMD-w is a process by which a wire-based feedstock material is cladded on a substrate or semi-finished product by applying laser energy (DVS 2011; Ngo et al. 2018). The main applications are part functionalization, hybrid workpieces and repair. In contrast to powder use, wire-based processes offer a material efficiency of almost 100%

(Bambach et al. 2018). The wire is easy to handle and causes less harmful effects on human health (Kaierle et al. 2012). Its production is less cost-intensive than powder fabrication (Abioye et al. 2013). Despite these advantages of wire use, most of today's established industrial LMD processes are powder-based. This is due to the comparatively low stability of LMD-w processes, where the stable process window is small (Abioye et al. 2013; Gipperich et al. 2021). Even weak variations of the process conditions can lead to process interruptions and significant defects. The instability of LMD-w processes is mainly caused by the complex melt pool dynamics of laser-based processes (Arrizubieta et al. 2017). The complexity of forces and interactions is even increased in the case of LMD-w, where the solid wire is connected to the liquid melt pool.

One process variant to increase the LMD-w stability consists in adding a pulsed wave (pw) laser to the continuous wave (cw) process laser beam. The pw power is low (2–5% of cw power), but the process dynamics are highly influenced by the second laser (Gipperich et al. 2020). In this pulsed laser-assisted LMD-w, the pw laser can be identified as a stressor. During the process, it evaporates part of the melt pool material, which results into the formation of a vapor cloud. The vapor interacts both with the laser beams (change of the effective absorption coefficient) and with the melt pool. As the evaporation goes along with a material expansion, a force acting on the melt pool is created (Bergs et al. 2019). As a consequence, the melt pool shape and thereby the resulting welding bead cross section are altered with regard to a conventional LMD-w process. Moreover, the repeated evaporation by single pw laser pulses imposes small periodic oscillations to the melt pool. The irregular melt pool movements with higher amplitude occurring in conventional LMD-w are suppressed. Consequently, a reduction of the bead's surface roughness is observed in some ranges of the pw parameters (Gipperich et al. 2022). Recent studies show that the combination of modified absorption behavior and the change of melt pool shape and dynamics contributes to an overall process stabilization and an improvement of the part quality (Gipperich et al. 2020, 2021, 2022). As the process benefits from the pw laser as a stressor, these observations can be identified as antifragile-like behavior. In the future, it has to be investigated how the concept of antifragility can be used to further increase the understanding and stability of pulsed laser-assisted LMD-w processes.

4 Framework for Antifragility in Manufacturing

The examples discussed in Sect. 3 show that absorbing negative effects will not be sufficient to achieve antifragile manufacturing. Antifragility also requires exploiting stressors, e.g., through learning, selective pressure or optionality. Therefore, manufacturers have to implement mechanisms, which allow to generate upsides from shocks and volatility. In this regard, properties such as resilience and robustness are a necessary component for antifragile manufacturing systems, as they enable the systems to cap downsides and survive shocks and volatility while exploring the upsides associated with antifragility in the long run. Finally, antifragility requires the gains to prevail the potential losses (while preventing fatal losses). Therefore, means are necessary, which enable the detection and monitoring of fragility and antifragility, respectively, to balance robustness and resilience and the “love” of errors. In summary, three main components jointly contribute to achieving antifragility: (1) monitoring and detecting (anti)fragility, (2) increasing robustness and/or resilience, and (3) exploiting stressors. The antifragility examples presented in Sect. 3 rely on principles, which provide potential building blocks to implement these three main components. In the following, key principles from the different domains discussed in Sect. 3 are briefly highlighted, before they are mapped onto the three aforementioned main components and elaborated in more detail in Sects. 4.1, 4.2, 4.3 and 4.4.

Publications from the field of software engineering stress a mindset of “loving errors” and even propose self-injection of errors to learn and improve software systems. The learning process is based on trial and error and of exploratory nature to uncover “unknown unknowns”. Resilience is a necessary prerequisite of antifragile software systems, which allows to absorb shocks and enables learning in the first place.

In manufacturing, flexibility and optionality already contribute to a more antifragile behavior. Having multiple options and flexibility, manufacturers increase their chances to successfully react to disturbances as well as opportunities. Another principle is redundancy, which enables a system to absorb shocks, but also provides opportunities in volatile environments (as in the case of buffer inventory). Evolvable production systems envision evolvability in manufacturing through adaptivity of low-level system components and flexibility to replace components and reorganize.

In the field of biotechnology and synthetic biology, evolutive approaches are often applied to generate required properties on the organism or molecular level. Directed evolution (Nobel Prize in Chemistry 2018) that mimics the process of natural selection has become a widely accepted and broadly applied method for protein engineering (Bornscheuer et al. 2019). A directed protein evolution experiment comprises two main steps: generating diverse mutant libraries and screening for improved protein variants. Thus, directed evolution campaign the improvement of protein properties is achieved by generation of genetic diversity using mutagenesis followed by selection of better variants under “shock” conditions (i.e., high temperatures, presence of unusual solvents, extreme concentrations of salts, etc.) (Bornscheuer et al. 2019). Consequently, the performance of the proteins is improved as a result of selective pressure in an accelerated laboratory evolution format (Markel et al. 2020). The quality of a mutant library is decisive for the success of a directed evolution experiment and many methods have been developed for generating diversity at the gene level. These random mutagenesis methods (e.g., error-prone PCR (epPCR), SeSaM) differ significantly in the mutational spectra, mutation frequency and are differently affected by the redundancy of the genetic code. The experimental finding of improved variants is from a theoretical perspective highly surprising when the astronomical size of the protein sequence space (10,520; peptide with 400 amino acids) is taken into account. On the molecular level, protein sequence space can be considered antifragile by offering high degree of sequence diversity and "evolvability" that helps to withstand "shocking events" and unusual environments. Recently, several approaches toward continuous directed evolution were reported (Badran and Liu 2015; d'Oelsnitz and Ellington 2018; Hubbard et al. 2015; Morrison et al. 2020; Wang et al. 2018). These techniques allow performing many rounds of protein evolution without human intervention. Adaptive laboratory evolution is another example of mimicking natural evolution in artificial laboratory environment (Dragosits and Mattanovich 2013; Lee and Kim 2020). In this case, novel industrial strains of microorganisms are evolved toward improved metabolic pathways for their implementation in microbial production processes.

From the perspective of risk assessment, an antifragile manufacturing system would first avoid strong causal relationships between the structures and substructures. Although such causal connections facilitate the predictions about the systems behavior, they do not indicate big failures. Second, the question would be how to interconnect the subsystems as a nonlinear system to maintain stability (Hole 2016)? One way of risk assessment for nonlinear systems is to generate standardized options with a modular design (Mothes 2015). Such nonlinear systems are highly recursive (Taleb 2007) that is why the design of standardized options is also a redundant process. However, a certain number of subsystems has to stay exposed to stressors with unforeseeable consequences (like the welding process benefits from the stressor of the laser as a subsystem, see Sect. 3.4). In risk assessment of financial economics, these risk distributions between a majority of standardized low-risk and a minority of high-risk operations are called "barbell strategy", which should keep the risk of high losses very low and create options for high gains (Derbyshire and Wright 2014). Another method in risk assessment how to deal successfully with nonlinear systems is the monitoring of the so-called "unknown unknowns". While a lot of problems can be predicted in manufacturing systems, "unknown unknowns" are neither identifiable nor predictable in their consequences (Kim 2012). A manufacturing system that is exposed to such a randomness tends more to be prepared for events than to predict them (Taleb 2007). Thus, as a part of a framework for antifragile systems, the techniques of risk assessment put emphasis on the creation of standardized, redundant operations between loosely connected subsystems. Based on this, the system can be exposed to stressors with unknown risks and consequences to improve the systems performance without suspending the system to risks of high damage. Material as well as personal resources should therefore be more invested into the reliability of infrastructures made out of the redundant operations than into the quest for possible causal relationships in past and harmful events. The openness toward unknown risks emphasizes also a virtue of resistance to think in temporal orders of cause and effect. In manufacturing, this might be a counterintuitive way of thinking.

Figure 3 depicts a framework for antifragile systems comprising building blocks from different domains. The framework intends to offer guidance for practitioners to implement antifragility in manufacturing as well as for future research. A brief explanation of the single building blocks follows in the subsections below.

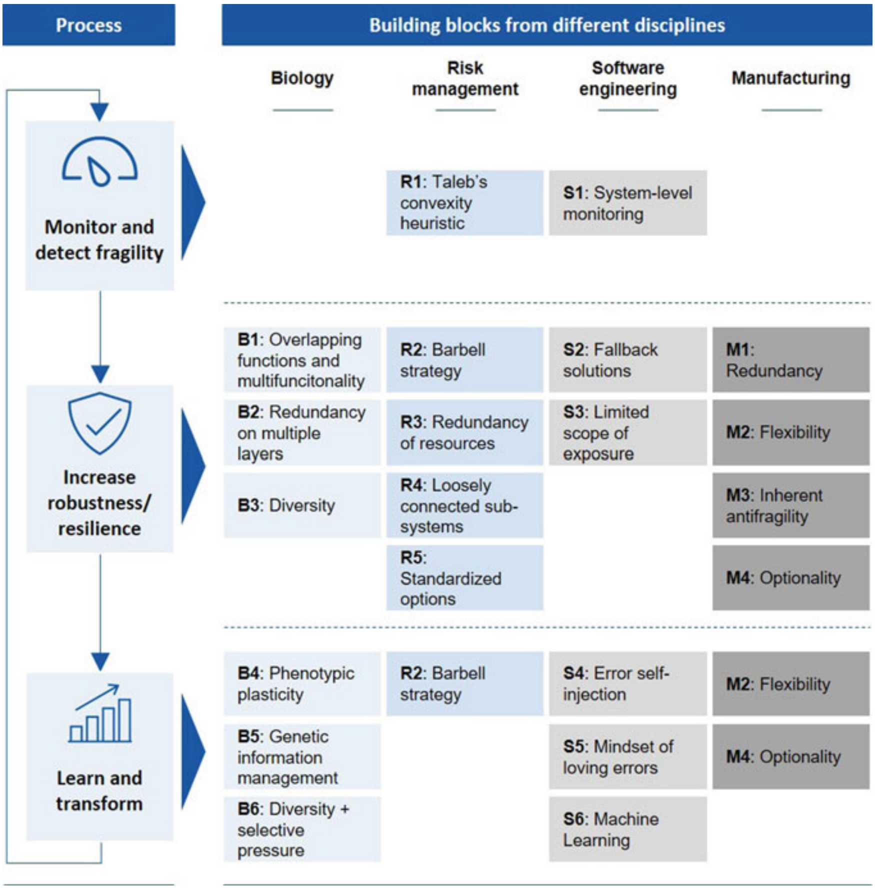

Fig. 3 Framework to design antifragile systems and guide future research for antifragile manufacturing systems

4.1 Building Blocks from Biology

(B1) Overlapping functions and multi-functionality: Different components fulfill the same functionality in biological systems. Besides, single components fulfill multiple functions. These two features, also called functional redundancy and functional plasticity (Asokan et al. 2017), increase the robustness to a failure of system components.

(B2) Redundancy on multiple layers: Biological systems exhibit redundancy on multiple layers, starting already at the molecular level in organization of genetic code and continuing up to ecosystem level where richness of the biota and species redundancy contribute to reliable functioning of ecosystem (Naeem 1998).

(B3) Diversity: Diversity increases nature's chances to have a suitable solution to unforeseeable shocks. This is especially true in the context of (directed) evolution.

(B4) Phenotypic plasticity manifests itself as changes in organism's characteristics in response to environmental signals. In a heterogeneous environment, plasticity is highly favored as the organism can convert to optimum phenotype upon changes in the internal or external conditions. Organisms have hierarchical molecular organization and regulation starting from genome and moving further to transcriptome and proteome that ultimately defines any characteristics or action. Internal or external signals can interfere at any level by regulating transcription, translation or enzyme activity causing phenotypic heterogeneity. The mechanisms of phenotypic heterogeneity include stochastic gene expression, protein synthesis errors, protein promiscuity and epistatic modifications (Schlichting and Smith 2002).

(B5) Genetic information management: Replication of genetic information is not a perfect error-free process. Genetic mutations resulting from errors in DNA replication can increase the genetic diversity without affecting the phenotype. This enhances organism's evolvability or ability to produce heritable variation. Evolvability is balanced with robustness required to preserve functionality. Genetic mutations that improve protein stability enhance the robustness by widening the range of possible follow-up mutations that do not cause the loss of functionality. On the other hand, robustness assists evolvability by providing a certain degree of acceptable diversity in the genetic pool. This diversity can further enhance evolvability through, for example, epistatic interactions or recombinations (Kirschner and Gerhart 1998).

(B6) Selective pressure: Through selective pressure the best solutions present in a biological system prevail ("survival of the fittest"). Thereby, the populations gain from unforeseen shocks.

4.2 Building Blocks from Risk Management

(R1) Taleb's convexity heuristic: Taleb's convexity heuristic (cf. Sect. 3) allows detecting antifragility or fragility, respectively. The shape of the nonlinearity of a system's output allows to prioritize efforts to achieve antifragility (see Fig. 4).

(R2) Barbell strategy: This strategy is characterized by combining low and high risk, while avoiding medium risks. If a majority of a company's operations is associated with no or low risks, it becomes possible to explore high risks with potentially high gains. Since the majority of risks is small, overall losses should be limited (Derbyshire and Wright 2014).

(R3) Redundancy of resources: Redundancy of resources allows to withstand adverse events and is a prerequisite to achieve antifragility (Hespanhol 2017).

(R4) Loosely connected subsystems: Loosely coupled subsystems mitigate the risk of failure propagation. A link between two subsystems is weak if the damage caused by misbehavior of one subsystem to a second dependent subsystem is low. Moreover, connections should be sparse and break quickly, if a subsystem misbehaves. Hole

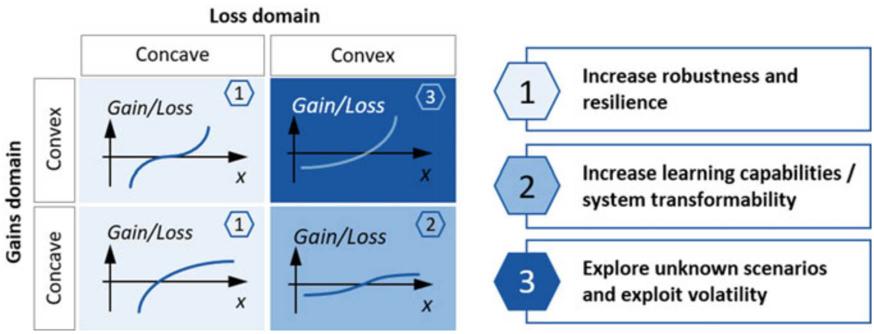

Fig. 4 Three types of system behavior [based on (Taleb and Douady 2012)] and their implications

proposes to implement "circuit breakers" between modules of a system, which ensure correct behavior, rather than direct links (Hole 2016).

(R5) Standardized options: Standardized options provide a form of redundancy in terms of scaling processes or systems (Manutchehr-Danai and Manutchehr-Danai 2009).

4.3 Building Blocks from Software Engineering

(S1) System-level monitoring: It is not feasible to monitor if single components of complex systems meet their specifications. Therefore, engineers at Netflix monitor system-level variables, which reflect if the system meets its ultimate goal (i.e., providing streams to customers). Moreover, they define variables that reflect real-world events such as server crashes and monitor whether system behavior variables are affected by changes of these event variables (Basiri et al. 2016).

(S2) Fallback solutions: A prerequisite for Netflix' Chaos Engineering approach (see Sect. 3.2) are fallback solutions, ensuring graceful degradation if a service fails (completely). For instance, if the bookmark service (allowing customers to resume watching from the previous location) fails, the video will start at the beginning rather than throwing an error. If servers fail, customers are rerouted to other servers (Basiri et al. 2016).

(S3) Limited scope of exposure: Deliberately exposing software systems to stressors allows to test the error-recovery capabilities of complex software. Limiting these experiments to subsets of the software's users is crucial to mitigate risk (Basiri et al. 2016).

(S4) Error self-injection: Self-injection of errors enables programmers to test and improve the error-recovery capabilities of software systems. Since it is infeasible to simulate the real world, injecting errors into live software systems provides insights that are more realistic.

(S5) Mindset of loving errors: Software engineering literature related to antifragility promotes a mindset, in which errors are a beneficial source of information. In contrast, manufacturing literature generally focuses on avoiding errors.

(S6) Machine Learning: Baruwal Chhetri et al. (2019) and de Florio (2014) propose machine learning to endow software systems with learning capabilities in order to become antifragile. On the other hand, Taleb (2013) points out that predictive models cause fragility, as they do not work well in case of low probability events. However, reinforcement learning algorithms explore yet unknown variations of their action space and benefit from trial and error. Hence, they have the potential to contribute to antifragile systems.

4.4 Building Blocks from Manufacturing

(M1) Redundancy: Redundancy, for instance in the form of buffer inventory, allows manufacturing systems to absorb negative consequences of shock events.

(M2) Flexibility: A flexible manufacturing system allows companies to adapt, for instance to market volatility or changing customer requirements. Hence, it increases the resilience, but also allows seizing opportunities (e.g., from a sudden increase in demand). Evolvable production systems, for instance, flexibly adapt their behavior through self-organization of autonomous, interoperable modules. Interoperability and self-organization also allow to flexibly add, replace or combine modules to introduce new features.

(M3) Inherent antifragility: Identifying and incorporating inherently antifragile phenomena, such as strain hardening or the pulsed laser-assisted wire-based laser metal deposition (see Sect. 3.4) may contribute to building more antifragile manufacturing systems overall.

(M4) Optionality: Examples from the semiconductor industry (presented in Sect. 3.4), illustrated that it is possible to utilize random deviations in produced components. If manufacturers were able to develop optional use cases for parts with quality deviations, they would become less susceptible to randomness or might even benefit from it.

5 Challenges of Antifragile Manufacturing and Future Research

The framework proposed in the previous section intends to provide a starting point for advancing antifragility in manufacturing. For example, a manufacturer could utilize the *barbell strategy* by defining a tolerable amount of extra scrap to explore new process setups which potentially lead to improvements, e.g., in sustainability or costs, while at the worst producing the predefined tolerable scrap amount. *Self-injecting volatility or stressors* with a limited scope as already done in software engineering could provide manufacturers with opportunities to improve their systems. For example, deliberately using raw material with poorer quality for a limited amount of workpieces could be a way to learn in which process steps problems occur in case of material quality variations and how they can be mitigated/compensated in subsequent process steps. Creating *optionality*, e.g., by learning how to achieve the desired product properties from different raw materials provides another potential opportunity to become antifragile. When there is a shortage of the preferred raw material, a manufacturer that is still able to manufacture the products from another material, might be able to charge higher prices.

However, challenges remain and must be overcome to realize antifragile manufacturing. For example, manufacturing companies typically strive to increase their efficiency. However, optionality and redundancy, which are crucial for antifragility, cause inefficiency. Hence, there is a trade-off between antifragility and efficiency (Derbyshire and Wright 2014; Blečić and Cecchini 2019). To become antifragile (long-term benefits) and also remain competitive (short term), manufacturing companies need tools that take the "price" of antifragility into consideration as well.

The mathematical definition of antifragility via the concept of convexity (see Sect. 3) is intuitive. However, its application in practice comes with challenges. Manufacturers have to determine suitable variables to monitor whether the response of a system to variations is convex. To that end, measurable dependent variables representing gains/losses as well as independent variables that represent the impact of unpredictable events are required. As Blečić and Cecchini (2019) put it, the question to be answered is "antifragility of what to what?".

The illustration of convexity (respectively antifragility) in Sect. 3 was two-dimensional. In reality, the behavior of complex technical systems depends on the interplay of multiple variables. Hence, real-world problems are high-dimensional. The effect of single variables, e.g., process parameters depends on the values of other variables, for instance material properties. Whether or not variations of a variable will cause a convex, hence antifragile, system response may depend on other variables (which are possibly unknown or not measured). In the presence of interaction effects between variables reliably assessing the antifragility of a system based on a convexity metric becomes challenging—especially when it is infeasible to measure all (relevant) variables. Potentially, reinforcement learning-based solutions, which balance robustness and exploration, may contribute to achieving convex behavior in high-dimensional manufacturing (sub-)systems. This also urges the question of how and at which scale data has to be sampled.

Concluding, the following research questions for future research arise: How can manufacturing companies balance short-term inefficiencies and long-term gains in the design of antifragile technical systems? What makes a variable suitable to monitor the antifragility of technical systems in manufacturing? How can manufacturing companies ensure the convexity of a system response in the presence of interaction effects and high dimensionality?

6 Conclusion

Complex systems are common in manufacturing. Small, local deviations can propagate to unpredictable, critical disturbances in such systems. The existing literature addresses this challenge by developing solutions to avoid negative effects of volatility and shock events through concepts such as resilience or robustness. Taleb coined the term "antifragility" to describe systems, which gain from stressors and therefore go beyond robustness and resilience. He recognizes that antifragile behavior is common in biological systems. Even though antifragility seems to be superior to resilience and robustness, the concept has received little attention in the manufacturing literature so far. Therefore, this article surveyed existing examples of antifragility from the domains of biology, risk management, software engineering and manufacturing itself. Moreover, a framework to design antifragile systems was proposed, intending to serve as guidance for practitioners as well as starting point for future research on the topic. The framework is comprised of three main components: (1) Monitoring and detecting (anti)fragility, (2) increasing robustness and/or resilience and (3) exploiting stressors. Potential building blocks to implement these three components were derived from the antifragility examples of the four, previously surveyed domains. While the domain of software engineering illustrates that antifragility offers advantages in technical, human-made systems, challenges of antifragile manufacturing remain. In particular, future research has to address challenges associated with the trade-off between long-term antifragility and short-term efficiency as well as reliably monitoring (anti)fragility and the "costs" of antifragility.

Acknowledgements/Funding Funded by the Federal Ministry of Education and Research (BMBF) and the Ministry of Culture and Science of the German State of North Rhine-Westphalia (MKW) under the Excellence Strategy of the Federal Government and the Länder.

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Humboldt^n and the Sustainable Transformation of Universities

Johanna Höhl, Annalena Tomazin, and Kathrin Greiff

Abstract The sustainable transformation of society is one of the greatest challenges of our time. Universities are central actors for knowledge generation and transfer in the sustainability field and, at the same time, are facing the question of how they can become sustainable social actors and make their activities and infrastructure sustainable. Against this background, the 16 member universities of the State Rectors' Conference of North Rhine-Westphalia have joined forces in the Humboldt^n initiative to pool their efforts in the field of sustainability and to anchor generational responsibility for sustainable action in research, teaching, administration, infrastructure, and transfer. How the joint responsibility for the questions for the future in the aforementioned complex of topics is addressed via Humboldt^n and which focal points are set in the process will be presented and discussed using examples from the institutional sustainability transformation and examples from the research area from RWTH Aachen University. In this way, the implementation of transformation processes at universities and their possible blueprint effect can be illuminated.

Keywords Sustainability · Universities · Whole institution approach · North Rhine-Westphalia · RWTH Aachen University · Humboldt^n

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P. Letmathe et al. (eds.), *Transformation Towards Sustainability*,
https://doi.org/10.1007/978-3-031-54700-3_17

1 Introduction

The implementation of sustainable development is one of the greatest challenges for today's but also future generations. Many universities around the world have recognized this, and the importance of sustainability in its three dimensions—social, economic, and ecologic (Corsten and Roth 2012)—has increased significantly at universities in recent years. The transformation of universities also plays an important role in societal transformation processes. On the one hand, universities respond to societal needs, and on the other, through their knowledge production, they shape socio-technical systems in which the respective society moves (Stephens and Graham 2010). As so-called change agents (Purcell et al. 2019: 1344), they play a central role in implementing measures to transform to a more sustainable society (Schneidewind 2014). Moreover, universities are key learning sites that educate future generations of citizens and leaders. Thus, they have a leadership role in raising awareness regarding sustainability among young scholars and future decision-makers (Kohl et al. 2021), as well as in motivating and inspiring them to act on a shared vision of the future (Purcell et al. 2019).

The actions that started with the UN Conference on the Human Environment in 1972 aiming at contributing to sustainable development (Findler et al. 2019) have therefore been strengthened over the years to make universities more sustainable and increase their impact for societal transformation (Wals 2014; Pashby and de Oliveira Andreotti 2016). The structural transformation of universities has been flanked by declarations of intent, such as the 2009/2010 German Rectors' Conference statement on sustainability, as well as the establishment of networks at regional and global levels, such as Humboldt^{n}, and is further driven by student movements such as *Students for Future*.

Sustainability is thus increasingly entering into university efforts as a guiding principle (Kohl et al. 2021), as the necessary change can only occur and the future be shaped through a strategic (re)orientation of universities. However, translating sustainability principles into corresponding strategies at universities is fraught with challenges (Leal Filho et al. 2015, 2020). The development and presentation of a sustainability strategy confront university administrations with various tensions and conflicting goals. These include, for example, conflicts between institutional goals, cultural preferences, and individual and organizational drivers. Innovative perspectives, such as the Whole Institution Approach (WIA), therefore aim at a holistic view of the entire organization. By involving all members of the university—individuals and groups as well as communities—the transformation process can be implemented systemically. University leaders, such as the rectorate, are central to this. They must shape the transformation process and drive implementation within a given timeframe, but not neglect associated frustration, anxiety, and uncertainty (Purcell et al. 2019).

Further barriers to the sustainable transformation of higher education institutions include government regulations and a lack of engagement from external stakeholders (Blanco-Portela et al. 2017). This leads to delays in, for example, the establishment of sustainability initiatives at universities, despite an increasing focus on and internalization of measures to implement sustainability goals. At the same time, the institutionalization of these initiatives, which are often supported by committed students, staff, and professors working on a voluntary basis, is slow to get off the ground. It is therefore of great importance for anchoring sustainability as a transversal topic at universities that the measures are accompanied by appropriate funding (Kohl et al. 2021).

While collaboration between different stakeholders within a university is important to meet sustainability goals, cooperations between higher education institutions are necessary to achieve their sustainable transformation within the challenging timeframes set. The sustainability initiative Humboldt^n of the State Rectors' Conference of the Universities in North Rhine-Westphalia (NRW) founded in 2021 thus bundles the sustainability efforts of 16 universities. How is the initiative addressing the issue of sustainability? What are their priorities? How do they succeed in implementing them? These central questions are explored in chapter three. First, Humboldt^n is embedded in the processes for sustainable transformation of universities, and the developments in this area to date are outlined. In doing so, the WIA which is applied in transformation processes at universities worldwide is also addressed. Finally, chapter four presents the process of sustainability transformation of the RWTH Aachen University as a best-practice example in order to outline the concrete implementation of sustainability activities in North Rhine-Westphalia as an example for Humboldt^n.

2 Sustainability at Universities

The term and concept of sustainability were established at universities shortly after the United Nations Brundtland Report in 1987 (Giesenbauer 2021), and activities to implement it have continued ever since (Findler et al. 2019). Moreover, with the signing of the Magna Charta, which stated "that the universities must give future generations education and training that will teach them, and through them others, to respect the great harmonies of their natural environment and of life itself"[1] in September 1988, numerous European universities formalized their efforts to contribute to climate goals in Bologna. Specifically, however, developments over the past three decades have focused on attempts to integrate sustainability into university systems via statements and charters (Lozano et al. 2013), curriculum redesign (Qian 2013), regional and global partnerships, and sustainable campus initiatives (Findler et al. 2019), in order to increase the focus on people and nature. Numerous initiatives have been implemented to green campuses since the 1970s and make them more climate-friendly and livable (Lozano et al. 2015; Blanco-Portela et al. 2017; Washington-Ottombre et al. 2018; Giesenbauer 2021). By doing so, universities aim to contribute to the reduction of greenhouse gases as well as to regional sustainable development (Blanco-Portela et al. 2017), which is

[1] http://www.magna-charta.org/resources/files/the-magna-charta/english.

why they clearly differ from companies: While the latter focus on developing more sustainable products and services, universities aim to generate knowledge on and about sustainability and provide skills and values for future professionals, decision-makers, entrepreneurs, and leaders that go hand in hand with a greater awareness of sustainability (Blanco-Portela et al. 2017).

Accordingly, the focus of universities for several years was on the generation of knowledge on and about sustainability as well as its transmission (Michelsen 2016). However, as Wu and Shen (2016) make clear, an integrated understanding of sustainability in university curricula (beyond environmental and engineering topics) has developed only recently. Meanwhile, and especially as a result of the pandemic, mass lectures are increasingly being replaced by online lectures to provide basic knowledge. In-depth content is taught in face-to-face seminars and project work, with the aim of promoting and developing competencies individually (Giesenbauer 2021). But, sustainability is increasingly also integrated into research, transfer, operations, assessment and reporting, collaborations, the institutional framework, multiplier programs, university management, institutional policies, and the university community in general through various focal points. Examples include the University of Hamburg, Leuphana University in Lüneburg, and Eberswalde University for Sustainable Development, which have established sustainability as a guiding principle in the past (Schneidewind 2014). In this context, the transformation of the universities is being driven forward via various measures. These include the institutionalization of sustainability through the development of corresponding strategies, the establishment of staff positions and vice-rectorates as well as student initiatives such as Green Offices and data collection in the form of sustainability reports (Leal Filho et al. 2019). However, while converting teaching, research, campus management, and operations to more sustainable forms special attention should be paid to avoid that these processes remain limited to further digitalization (Giesenbauer 2021).

In some cases, however, a new discipline—sustainability science—has been introduced and established to "understand the complex and dynamic interactions between natural and human systems" (Kohl et al. 2021: 224). Furthermore, bachelor's and master's degree programs, both undergraduate and graduate, related to sustainable development have been established, and research activities on sustainability have been initiated (Weiss and Barth 2019). In addition, attempts are also being made to position the topic via various sustainability rankings as well as networks. However, Kohl et al. (2021) state that this partly hinders the holistic approach to implementing sustainability at universities, as these developments establish new sustainability satellites that do not include all disciplines and thus ultimately do not establish sustainability as a transdisciplinary idea.

Further, universities have been identified as being at the forefront of the scientific and technical implementation of sustainability goals, as well as the dissemination and sharing of knowledge, and the training of future leaders and professionals and their awareness of sustainability issues (Kohl et al. 2021; Purcell et al. 2019). However, they hardly played a role in policy advice and active implementation of national sustainability strategies. As a consequence, their role in policy formulation at national and international levels has often been underestimated, even though all UN agencies and most governments work closely with the scientific community, as they have knowledge that can make a significant contribution to finding solutions as well as initiating the necessary change (Kohl et al. 2021). However, this is increasingly changing. The role of universities as potential influencers of future societies, for example through knowledge communication (Bonaccorsi et al. 2010), is becoming increasingly clear and more emphasized (Kohl et al. 2021). In this context, it is also important to explore the impact of sustainability activities at universities for the transformation processes toward a more sustainable society, as less is known about this so far than about the measures themselves (Findler et al. 2019).

The adoption of the Sustainable Development Goals (SDGs) in September 2015 by the United Nations General Assembly established new drivers for the implementation of sustainable development also at the political level (Giesenbauer 2021). They also serve as new guidance for higher education institutions to align and adapt their core processes with the related SDGs. This allows Higher Education Institutions to increasingly align their academic activities and operational processes with sustainable development. Moreover, the application of the SDGs brings universities into sharper focus as key players in the context of sustainability. At the same time, by embedding the SDGs at a strategic level in universities and using them to connect higher education with business, industry, health care, community partners, and entrepreneurs, the shift toward a more sustainable society can be more fully advanced (Purcell et al. 2019). In this context, the actual commitment of universities to sustainability is subject to constant change. Thus, transformation processes—especially in the field of sustainability—can be actively promoted and socially articulated challenges can be incorporated into teaching and research in order to increasingly feed the evolving issues back with external societal needs (Schneidewind 2014). In this way, changes within universities in cooperation with external stakeholders can help create a more sustainable and inclusive future (Purcell et al. 2019).

In the context of societal efforts toward a more sustainable society, universities become "living labs" where sustainable lifestyles, new ways of doing business, and documenting the benefits of sustainability practices can be tried out (Purcell et al. 2019), which in turn can be explored locally in an inter- and transdisciplinary way (Giesenbauer 2021). Universities thus become places where real sustainability challenges are formally addressed in collaboration with stakeholders (König and Evans 2013), creating an experimental form of governance (Evans et al. 2015). Nevertheless, it is central to engage all stakeholders, processes, and operations in the sustainable transformation of universities, thus addressing change holistically. How this can be achieved is outlined in the following chapter.

2.1 WIA as an Approach to Sustainable Transformation of Universities

The structural anchoring of sustainability in a central position within universities can be achieved via the WIA (Michelsen 2016). This perspective allows a transversal view of changes in the three central areas of the university mandate: Teaching, Research, and the Community Service (Kohl et al. 2021). Only in this way can a systemic upgrade and a shift in basic attitudes as well as worldviews (Giesenbauer 2021) be achieved.

Therefore, WIA is recommended by the World Action Program on Education for Sustainable Development in its Roadmap ESD for 2030, the National Action Plan on ESD as well as the German Rectors' Conference and the German Association for Sustainability at Universities e.V. for the successful transformation of universities toward more sustainability. It enables universities' core competencies in the fields of action teaching, research and transfer to be consistently interlinked and effective sustainability solutions to be developed. At the same time, the WIA provides for the inclusion of all university members and their commitment to sustainability in the transformation processes. In this way, they can be initiated and implemented.

Defined by UNESCO (2012), WIA is a process that requires the active engagement of a wide range of stakeholders in the collaborative redesign of fundamental operations, processes, and relationships to make significant progress toward sustainability. Today, WIA is understood as a way to holistically implement sustainability at the institutional level. It encompasses all areas of university life: facilities, operations, interaction with stakeholders in the university community, governance, capacity building, teaching content and methods, and the learning process itself (UNESCO 2014). Thus, this approach involves all stakeholders—leadership, faculty, learners, administrative staff—in the transformation process, developing a common strategy and plan to implement sustainability and education for sustainable development across the institution. This requires both technical and, where possible, financial support for the realignment of higher education institutions. Specifically, this includes providing relevant best practices, training for university leadership and administration, and guideline development, as well as related research. Inter-institutional networks should also be mobilized and expanded to promote exchange and make WIA more visible as an approach to transformation processes (UNESCO 2014).

Thus, WIA is an important tool to transform universities (Kohl et al. 2021), as it seeks to holistically address the challenges involved. Thus, departmental thinking, conservative management, lack of incentives, low institutionalization of sustainability, lack of interdisciplinarity, and lack of financial resources should be addressed (Blanco-Portela et al. 2017). This also requires a redefinition of sustainability. Sustainability needs to be seen as a problem-solving approach to unleash innovation and encourage leaders to think and work systemically and look beyond their domain (Nidumolu et al. 2009).

3 Humboldt^n as an Example for the Joint Sustainable Transformation of the Higher Education Landscape of North Rhine-Westphalia

In order to drive forward the systemic transformation of the universities of North Rhine-Westphalia, they have joined forces in the initiative Humboldt^n in order to take responsibility for the future issues arising in the thematic complex of sustainability. In doing so, Humboldt^n is financially supported by the Ministry of Culture and Science of the state of North Rhine-Westphalia for two years (2022–2024). The political relevance of the topic as well as the initiative is also made clear by the reference to Humboldt^n in the coalition agreement of the CDU and Die Grüne (2022–2027). Humboldt^n aims to combine efforts on the way to becoming a sustainable university and thus to take a pioneering role in tackling the major challenges society is facing. The universities are supported in this by two strong partners (see Fig. 1). The Wuppertal Institute contributes expertise in research and project support, and the North Rhine-Westphalian Academy of Sciences, Humanities and the Arts plays a central role in promoting young scientists.

Fig. 1 Participating universities and partners

Fig. 2 Humboldt^n scopes of work

Humboldt^n pursues as a central goal the strengthening of capabilities to shape the sustainability transformation. The universities themselves shall be places of sustainability transformation. Thus, central impulses for anchoring generational responsibility for sustainability emanate from Humboldt^n, which are to be expressed in sustainable action in the fields of research, teaching, transfer, administration, and infrastructure. Thus, Humboldt^n anchors sustainability strategically and holistically at the universities, for which the foundation was laid with the Humboldt^n Declaration.[2]

Humboldt^n concentrates on four scopes: the sustainability map, promoting young academics, project management and an interministerial dialogue—as well as the cross-sectional area of public relations and events (see Fig. 2). In this way, attention is to be drawn to the topic of sustainability and the associated challenges and areas of tension at the universities and beyond. In addition, Humboldt^n aims to strengthen the transfer in the context of sustainability research to all areas of society as a contribution to holistic transformation. The topic of sustainability is addressed in both fundamental and application-oriented research. In addition to research, Humboldt^n also focuses on teaching activities. The participating universities strive for the transversal integration of sustainability topics and research into university curricula. Thus, the network is to promote and strengthen the establishment and continuation of courses of study on the subject complex. In addition, the anchoring of the topic of sustainability in teaching is to be strengthened via a lecture series, which is to be digitally supported and carried out across different sites.

Structurally, Humboldt^n is composed of a leading advisory board, an overall advisory board as well as the office. The leading advisory board is involved in the project leadership and management and consists of the rectors of the universities of Bonn,

[2] https://humboldt-n.nrw/fileadmin/Public/Files/2021-11-17_LRK-NRW_HumboldtN_Rahmenerklaerung_unterschrieben.pdf.

Siegen, Witten/Herdecke, Wuppertal, the chairman of the Landesrektorenkonferenz NRW (LRK) as well as the president of the Wuppertal Institute and the secretary general of the Academy of Sciences, Humanities, and the Arts. This body maintains a close exchange with the office, which coordinates the central work areas and carries out and organizes the public relations work and events of the initiative. Furthermore, the work of the advisory board is supported by an overall advisory board, which includes the presidents and rectors of the LRK member universities, chairpersons of the participating non-university institutions, and representatives of the state of North Rhine-Westphalia. Both committees develop strategic objectives for Humboldt^n and define central tasks for the working areas. In doing so, they engage in an interministerial dialogue with the state of North Rhine-Westphalia in order to introduce the scientific results on the topic of sustainability into political debates and discourses.

3.1 Sustainability Map and Poster Exhibition

The visualization of sustainability projects and activities at universities in North Rhine-Westphalia is driven by the sustainability map (for access see Fig. 3). It is a dynamic, participatory mapping, as projects can be entered at any time and by all status groups via the website. Different statuses can be selected during registration—from in planning to completed. The Humboldt^n office checks the entries for accuracy and then activates them. In addition to increasing the visibility of sustainability activities at the state's universities, the map aims to strengthen networking among themselves but also with representatives from industry, society, and politics. Among other things, potential synergies can be identified and experiences on best practices with regard to the implementation of sustainability can be exchanged in order to further advance the sustainable transformation of universities in North Rhine-Westphalia as well as the emergence of new initiatives (Giesenbauer 2021). This creates dynamic feedback processes that, as Blanco-Portela et al. (2017) makes clear, are of great importance for organizational change as well as the implementation of sustainability strategies.

In the poster exhibition "Humboldt^n focuses: Under pressure. Sustainability and its areas of conflict" (for access see Fig. 3), selected sustainability projects and activities of the 16 universities depict and address areas of tension and conflicting goals of sustainability. How, for example, can sports activities contribute to the preservation of biodiversity? The Cologne Sports University addresses this question by introducing school classes to nature through sports activities in summer and winter camps, thereby raising awareness of nature conservation and avoiding a disconnection between the experience of nature and the overall systemic context. The transfer field of action in particular shows how conflicting goals can be addressed. Using the example of the mobility transition, the University of Wuppertal shows how apps developed in Living Labs can be used to promote climate-friendly journeys within the city by combining public transport with private providers. If possible, this traveling exhibition will be shown at all university locations in North Rhine-Westphalia as part of or in the

Fig. 3 Access to the sustainability map in German (on the left) and the virtual poster exhibition in German (on the right)

context of sustainability events. It can also be viewed virtually on the website of the sustainability initiative. The exhibition thus complements the sustainability map with the aim of making the sustainability efforts and transformation processes at the universities more visible.

3.2 Promoting Young Researchers

As outlined in the introduction, the promotion of young researchers is at the core of the sustainability alliance. Humboldt^{n} specifically focuses on the training of young researchers. Young researchers are to be sensitized to sustainability issues and incorporate them into their work. In view of the SDGs and the national climate goals, which include the transformation processes for phasing out coal in the Rhenish coalfield, Humboldt^{n} not only provides students and researchers in North Rhine-Westphalia with excellent research and networking opportunities, but also points to concrete fields of action and opportunities for impact. In this context, a permanent working group on sustainability will be established at the Junge Kolleg of the Academy for all fellows, and additional fellowship positions will be offered. The Junge Kolleg is a place for research and interdisciplinary dialogue and connects scholars from the humanities, natural sciences, engineering, economics, and medicine as well as artists at a similar career stage. Through the newly created working group "Sustainability" interdisciplinary and transdisciplinary cooperation is to be strengthened and the insights gained from this are to be brought back to the respective university as well as incorporated into the university's own research.

In addition to the Junge Kolleg, Humboldt^{n} strengthens the engagement with the topic of sustainability via the Humboldt^{n}-Schools. This format, which is explicitly aimed at doctoral students and postdocs, serves to bring together junior researchers from different disciplines on a specific sustainability issue. Scientific input is combined with the teaching of methods of transdisciplinary research. In this way, participants from all universities in North Rhine-Westphalia are sensitized to issues of transdisciplinary and transformative research—irrespective of their previous disciplinary training and the concrete reference of their own research work to sustainability issues—and at the same time introduced to an examination of the associated problems. This shall enable them to integrate sustainability into their research work as well as their teaching. The topics of the Humboldt^n-Schools are defined bottom-up from within the scientific community and prepared together with partners from society, politics and business. The first Humboldt^n-School at the University of Bonn dealt with climate change and its risks and required adaptation strategies. The participants received input from various disciplines as well as from the field and worked on incorporating sustainability in its broader sense into their research. In the upcoming Humboldt^n-School addressed at postdocs and to be held at RWTH Aachen University, hydrogen, which is of central importance for the transformation of carbon-intensive industry, among other things, will be the focused upon as well as associated innovations.

3.3 Project Management and Interministerial Dialogue

In addition to the scopes already described, Humboldt^n is to initiate projects to implement sustainable higher education and, in doing so, strengthen networking and synergy building among the members of the State Rectors' Conference. The two partners, the Wuppertal Institute and the Academy, will also be involved where appropriate, as well as other external partners. Thus, Humboldt^n is to make a central contribution as a platform in project acquisition. This has already been done, for example, with project applications that are currently in the review phase and are to be expanded in the future in order to further promote the anchoring of sustainability at the universities through central projects.

At the same time, the universities have committed themselves to developing a joint state-wide sustainability concept for the universities in North Rhine-Westphalia. To this end, the universities are developing specific sustainability goals with measurable indicators in the fields of action of research, teaching, infrastructure, administration and transfer, based on the state government's sustainability strategy, in order to then implement these in a timely manner. In this context, the interministerial dialogue is of central importance, which should help to exchange and transfer best-practice examples within and between universities and thus further highlight the leading role of universities in the transformation of society, industry, companies, and municipalities and drive forward their implementation based on scientific findings. Furthermore, this dialogue is important in order to take up the challenges formulated by society, but also on the part of companies as well as industry, in the universities and to integrate them into research and teaching. How this can be achieved in the area of research and, moreover, how the sustainable transformation of universities can be advanced through corresponding research activities is illustrated below using examples of transformation research at RWTH Aachen University.

4 Transformation Process Toward a Continuously More Sustainable RWTH Aachen University as a Practice Example of the Transformation of NRW's Higher Education Landscape

RWTH Aachen University considers as its duty to ensure that the university, in all its diversity and its wide range of different organizational units—from teaching and research institutions to administration—is structured to accommodate and facilitate sustainable development as set out in the WIA. RWTH Aachen aims to guarantee and encourage this by embedding tools, processes, and measures in all of the university's everyday activities—research, teaching, operations, and governance. RWTH Aachen University is part of the Humboldt^n sustainability initiative and contributes to this network, among other things, its experience in implementing its sustainability strategy as well as research approaches and results. In doing so, it additionally benefits from the exchange on transformation paths to a sustainable university with the other universities in NRW. In the following, it is described which structures have been established especially for participation, how the strategy process is conducted, and with the focus on one field of action of the WIA, it is pointed out how sustainability is implemented in the field of research.

4.1 Structures and Participation at RWTH University

In line with the WIA approach, appropriate governance structures were first created at RWTH. Since mid-2020, the **Sustainability and University Governance staff unit** has had the special task of driving forward the continued development process toward a more sustainable RWTH (see Fig. 4 for the timeline). Its task is to pool existing sustainability structures, projects, and initiatives and to coordinate and promote their implementation. This also includes providing support to university management when they are preparing to make decisions. As a central contact partner, the staff unit works in close collaboration with all university groups—professors, academic, and non-academic staff as well as students, to coordinate initiatives and strategic targets regarding sustainability.

The rectorate appoints RWTH professors to take on individual tasks of strategic importance for the university and to carry out representative functions in specific areas. In 2021, the rectorate appointed **rectorate delegates for sustainability** for the first time to help guide the operational sustainability process with strategic

Fig. 4 Sustainability process of RWTH Aachen University (selection)

planning support. In addition to advising the rectorate and promoting collaboration between RWTH and other universities and networks, they are leading the so-called GreenTeams (see below).

Next to these developments in the university's governance, the elected representative committee of the university students (AStA) has established a department for sustainability. **The Department for Sustainability and Student Engagement of the AStA** promotes awareness of, and commitment to, sustainability among students and all other members of the university. The department was established in 2019 and is involved in the strategy process, in close collaboration with the Sustainability and University Governance staff unit.

The aim of the **Internal Sustainability Network** is to establish good communication channels and transparent responsibilities for sustainability at RWTH Aachen University. To this end, sustainability officers have been appointed for all faculties, central institutions, and administrative units. On the student level, the AStA Department for Sustainability and Student Engagement is involved as well as partly appointed sustainability officers of individual departments. In addition to internal networking and the forwarding of information, instruments are also implemented to facilitate work, such as a virtual "sustainability bulletin board."

Through various exchange formats, the staff unit, in close cooperation with the rectorate delegates for sustainability, as well as AStA, offers opportunities for participating, dialogue, and networking among the various stakeholder groups. In addition to the weekly sustainability consultation hour, three GreenTeams (each for the topics teaching, research, and operations) take place every six months under the leadership of the rectorate delegates. These Green Teams have been established in order to implement the commitment to a more sustainable RWTH in everyday university life, as stipulated in the sustainability mission statement. Next to these, the sustainability round table for exchange between student initiatives, the staff unit and the AStA takes place every six months as well.

Sustainability is also a central guiding theme in the cooperative ventures with different partners from regional, e.g., with the city of Aachen on heating transition, to international level, e.g., within the IDEA League—Working Group Sustainability and Climate Change Adaptation on university campuses.

4.2 Strategy Process as Part of Governance

The process for a sustainable transformation of the university can be divided into a strategy process with clearly defined milestones and parallel measures in the fields of teaching, research, and operations. The strategy process essentially focuses on three milestones—sustainability mission statement, sustainability report, and the sustainability roadmap.

The challenge of synchronizing a common understanding of sustainability and commitment of all members of RWTH to sustainable action as a basis for joint work for sustainable development was addressed at the beginning of the sustainability process by developing the **sustainability mission statement**.[3] Based on the open consultations in which all university members could participate, a draft mission statement was developed. The mission statement—with reference to fundamental frameworks applying across the universities' borders—such as the SDGs—was finally approved by the Senate and all the university groups on July 22, 2021.

The first **sustainability report**[4] **(access via** Fig. 5), exclusively available in a digital format, shows where the university is already fulfilling its responsibility and where there is some room for improvement. The report features six different sections, each one explaining how sustainability is embedded in the university's underlying strategies, its responsibilities, developments to date, and selected current projects. In addition, the report summarizes key figures in RWTH's various spheres of action and outlines the current situation concerning sustainability activities. It transparently presents how, for example, energy consumption and the number of business trips have developed in recent years. It was the first time that the data was collected altogether, rather than in the individual organizational units. At the same time, the report is intended to shine a light on RWTH's activities in sustainable development and to serve as a starting point for monitoring the university's sustainability performance.

The **Sustainability Roadmap**[5] shall outline the process of RWTH to become a sustainable university and implement the vision from the sustainability mission statement (Corsten and Roth 2012)—establish sustainability as a core topic in research, empower learners and instructors to use innovative ideas to drive the development of sustainable solutions as well as developing the campus operations more sustainable, reducing the environmental footprint in the spirit of climate neutrality, and actively foster a culture of responsible and inclusive cooperation. The roadmap will cover the period until 2030. To decide on and implement the necessary activities, concrete and measurable goals including indicators and corresponding measures

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[3] https://www.rwth-aachen.de/Nachhaltigkeitsleitbild.

[4] https://magazines.rwth-aachen.de/en/sustainabilityreport.

[5] https://www.rwth-aachen.de/nachhaltigkeit/roadmapnachhaltigkeit.

Fig. 5 Access to the sustainability report

need to be defined. On behalf of the rectorate, the Sustainability and University Governance staff unit organizes the corresponding exchange in coordination with the Rector's Delegates for Sustainability and the AStA Department for Sustainability and Student Engagement. Progress reports and updates on current developments will be presented and discussed in the GreenTeams. The finalized roadmap will be presented and approved in the Senate. A continuous review of the performance related to sustainability efforts will be the basis to make adjustments required in case of deviations.

4.3 Sustainability in Research at RWTH Aachen University as One Example for the Fields of Action of WIA

RWTH's commitment to excellence also holds the university responsible for pursuing a self-reflective and pluralistic value debate regarding excellent research—both among the stakeholders of the teaching and research projects at RWTH and with additional scientific and non-scientific bodies at the local, national, and international level. The students and early career researchers are an important pillar of change. They are the ones who are pushing toward more sustainable practices and are ready to take the reins on this transformation process themselves bringing challenges and chances simultaneously.

In order to meet these requirements, a future-oriented university needs to be particularly agile while also contributing to meeting the SDGs. In the **University of Excellence proposal** "The Integrated Interdisciplinary University of Science and Technology. Knowledge. Impact. Networks.",[6] RWTH's goal is to contribute to and help shape a sustainable society. This requires a holistic understanding of sustainability; the transformation to a sustainable society for future generations can only succeed, if the three dimensions of environment, economy, and society are tackled

[6] https://www.rwth-aachen.de/cms/root/Die-RWTH/Exzellenzinitiative.

at the same time. With its fundamental and application-oriented research in a variety of fields, RWTH is making significant contributions to sustainable development.

RWTH therefore has pooled its scientific expertise in an interdisciplinary research environment of **eight cross-faculty profile areas** to work on solving the great social challenges of our time in interdisciplinary teams using innovative approaches. In these profile areas, scientists from the different disciplines work together to create a solid foundation for societally relevant innovations based on the findings from fundamental and applied research. They coordinate their research activities, use state-of-the-art infrastructures, and create large research networks with national and international partners from science and industry.

Sustainability and social responsibility are firmly integrated in the University's approach to research and run through almost all research areas. Sustainability in research can manifest in many different ways (see Fig. 6):

In the following, concrete examples of sustainable RWTH research projects will practically give an introduction of the three dimensions of sustainable research as seen in Fig. 6—sustainability research, socially responsible research and research for sustainable development—as well as how RWTH is contributing to them.

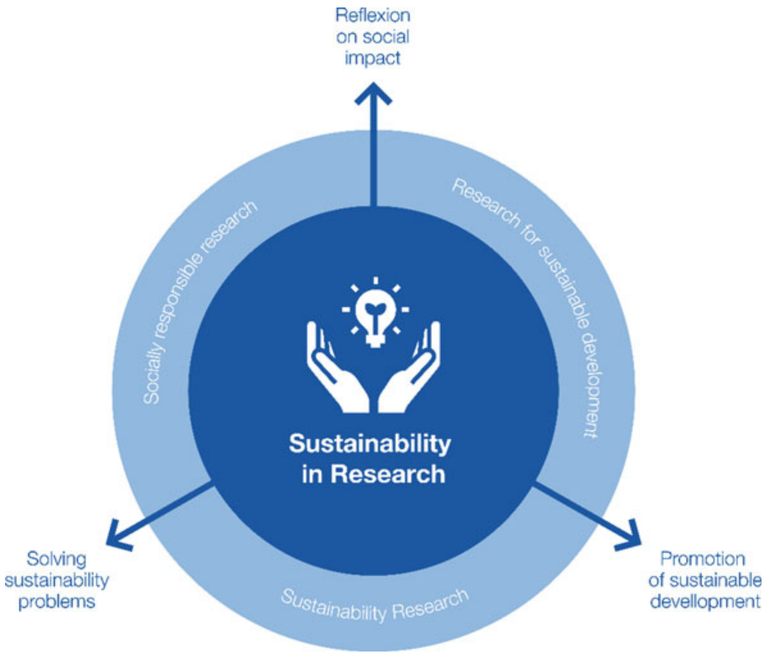

Fig. 6 Understanding Sustainability in Research (Own illustration based on Wedl, I.; Reimoser, C. (o.D.): Explikation zum BMBF-Verbundvorhaben Leitfaden Nachhaltigkeitsmanagement »LeNa Management«. BMBF-Project "Leitfaden Nachhaltigkeitsmanagement in außeruniversitären Forschungsorganisationen (LeNa)," Munich.)

RWTH initiates projects that research concrete sustainability-related questions and are explicitly intended to contribute to their solutions. These include for example the „Forschungskolleg Verbund.NRW“[7].

Forschungskolleg Verbund.NRW

Research concerning the increase of resource-efficiency regarding Composite Building Materials.

In its Ph.D. projects, Forschungskolleg Verbund.NRW deals with all areas belonging to the value chain of relevant composite materials and constructions:

- Production and development
- Construction and processing
- Usage and removal
- Recycling and disposal.

Cooperation between various scientific disciplines, meaning the interdisciplinary collaboration of researchers on technological, ecological, social, and economic levels, plays a crucial role. At the same time, a transdisciplinary research approach is employed in order to incorporate the requirements of affected actors such as industrial actors, associations, and public authorities right from the beginning.

The objective of Verbund.NRW is to tackle social challenges like the increasing need for climate protection, resource-efficiency, and recovery of raw materials in order to contribute to sustainable development and to a resource-efficient usage of the aforementioned innovative materials (Fig. 7).

Fig. 7 Access to the website of the ‚Forschungskolleg Verbund.NRW‘

[7] https://www.verbund-nrw.de.

In contrast to this specific, more narrowly focused “sustainability research,” other teams deal with the societal impact of research findings and thus conduct “socially responsible research” (see Fig. 6) in their projects, such as those undertaken at the Responsible Research and Innovation Hub.[8]

Responsible Research and Innovation Hub

In the Responsible Research and Innovation (RRI) Hub, which is funded by the Excellence Strategy, intensive collaborations are pursued between science and society, which contributes to more mutual transparency and acceptance and more sustainable results. The intention is that solutions to complex societal challenges will emerge as a result of this cooperation. The Hub is a driving force and a platform for joint action at the interface between science and society and initiates and provides support for various different projects. Its activities include projects for setting up governance structures, the establishment of cooperation and networks at a regional level with the Aachen Volunteering Office through to the United Nations Innovation Network or the ENHANCE Network at an international level. It also offers participatory procedures and processes as well as education programs for citizens such as the Festival of Sustainable Action or the course, Sustainability as Challenge and Opportunity for Society. The course was developed by the RRI Hub together with representatives from the FH Aachen University of Applied Sciences and the Catholic University of Applied Sciences in Aachen as part of the Lehre^n professional program by the German Ministry of Education and Research for students from all three universities. Since 2020, the City of Aachen has been part of the national network “Engagierte Stadt” (Committed City). Based on the question of “what constitutes a good life and how do we shape it together as a collective,” the RRI Hub and various regional partners want to show the potential of a diverse and engaged urban society. Responses will be developed based on a cooperative and creative approach, and regional structures sustainably consolidated. Participatory research is seen as an indispensable part to develop sustainable solutions with and for society. As an “Engagierte Stadt,” communities of responsibility made up of bodies from civil society, politics, administration, science, and the economy are accompanied on their journey toward increased collaborations for local engagement and participation, and support is also provided for the nationwide exchange of information and knowledge transfer (Figs. 8 and 9).

[8] https://www.hub.rwth-aachen.de.

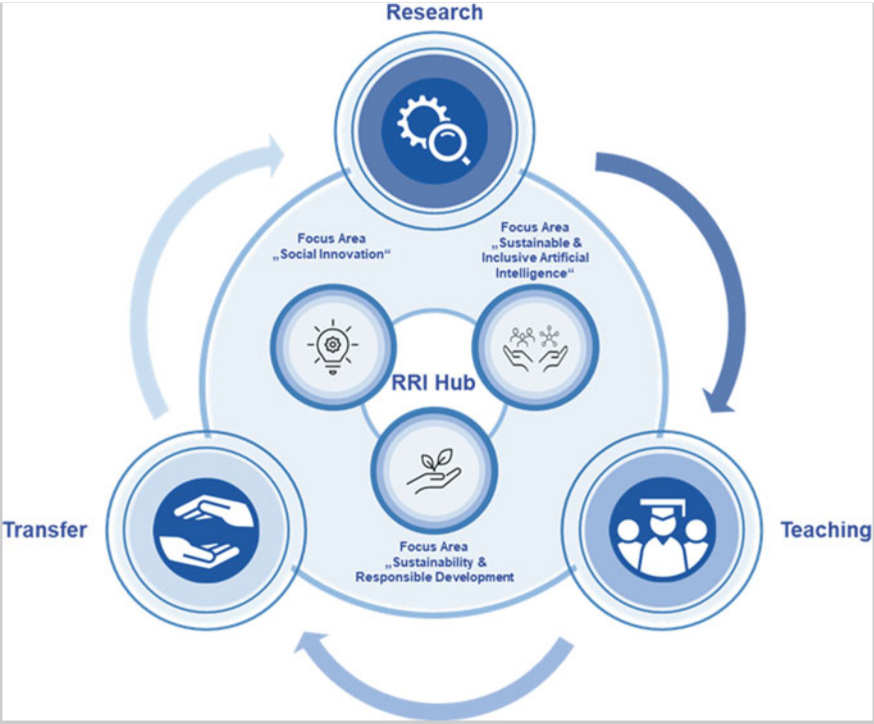

Fig. 8 Berg-Postweiler, Decker, Leicht-Scholten (2023): Academia as a Key Factor in Fostering Responsible Research and Innovation with and for Society: The Case of the RRI Hub at RWTH Aachen University

Fig. 9 Access to the website of the, RRI Hub’

"Research for sustainable development" (see Fig. 6) is, however, the largest area explored at RWTH. This category encompasses a large number of projects where scientists examine the major societal challenges of our time in interdisciplinary teams. In addition to the eight profile areas[9] at RWTH, these teams also include new structures as the Center for Circular Economy (CCE).[10]

Center for Circular Economy

Circular economy as a circular management of resources and valuable materials enables our future generations to have unrestricted access to raw materials. The objective is to enable a sustainable and resource-efficient economy by keeping recyclable materials in the economic cycle for as long as possible while producing as little waste and environmental impact as possible. To implement this vision, various players must be made responsible. Policymakers must create appropriate framework conditions, producers must design products sustainably, and consumers must be made aware of the issue. A successful circular economy requires interdisciplinary cooperation between politics, business, research and society. The CCE bundles the competences of RWTH Aachen University in the field of the circular economy and acts as an impulse generator for internal and external partners. The network thus connects stakeholders from business with regional municipalities to international communities. Since the founding of CCE in 2020, themed issues and editorials have been published in trade magazines on the circular economy, the first conferences have been held, and workshops have been held at trade fairs. By signing the Circular City Declaration at the end of 2021, the city of Aachen also sent a strong signal to promote the circular economy (Fig. 10).

Fig. 10 Access to the website of the 'CCE'

[9] https://www.rwth-aachen.de/profileareas.

[10] https://www.cce.rwth-aachen.de.

Next to the objectives of research itself, there is always the discussion of how research is conducted. This issue is strongly linked to the operational field of action, which also shows that it is difficult to make a clear differentiation between the individual fields and the goals to be defined. However, it is precisely the structures in research that are essential in order to arrive at new and innovative solutions in the area of operations as well.

5 Conclusions

In this article, it is shown how universities in North Rhine-Westphalia are approaching holistically sustainability challenges through the joint sustainability initiative Humboldt^n. Concrete examples from the RWTH Aachen University from a strategic perspective as well as from the research area furthermore show how universities address these issues as an institution. It becomes clear that a WIA must be chosen in order to integrate sustainability holistically into the higher education landscape and universities. Working with a WIA is mandatory to achieve a sustainable transformation in the fields of research, teaching, infrastructure, administration and transfer.

However, these transformations involve areas of tension and conflicting goals. Examples from the Humboldt^n Sustainability Initiative show that, for example, a balance must be struck between top-down and bottom-up measures when implementing transformation processes at universities. Areas of tension are also addressed in research as the examples from RWTH Aachen University have shown. Thus, conflicts of goals exist in various areas, both in terms of content between individual sustainability goals and also administratively between different fields of action. Also, given framework conditions, such as the existing budget, create tensions, which makes it necessary to prioritize the fields of activity and measures in the area of sustainability. In dealing with conflicting goals of all kinds, universities benefit from collaboration in initiatives such as Humboldt^n: They can support each other, learn from each other, and share implementation paths. In addition, Humboldt^n enables the universities in NRW to speak with one voice to other actors, e.g., politicians, and to jointly demand, e.g., overall necessary changes in the framework conditions.

In addition, however, it is also necessary to feed back the activities for the implementation of sustainability at the universities with the political framework conditions as well as society and the economy. For example, in the case of construction measures that focus on sustainability, it is essential to weigh up the options within the given budget by the state.

The strengthening of the dialogue between science and politics on the implementation of the SDGs envisaged by Humboldt^n can be a central contribution to setting the course for the sustainable transformation of universities in North Rhine-Westphalia.

Acknowledgements/Funding Humboldt^n is financially supported by the Ministry of Culture and Science of the state of North Rhine-Westphalia.

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