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

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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

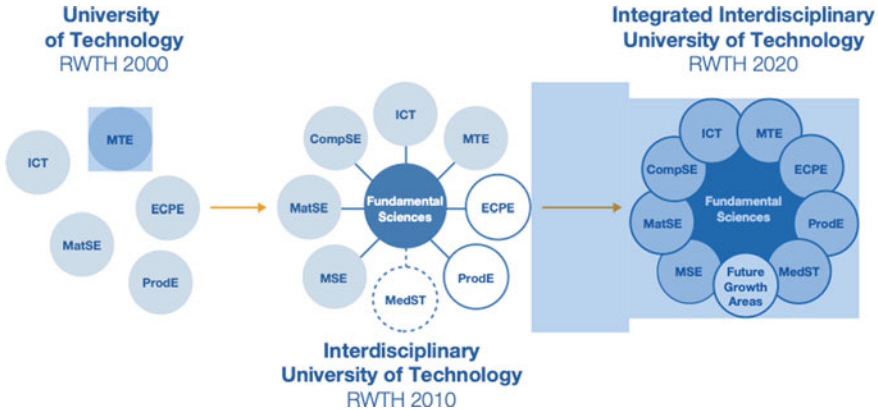

Fig. 2 Development of the RWTH Aachen. *Source* RWTH Aachen University (2019, p. 3)

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.

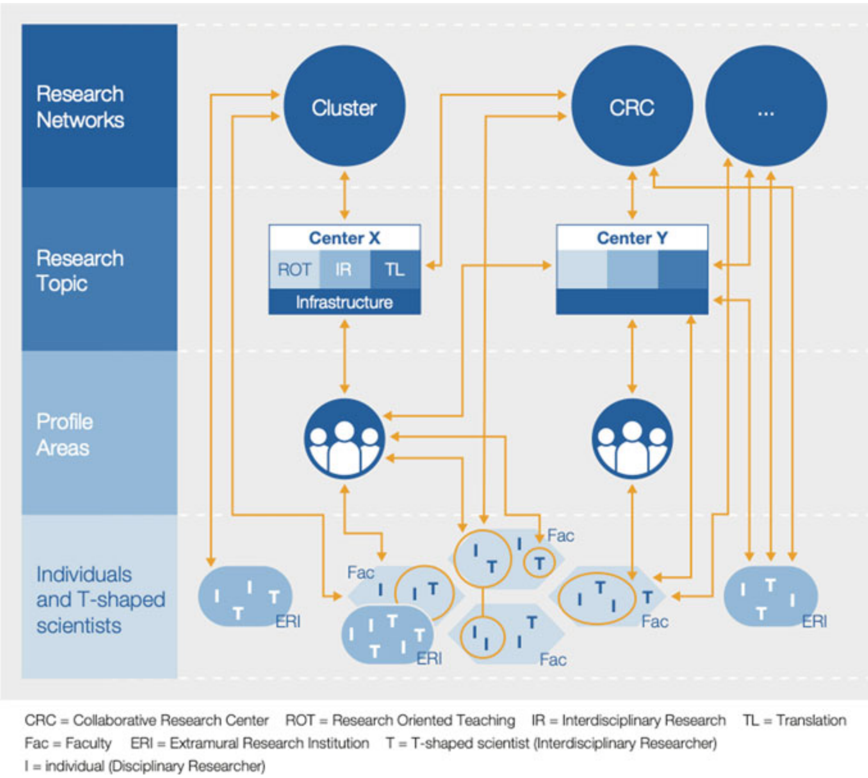

Fig. 3 Creation of research networks. *Source* RWTH Aachen University (2019, p. 25)

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.

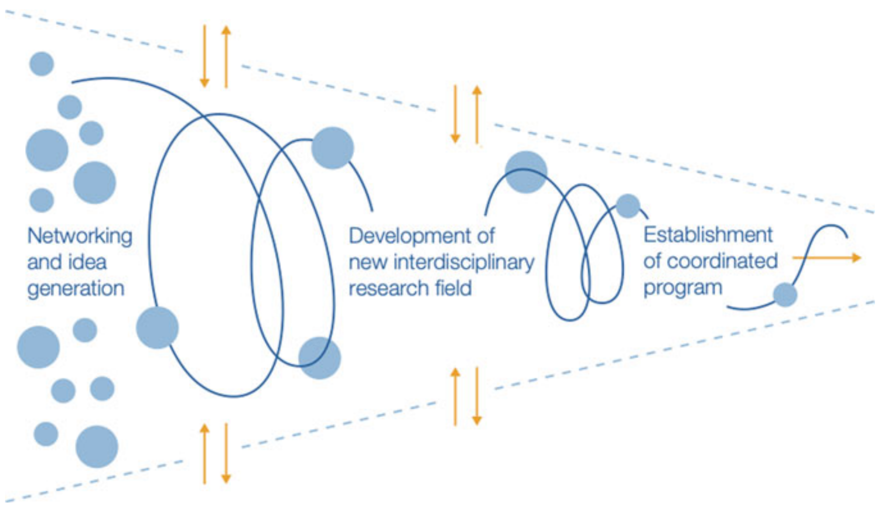

Fig. 4 From idea generation to a coordinated program. *Source* RWTH Aachen University (2019, p. 12)

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

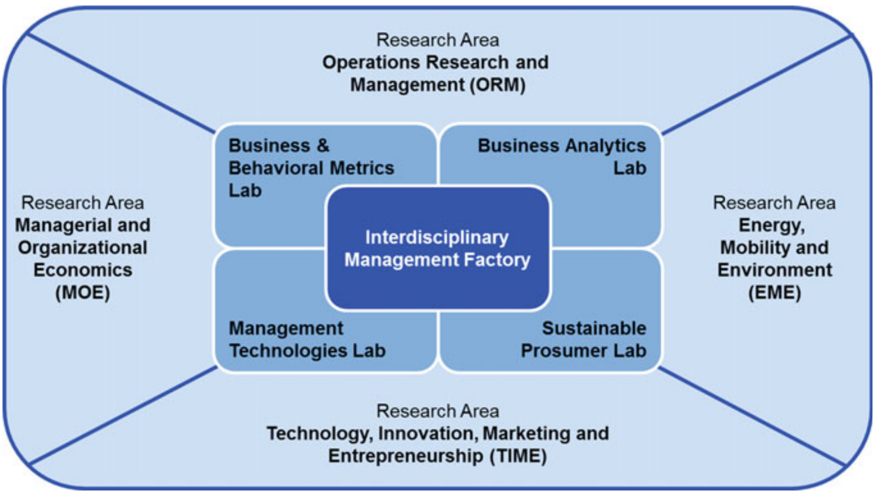

Fig. 5 Interdisciplinary management factory as an example of a project house at RWTH Aachen University (RWTH Aachen University 2015)

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.

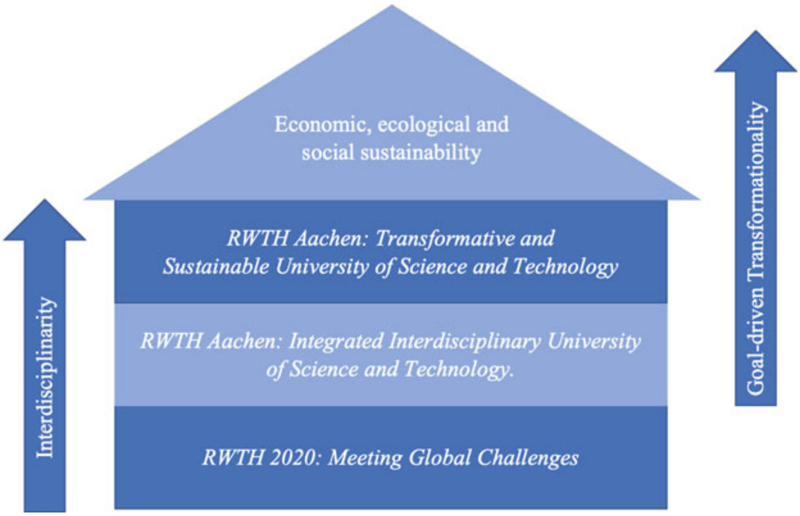

Fig. 6 Development of RWTH Aachen University toward a transformative and sustainable university (own figure)

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

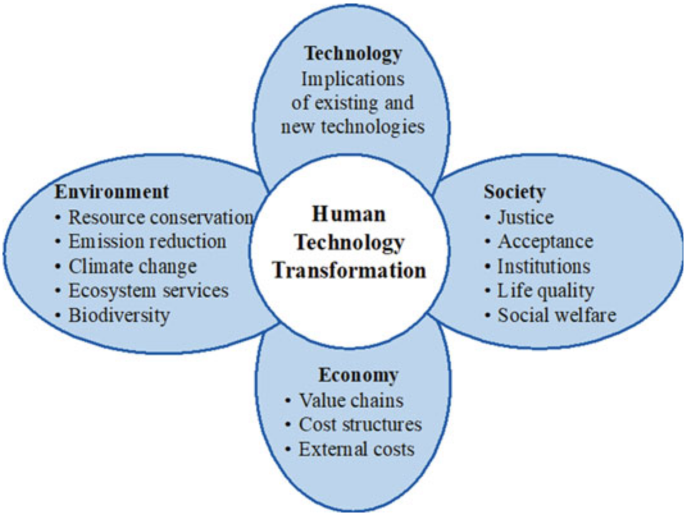

Fig. 7 Human-technology transformation (own figure)

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

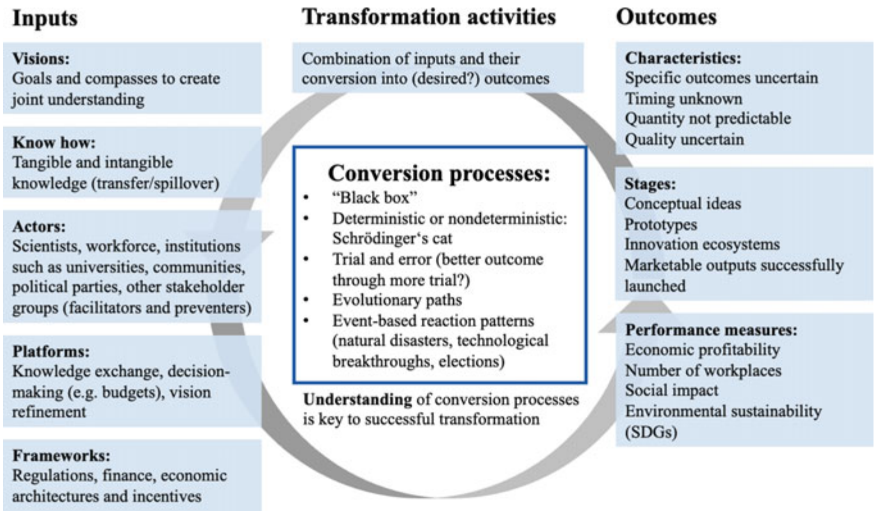

Fig. 8 Aspects of transformation processes (own figure)

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 policymakers. 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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