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

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

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

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

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# 1 Introduction

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

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

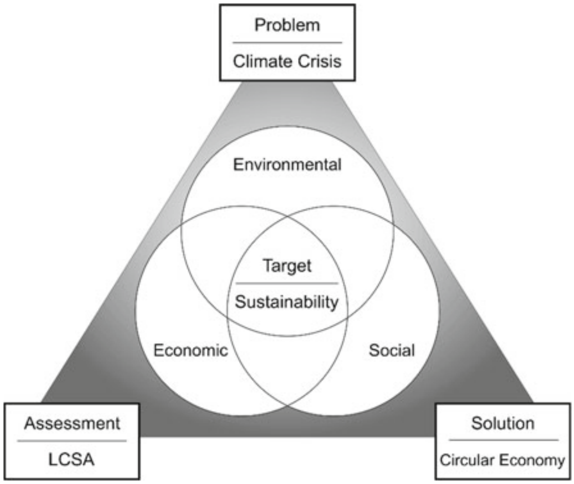


**Fig. 1** Interconnection of fundamental frameworks

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

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

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

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

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

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

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

## 2 Transformation from a Labor Market Perspective

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

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

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

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

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

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

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

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

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

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

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

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

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

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

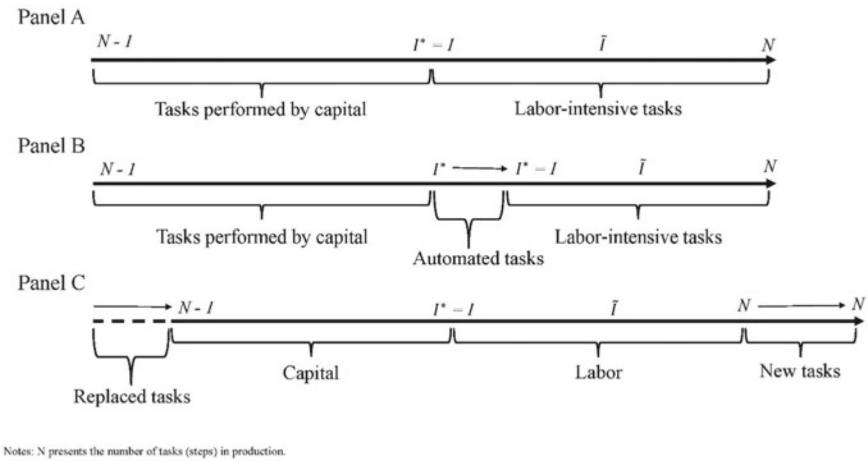


**Fig. 2** Production process as a sequence of tasks (according to Acemoglu and Restrepo 2018)

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

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

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

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

## 3 Transformation from the Perspective of the Circular Economy

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

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

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

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

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

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

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

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

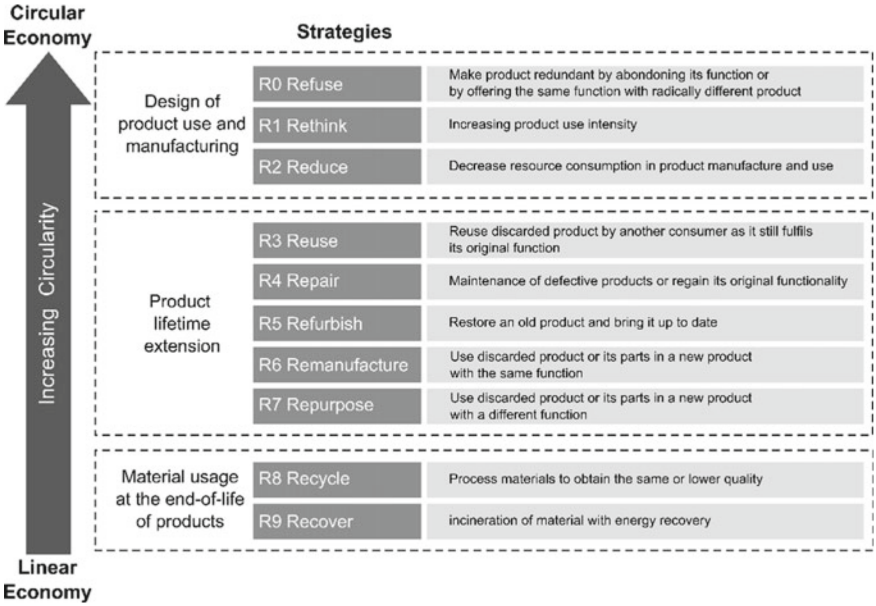


**Fig. 3** Translation of the circular economy onto product level (according to Potting et al. 2017)

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

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

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

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

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

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

**Table 1** Possible labor market effects due to different R strategies

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

(continued)

**Table 1** (continued)

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

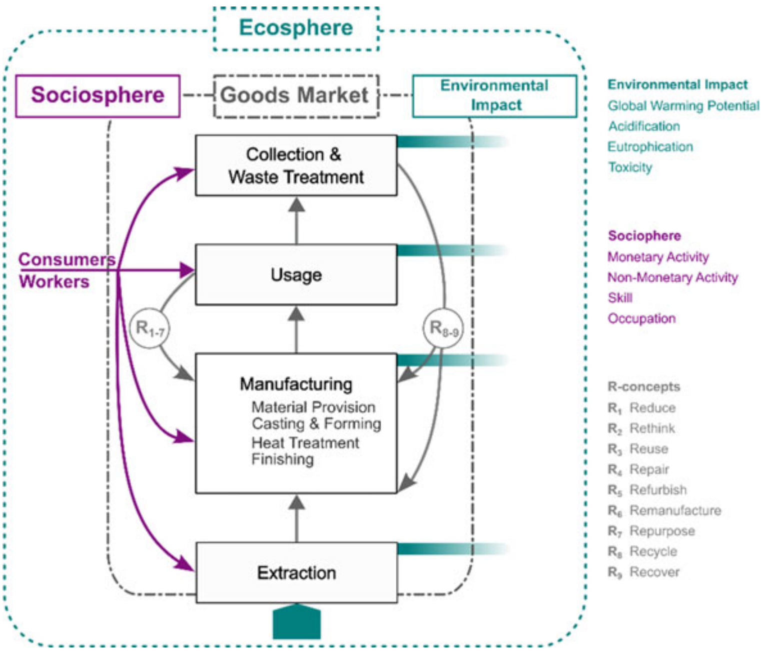


**Fig. 4** Multi-level perspective on a generic process flow and examples for environmental impacts and sociophere (own graphic)

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

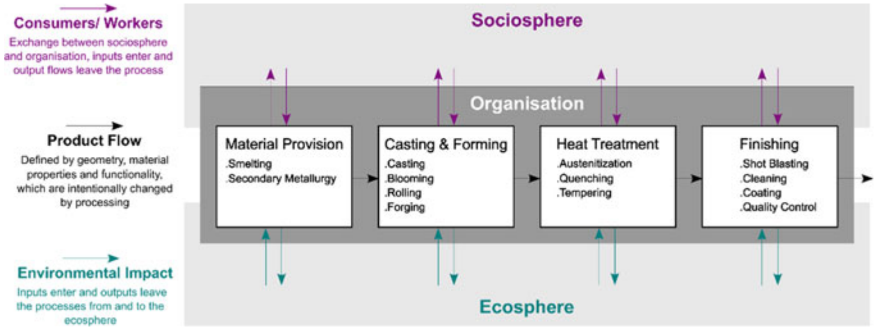


**Fig. 5** Technical process flow of the production of U-bolts (own graphic)

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

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

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

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

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

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

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

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

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

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

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

## 5.2 Discussion of Labor Market Assessment for R-concepts

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

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

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

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

## 6 Conclusion

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

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

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

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

## References

Acemoglu D (2002) Directed technical change. Rev Econ Stud 69(4):781–809. https://doi.org/10.1111/1467-937X.00226

Acemoglu D (2009) introduction to economic growth. Princeton University Press, Princeton New Jersey. https://press.princeton.edu/books/hardcover/9780691132921/introduction-to-modern-economic-growth. Accessed 10 April 2023

Acemoglu D, Restrepo P (2018) The race between man and machine: implications of technology for growth, factor shares, and employment. Am Econ Rev 108(6):1488–1542. https://doi.org/10.1257/aer.20160696

Acemoglu D, Aghion P, Bursztyn L, Hemous D (2012) The environment and directed technical change. Am Econ Rev 102(1):131–166. https://doi.org/10.1257/aer.102.1.131

Autor DH (2013) The “task approach” to labor markets: an overview. J Labour Mark Res 46(3):185–199. https://doi.org/10.1007/s12651-013-0128-z

Autor DH (2014) Skills, education, and the rise of earnings inequality among the “other 99 percent.” Science 344(6186):843–851. https://doi.org/10.1126/science.1251868

Balleer A, Link S, Menkhoff M, Zorn P (2022) Demand or supply? Price adjustment during the Covid pandemic. CEPR Working Paper 14907. https://cepr.org/active/publications/discussion_papers/dp.php?dpno=14907. Accessed 10 April 2023

BAFU (2021) Kreislaufwirtschaft

Benoît-Norris C, Vickery-Niederman G, Valdivia S, Franze J, Traverso M, Ciroth A, Mazijn B (2011) Introducing the UNEP/SETAC methodological sheets for subcategories of social LCA. Int J Life Cycle Assess 16(7):682–690. https://doi.org/10.1007/s11367-011-0301-y

Bocken NMP, Pauw I, Bakker C, van der Grinten B (2016) Product design and business model strategies for a circular economy. J Ind Prod Eng 33(5):308–320. https://doi.org/10.1080/21681015.2016.1172124

Boppart T, Krusell P (2020) Labor supply in the past, present, and future: a balanced-growth perspective. J Polit Econ 128(1):118–157. https://doi.org/10.1086/704071

Brütting J, Desruelle J, Senatore G, Fivet C (2019) Design of truss structures through reuse. Structures 18:128–137. https://doi.org/10.1016/j.istruc.2018.11.006

Buhl J, Liedtke C, Bienge K (2017) How much environment do humans need? Evidence from an integrated online user application linking natural resource use and subjective well-being in Germany. Resources 6(4):67. https://doi.org/10.3390/resources6040067

Cambridge Econometrics, Trinomics, ICF (2018) Impacts of circular economy policies on the labour market. European Commission, Brussel

Carvalho V, Gabaix X (2013) The great diversification and its undoing. Am Econ Rev 103(5):1697–1727. https://doi.org/10.1257/aer.103.5.1697

Corona B, Shen L, Reike D, Carreón JR, Worrell E (2019) Towards sustainable development through the circular economy—a review and critical assessment on current circularity metrics. Resour Conserv Recycl 151:104498. https://doi.org/10.1016/j.resconrec.2019.104498
Dauth W, Findeisen S, Suedekum J, Woessner N (2021) The adjustment of labor markets to robots. J Eur Econ Assoc 19(6):3104–3153. https://doi.org/10.1093/jeea/jvab012
Domenech T, Bahn-Walkowiak B (2019) Transition towards a resource efficient circular economy in Europe: policy lessons from the EU and the member states. Ecol Econ 155:7–19. https://doi.org/10.1016/j.ecolecon.2017.11.001
Elia V, Gnoni MG, Tornese F (2017) Measuring circular economy strategies through index methods: a critical analysis. J Clean Prod 142:2741–2751. https://doi.org/10.1016/j.jclepro.2016.10.196
Ellen MacArthur Foundation, Hrsg (2012) Towards the circular economy. Economic and business rationale for an accelerated transition
EN ISO (2020a) Environmental management—life cycle assessment—principles and framework. ISO 14040:2006 + Amd 1:2020
EN ISO (2020b) Environmental management—life cycle assessment—requirements and guidelines. ISO 14044:2006 + Amd 1:2017 + Amd 2:2020
European Commission, Hrsg. (2020) Circular economy action plan. For a cleaner and more competitive Europe
European Commission and Joint Research Centre (2010) ILCD handbook: general guide for life cycle assessment: detailed guidance. Publications Office of the European Union, Luxembourg
Fitzenberger B, Fedorets A, Spitz-Oener A (2020) Resilient men in prime working age. Working paper
Gabaix X (2011) The granular origins of aggregate fluctuations. Econometrica 79(3):733–772. https://doi.org/10.3982/ECTA8769
Gramlich A, Bleck W (2021) Tempering and intercritical annealing of air-hardening 4 wt% medium manganese steels. Steel Res Int:2100180. https://doi.org/10.1002/srin.202100180
Gramlich A, van der Linde C, Ackermann M, Bleck W (2020a) Effect of molybdenum, aluminium and boron on the phase transformation in 4 wt% manganese steels. Results Mater 8:100147. https://doi.org/10.1016/j.rinma.2020.100147
Gramlich A, Schmiedl T, Schönborn S, Melz T, Bleck W (2020b) Development of air-hardening martensitic forging steels. Mater Sci Eng, A 784:139321. https://doi.org/10.1016/j.msea.2020.139321
Hagedorn W, Kick M, Greiff K, Jarchow S (2020) Zirkuläres Wirtschaften auf Produktebene. MÜLL und ABFALL (10):6. https://doi.org/10.37307/j.1863-9763.2020.10.06
Hagedorn W, Gramlich A, Greiff K, Krupp U (2022) Alloy and process design of forging steels for better environmental performance. Sustain Mater Technol:e00509. https://doi.org/10.1016/j.susmat.2022.e00509
Harris S, Martin M, Diener D (2021) Circularity for circularity's sake? Scoping review of assessment methods for environmental performance in the circular economy. Sustain Prod Consump 26:172–186. https://doi.org/10.1016/j.spc.2020.09.018
Hauschild MZ, Rosenbaum RK, Olsen SI (eds) (2018) Life cycle assessment. Springer International Publishing, Cham
Helander H, Petit-Boix A, Leipold A, Bringezu S (2019) How to monitor environmental pressures of a circular economy: an assessment of indicators. J Ind Ecol 23(5):1278–1291. https://doi.org/10.1111/jiec.12924
Herrendorf B, Rogerson R, Valentinyi Á (2014) Growth and structural transformation. In: Handbook of economic growth, vol 2, pp 855–941.https://doi.org/10.1016/B978-0-444-53540-5.00006-9
Hertwich E, Reid L, Pauliuk S, Heeren N, Ali S, Tu Q, Ardente F, Berrill P, Fishman T, Kanaoka K, Kulczycka J, Makov T, Masanet E, Wolfram P (2019) Resource efficiency and climate change: material efficiency strategies for a low-carbon future. Zenodo. https://doi.org/10.5281/ZENODO.3542680

Hoogmartens R, Passel SV, Van Acker K, Dubois M (2014) Bridging the gap between LCA, LCC and CBA as sustainability assessment tools. Environ Impact Assess Rev 48:27–33. https://doi.org/10.1016/j.eiar.2014.05.001

Hornstein A, Krusell P, Violante GL (2005) The effects of technical change on labor market inequalities. In: Handbook of economic growth, vol 1, pp 1275–1370. https://doi.org/10.1016/S1574-0684(05)01020-8

Horvath M (2000) Sectoral shocks and aggregate fluctuations. J Monet Econ 45(1):69–106. https://doi.org/10.1016/S0304-3932(99)00044-6

Huertas-Valdivia I, Ferrari AM, Settembre-Blundo D, García-Muiña FE (2020) Social life-cycle assessment: a review by bibliometric analysis. Sustainability 12(15):6211. https://doi.org/10.3390/su12156211

Hunkeler D, Lichtenvort K, Rebitzer G (2008) Environmental life cycle costing. CRC Press, Boca Raton, Fla.

Jerome A, Helander H, Ljunggren M, Janssen M (2021) Testing product-level indicators for a more circular economy. Limerick

Kirchherr J, Reike D, Hekkert M (2017) Conceptualizing the circular economy: an analysis of 114 definitions. Resour Conserv Recycl 127:221–232. https://doi.org/10.1016/j.resconrec.2017.09.005

Kristensen HS, Mosgaard MA (2020) A review of micro level indicators for a circular economy—moving away from the three dimensions of sustainability? J Clean Prod 243:118531. https://doi.org/10.1016/j.jclepro.2019.118531

Larsen VG, Tollin N, Sattrup PA, Birkved M, Holmboe T (2022) What are the challenges in assessing circular economy for the built environment? A literature review on integrating LCA, LCC and S-LCA in life cycle sustainability assessment, LCSA. J Build Eng 50:104203. https://doi.org/10.1016/j.jobe.2022.104203

Laubinger F, Lanzi E, Chateau J (2020) Labour market consequences of a transition to a circular economy: a review paper. OECD Environ Work Pap 162. https://doi.org/10.1787/e57a300a-en

Maister K, Noi CD, Ciroth A, Srocka M (2020) PSILCA—a product social impact life cycle assessment database; database version 3, documentation. https://psilca.net/. Accessed 10 Apr 2023

Markard J, Raven R, Truffer B (2012) Sustainability transitions: an emerging field of research and its prospects. Res Policy 41(6):955–967. https://doi.org/10.1016/j.respol.2012.02.013

Nicholson AL, Olivetti EA, Gregory JR, Field FR, Kirchain RE (2009) End-of-life LCA allocation methods: open loop recycling impacts on robustness of material selection decisions. In: IEEE international symposium on sustainable systems and technology. IEEE, Tempe, AZ, USA, pp 1–6

Onat NC, Kucukvar M, Halog A, Cloutier S (2017) Systems thinking for life cycle sustainability assessment: a review of recent developments, applications, and future perspectives. Sustainability 9(5):706. https://doi.org/10.3390/su9050706

Padilla-Rivera A, do Carmo BBT, Arcese G, Merveille N (2021) Social circular economy indicators: Selection through fuzzy delphi method. Sustain Prod Consump 26:101–110. https://doi.org/10.1016/j.spc.2020.09.015

Parchomenko A, Nelen D, Gillabel J, Rechberger H (2019) Measuring the circular economy—a multiple correspondence analysis of 63 metrics. J Clean Prod 210:200–216. https://doi.org/10.1016/j.jclepro.2018.10.357. Accessed 10 Apr 2023

Potting J, Hekkert MP, Worrell E, Hanemaaijer A (2017) Circular economy: measuring innovation in the product chain. Planbureau voor de Leefomgeving 2544

Reike D, Vermeulen WJV, Witjes S (2018) The circular economy: new or refurbished as CE 3.0? Exploring controversies in the conceptualization of the circular economy through a focus on history and resource value retention options. Resour Conserv Recycl 135:246–264. https://doi.org/10.1016/j.resconrec.2017.08.027

Rohrbach-Schmidt (2009) Data and methods manual; BIBB-FDZ Daten- und Methodenbericht Nr. 1/2009; Version 1.1. https://www.bibb.de/dienst/veroeffentlichungen/de/publication/show/6526. Accessed 10 Apr 2023

Schroeder P, Anggraeni K, Weber U (2019) The relevance of circular economy practices to the sustainable development goals. J Ind Ecol 23(1):77–95. https://doi.org/10.1111/jiec.12732

Svensson-Hoglund S, Richter JL, Maitre-Ekern E, Russell JD, Pihlajarinne T, and Dalhammar C (2021) Barriers, enablers and market governance: a review of the policy landscape for repair of consumer electronics in the EU and the U.S. J Clean Prod 288:125488. https://doi.org/10.1016/j.jclepro.2020.125488

Tokede O, Traverso M (2020) Implementing the guidelines for social life cycle assessment: past, present, and future. Int J LCA 25:1910–1929. https://doi.org/10.1007/s11367-020-01814-9

UNEP (2020) Guidelines for social life cycle assessment of products and organisations. United Nations Environment Programme (UNEP), Paris, France

UNEP (2021) Traverso M, Valdivia S, Luthin A, Roche L, Arcese G, Neugebauer S, Petti L, D'Eusanio M, Tragnone BM, Mankaa R, Hanafi J, Benoît Norris C, Zamagni A (eds) Methodological sheets for subcategories in social life cycle assessment (S-LCA). United Nations Environment Programme (UNEP)

United Nations, Hrsg. (2015) Transforming our world: the 2030 agenda for sustainable development (A/RES/70/1).

Visentin C, Trentin AWdS, Braun AB, Thomé A (2020) Life cycle sustainability assessment: a systematic literature review through the application perspective, indicators, and methodologies. J Clean Prod 270:122509. https://doi.org/10.1016/j.jclepro.2020.122509