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Life Cycle Sustainability Assessment Approaches for Manufacturing

Ya-Ju Chang, Sabrina Neugebauer, Annekatrin Lehmann, René Scheumann and Matthias Finkbeiner

Abstract Sustainability assessments considering the three dimensions environment, economy, and society are needed to evaluate manufacturing processes and products with regard to their sustainability performance. This chapter focuses on Life Cycle Sustainability Assessment (LCSA), which considers all three sustainability dimensions by combining the three methods Life Cycle Assessment (LCA), Life Cycle Costing (LCC), and Social Life Cycle Assessment (SLCA). Existing LCSA approaches as well as selected ongoing work are introduced, both regarding the individual approaches as well as the combined LCSA approach. This includes, for instance, the Tiered Approach. This approach facilitates the implementation of LCSA, for instance, within the manufacturing sector, by providing a category hierarchy and guiding practitioners through the various impact and cost categories proposed for the three methods. Furthermore, ongoing developments in LCC and SLCA are presented, such as the definition of first economic and social impact pathways (linking fair wage and level of education to social damage levels) for addressing the current challenges of missing impact pathways for economic and social aspects. In addition, the Sustainability Safeguard Star suggests a new scheme for addressing the inter-linkages between the three sustainability dimensions. These approaches foster the application and implementation of LCSA and thus contribute to developing sustainable processes and products.

Keywords Life Cycle Sustainability Assessment (LCSA) · Sustainability assessment · Tiered approach · Life Cycle Assessment (LCA) · Life Cycle Costing (LCC) · Social Life Cycle Assessment (SLCA)

Y.-J. Chang (✉) · S. Neugebauer · A. Lehmann · R. Scheumann · M. Finkbeiner
Department of Environmental Technology, Technische Universität Berlin, Berlin, Germany
e-mail: ya-ju.chang@tu-berlin.de

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R. Stark et al. (eds.), *Sustainable Manufacturing*, Sustainable Production, Life Cycle Engineering and Management, DOI 10.1007/978-3-319-48514-0_14

1 Introduction

Sustainability and sustainable manufacturing are relevant topics for governments and industries worldwide. In that pursuit, various concepts for sustainability exist and approaches for sustainability assessment have already been introduced. Nevertheless evaluating the sustainability performance at the product level remains a challenge. One of the most widespread concepts of sustainability lies in the triple-bottom-line theory, which considers environmental, economic and social aspects (Finkbeiner et al. 2010; Remmen et al. 2007; Elkington 1998). Moreover, with regard to assessing the sustainability performance of products and processes, life cycle thinking approaches which include the whole life cycle from "cradle to grave," are increasingly gaining in importance. By employing such approaches, a shifting of impact between the different life stages and sustainability dimensions can be identified and avoided (Finkbeiner et al. 2010).

By combining both the triple-bottom line theory and life cycle thinking approaches, the Life Cycle Sustainability Assessment (LCSA) framework has been proposed as a mean of evaluating the sustainability performance of products. LCSA analyses environmental, economic and social sustainability aspects by combining the methods Life Cycle Assessment (LCA), Life Cycle Costing (LCC), and Social Life Cycle Assessment (SLCA). The LCSA framework has been initiated with the development of the "Product Portfolio Analysis" (PROSA; German: Produktlinienanalyse) (Öko-Institut 1987; Rainer Grießhammer et al. 2007) and was further developed and formulated by Klöpffer and Finkbeiner (Klöpffer 2008; Finkbeiner et al. 2010). LCSA has so far been identified and promoted as a feasible framework for measuring the performance of products in the three sustainability dimensions (UNEP 2012; Valdivia et al. 2012).

Yet, challenges in LCSA's applicability, scientific robustness, comprehensiveness, interpretation and practical implementation persist (Valdivia et al. 2012; Lehmann 2013; Neugebauer et al. 2015). These challenges mainly relate to the different maturity levels of the three methods considered. LCA is widely accepted and used in practice for assessing a variety of products and services (including e.g. technologies). Although LCA still contains some challenges (Finkbeiner et al. 2014), its general application and implementation stand unhindered. Yet, to date, SLCA and LCC have not yet reached a mature level of assessment. Their main methodological difficulties lie in insufficient guidance on indicator selection, missing sets of defined impact categories and areas of protection (AoPs, also called safeguard subjects), as well as missing links between indicators, impacts and AoPs (Valdivia et al. 2012; Lehmann 2013; Neugebauer et al. 2015, 2016). To overcome these challenges, new approaches have been proposed. One of them is the Tiered Approach, which provides a category hierarchy to facilitate the implementation of LCSA, for instance, in the manufacturing sector. Furthermore, social impact pathways (e.g. fair wage) have been defined and a new LCC approach (the economic LCA framework) has been proposed, addressing some of the methodological challenges associated with LCSA.

The following subsections present the three underlying methods of LCSA in detail, including state-of-the-art, research needs and outlook, elaboration on the application of LCSA in manufacturing (e.g. by using the Tiered approach), followed by an introduction to selected developments for improving on the LCSA framework.

2 Life Cycle Sustainability Assessment (LCSA)

As aforementioned, the LCSA framework consists of the three methods Life Cycle Assessment (LCA), Life Cycle Costing (LCC), and Social Life Cycle Assessment (SLCA), and thus considers positive and negative environmental, social and economic impacts. This combination of different life cycle methods is illustrated by the following Eq. (1) (Klöpffer 2008), which provide helpful guidance in the decision-making processes towards more sustainable products (UNEP/SETAC Life Cycle Initiative 2011).

$$\text{LCSA} = \text{LCA} + \text{LCC} + \text{SLCA} \tag{1}$$

In the following sections, the state-of-the-art of the three methods within LCSA as well as their contribution to sustainable manufacturing are introduced. In addition further research needs and outlook are described.

2.1 Life Cycle Assessment (LCA)

LCA analyses the potential environmental impacts of products and processes from a life cycle perspective. The current development of LCA, and the research needs and outlook are introduced in the following sections.

2.1.1 State-of-the-Art

According to the European Commission (2015), LCA is the best available tool for evaluating the potential environmental impacts of manufacturing processes or products from cradle-to-grave. LCA is an ISO-standardised (ISO 2006a, b) method and structured into four phases: (1) goal and scope definition, (2) life cycle inventory analysis, (3) life cycle impact assessment, and (4) interpretation. Based on the standardised phases, environmental impact can be assessed in an iterative process.

The relation between inventory results, midpoint and endpoint impact categories and AoPs is determined through impact pathways, as displayed in Fig. 1. Inventory

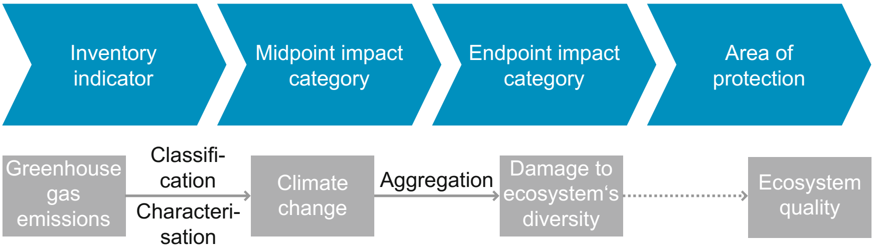

Fig. 1 Relation of inventory indicators, indicators on midpoint and endpoint impact category levels, and AoPs (exemplary illustration for greenhouse gas emissions)

indicators (e.g. greenhouse gas emissions) are classified into impact categories and characterised[1] at the midpoint level (e.g. climate change). The category indicator results achieved at the midpoint level can then be aggregated into impact categories at the endpoint level (e.g. damage to ecosystem's diversity). Those endpoint damage levels are then linked to AoPs (e.g. ecosystem quality).

After decades of method, database and software development, various case studies as well as international standardisation processes have emerged, so that one can now safely say that LCA has reached a mature stage and is robust enough to be applied in decision-making in both private organisations and governments (Finkbeiner et al. 2014).

2.1.2 Research Needs and Outlook

Although LCA has reached a mature level in implementation and has been internationally standardised, LCA still faces some challenges. Finkbeiner et al. (2014) identified 34 challenges with regard to inventory (e.g. dealing with allocation and delayed emissions), impact assessment (e.g. analysing impacts such as land use and odour), generic aspects (e.g. handling weighting and data quality analysis) and evolving aspects (e.g. considering littering, animal well-being or positive impacts), which have not been comprehensively addressed in the current literature and practice. Moreover, collecting relevant and robust data stands as an overall obstacle in carrying out LCA. Although several databases covering numerous different products and processes exist, specific applications (e.g. production of electronics) have so far been insufficiently contemplated. Work is currently ongoing to address some of the challenges, such as improving impact assessment methods (e.g. Bach and Finkbeiner 2016). Until challenges are resolved, practitioners should carefully

[1]The individual contribution of the emissions to the impact is calculated by multiplying the amount of each emission with a characterisation factor (for example, CH_4 has a 28 times higher contribution to global warming than CO_2).

check if the challenges identified limit the conclusions of LCA case studies (Finkbeiner et al. 2014).

2.2 Life Cycle Costing (LCC)

LCC evaluates different costs along the life cycle of a product or process in order to reflect the economic sustainability monetarily. Meanwhile, the current developments of LCC, the research needs in the context of LCSA, along with the overall outlook, are all introduced in the following sections.

2.2.1 State-of-the-Art

LCC appeared in the mid-1960s. Originally, it was used to rank different investment alternatives, but for a long time failed to consider operating costs occurring during the product's lifetime (Glucha and Baumann 2004). A first international standard was published in 2008 with ISO 15686-5 focusing on buildings and construction assets. Therein, LCC is defined as a tool that enables comparative cost assessments (in terms of initial costs and future operational costs) over a specified period of time (ISO 2008).

A similar approach was adopted by Hunkeler et al. (2008), who include producers, suppliers, consumers and end of life actors in the assessment for reflecting costs associated with a product's life cycle. They furthermore differentiate LCC into three types—conventional LCC, environmental LCC, and societal LCC. Conventional LCC focuses on internal costs directly associated with a product's life cycle. Environmental LCC goes beyond that scope and includes external costs likely to be internalised in the decision-relevant future, such as environmental taxes and subsidies (Hunkeler et al. 2008). Societal LCC even includes costs emerging from the side-effects of production which manifest in people's lives and society, whether today or in the long-term. Within the realm of LCSA, it is normally referred to as environmental LCC in the interest of avoiding overlap with the other two dimensions.

2.2.2 Research Needs and Outlook

Several challenges however hinder LCC's methodology development and thus implementation within the LCSA framework. They are, for example, oversimplifying the economic dimension down to a matter of costs, ignoring causalities, or unreliable data in connection with conceptual confusions (Neugebauer et al. 2016). To date, LCC in the context of LSCA is still not commonly implemented in industry, due to methodological confusion with other similar concepts, such as "total cost accounting" (Glucha and Baumann 2004). Furthermore, the limitation attached to costs has often been criticised especially in the context of LCSA. In contrast to LCA, LCC does not contain impact pathways following a cause-effect-chain. Consequently, several authors discuss whether LCC can sufficiently measure and represent economic sustainability within the LCSA framework (Jørgensen et al. 2010; Heijungs et al. 2013). The debate is associated with the question of whether or not LCC should stay at the cost level, or if the classical LCC framework should be extended to implement a broader economic perspective, e.g. by connecting costs on the microeconomic level to impact on the macroeconomic level. To mitigate this situation, May and Brennan (2006) suggested including value added (VA) as an economic indicator and relating it to wealth generation. Wood and Hertwich (2012) went even further by linking VA to gross domestic product through input-output modelling.

Furthermore, to bridge the gap in pursuit of aligning the economic dimension involved in LCSA with LCA, Neugebauer et al. (2016) proposed the concept of economic LCA (EcLCA), and defined midpoint and endpoint impact categories as well as AoPs for the economic dimension. This approach is further described in Sect. 4.1.2. Further research should focus on the definition of impact pathways as well as provision of concrete quantified measures for impact pathways.

2.3 Social Life Cycle Assessment (SLCA)

SLCA aims at analysing the social and socioeconomic impact of products and processes. In the following sections, the state-of-the-art, research needs and outlook for developing SLCA are presented.

2.3.1 State-of-the-Art

SLCA investigates the positive and negative social and socio-economic impact of products or processes along their life cycle. According to the 'Guidelines for SLCA of products' (UNEP/SETAC 2009), the impacts may affect the concerned stakeholder groups: workers, consumers, local communities, value chain actors and the society, and may be linked to the company's behaviour. Complying with the guidelines, the 'Methodological Sheets for Subcategories in SLCA' was published and provided practical guidance on the subcategories and potential indicators for conducting SLCA case studies (Benoît et al. 2013).

2.3.2 Research Needs and Outlook

Several deficiencies persist with the SLCA methodology and therefore impede its implementation in practice, e.g. in industry. Although the methodological sheets provided indicator sets related to relevant stakeholder groups, no widely agreed approach for selecting indicators, relevant social issues, and involved stakeholders exists (Lehmann et al. 2013; Martínez-Blanco et al. 2014; Andreas Jørgensen et al. 2009). In addition, since social impacts are usually associated with organisations' behaviour (Dreyer et al. 2006; Andreas Jørgensen et al. 2009), allocating social impact to a specific product is not straightforward and thus often hinders the implementation and meaningfulness of SLCA (Andreas Jørgensen 2013; Lehmann et al. 2013). Another big challenge lies in linking social indicators to impact categories and AoPs via social impact pathways (Lehmann et al. 2013; Neugebauer et al. 2014). Without such impact pathways, i.e. proper impact pathways and AoPs, a complete picture of potential social impacts cannot be fully anticipated. One of the first approaches for an impact pathway was developed by Jørgensen et al. (2010a, b), who developed impact pathways for child labour and also highlighted the difficulties in measuring the potential girth of the impact.

A more recent approach for impact pathways was provided by Neugebauer et al. (2014), proposing impact pathways for fair wage and the level of education. This approach is presented in more detail in Sect. 4.1.1. Further research is geared to focus on the development of databases and more impact pathways addressing social aspects beyond child labour, wage and education as well as regarding the concretisation of the impact pathways by providing e.g. concrete quantified impact pathways.

3 Application of LCSA in Manufacturing: Tiered Approach

So far, environmental indicators resulting from LCA or simplified LCA (e.g. carbon footprint) are widely employed in manufacturing sectors in order to evaluate the environmental performance of products or processes. Yet, economic and social indicators are currently just randomly considered in product or process assessments due to the methodological challenges associated with LCC and SLCA. Consequently, valid indicator sets for a holistic LCSA are currently lacking and thus hinder the implementation of LCSA in manufacturing sectors. A first attempt to foster application of LCSA is the Tiered Approach, which provides a step-by-step procedure going from a simplified LCSA to a comprehensive one (Neugebauer et al. 2015).

3.1 Framework of the Tiered Approach

The Tiered Approach is a "step-by-step" guidance for applying and implementing LCSA in practice (see Fig. 2). It provides an impact and cost categories hierarchy, which supports LCSA practitioners in selecting suitable indicators, and indicates potential directions of future development in LCSA. The categories proposed have been chosen from selected sources, e.g. the ILCD Handbook of LCA (JRC 2011), the Guidelines for SLCA of products (UNEP/SETAC 2009), and the Code of Practice for LCC (Swarr et al. 2011) based on three criteria (relevance, robustness of the methods, and practicality). For LCA, impact categories at midpoint level are selected since the midpoint results have more consensus characterisation methods and lower statistical uncertainty than the endpoint results (Bare et al. 2000).

Three tiers are recommended in the Tiered Approach: Tier 1, namely Sustainability Footprint, represents a "low entry-level" LCSA, where only few categories are considered (e.g. climate change, production costs and fair wages). Hence, Tier 1 provides a basis for aligning the different maturity levels of LCA, SLCA and LCC and allows for a screening assessment of all three dimensions of sustainability. Meanwhile, it lowers the entry barrier to implementing basics of LCSA in industry and communicating with non-expert practitioners.

Tier 2 represents a "best practice" of LCSA considering additional categories (e.g. the common used ones currently considered in the ILCD Handbook (JRC 2010b) of LCA and categories for SLCA and LCC, which have been ranked as important. Hence, additional impact categories for LCA, for example ozone depletion, eutrophication, photochemical oxidant formation, acidification, have been chosen. For LCC, consumer costs (e.g. purchase price, maintenance costs and energy costs) are included. For SLCA, health (including workers, consumers and local communities) and working conditions are taken into account. Thus, Tier 2 provides a broader range of environmental and economic aspects, and includes social topics beyond the stakeholder group workers.

The most advanced step, Tier 3, represents a comprehensive level of LCSA considering a broad set of categories (e.g. for potential new LCA impact categories like water footprint methods and land use). For LCC, production and consumer

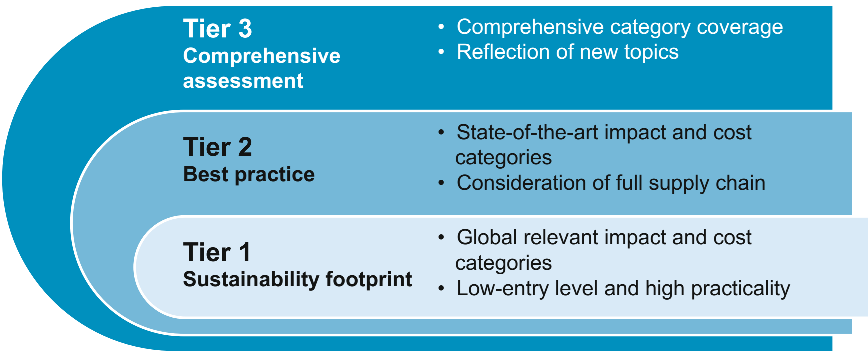

Fig. 2 Structure of the Tiered Approach—3 tiers reflecting different levels of comprehensiveness of LCSA (Neugebauer et al. 2015)

costs related to further operation, accidents, and environmental damage (if not considered within LCA and SLCA) are considered. For SLCA, the topics education, human rights, and cultural heritage are addressed.

The Tiered Approach supports a holistic sustainability assessment, as all three dimensions of sustainability are considered. In addition, it ensures practicality through its impact and cost categories hierarchy, reflecting different levels of comprehensiveness and different phases of LCSA's development.

3.2 Implementation in Manufacturing

The practicality of the Tiered Approach has been proven by first case studies on manufacturing technologies and products, e.g. modular machine tool frames and wireless micro systems (Peukert et al. 2015; Benecke et al. 2015), turning technologies as well as bicycles and pedal electric cycles (Neugebauer et al. 2013; Buchert et al. 2015). The case studies mainly focused on the Tier 1, i.e. the categories climate change, production costs and fair wages. They revealed environmental hotspots, described first selected social topics (e.g. wages) and first economic issues (e.g. production costs), and identified improvement potential for these technologies and products.

Meanwhile, by carrying out these case studies, knowledge and experience with regard to practical implementation were gained from the identification of hotspots and the interpretation of life cycle impacts of the three sustainability dimensions. Specific social aspects for example, fair wages and health, were mapped and thus compared for different countries involved in the production of smart modular machine tool frames, e.g. Germany, Brazil, and China (Peukert et al. 2015). Based on the results, recommendations could be given for advantageous material usage, supplier management and further technology improvements.

Moreover, trade-offs between the three sustainability dimensions were identified, e.g. a technology which performs better from an environmental perspective, could however lead to higher social risks. For instance, the switch from wet machined turning processes to inner-cooled ones showed potential environmental benefits (e.g. recycling of titanium chips), but at the same time increased the social risk due to the African workers involved in the inlay production being potentially paid below the poverty line.

3.3 Research Needs and Outlook

The Tiered Approach is a first step with regard to fostering LCSA in practice. However, challenges remain as comprehensive category sets as well as well-defined impact pathways for all three tiers are missing in the case of both SLCA and LCC. Moreover, at the interpretation phase, challenges occur due to the potential trade-off of the results between and within the three sustainability dimensions (Zamagni et al. 2013; Arcese et al. 2013). In the case studies described above, those trade-offs were displayed transparently for each dimension in the Tiered Approach without giving weights.

The next steps will focus on updating the selected categories and the hierarchy of the Tiered Approach, and on developing impact pathways for social and economic aspects suitable for LCSA with regard to production technologies.

4 Selected Ongoing LCSA Work

Currently, many studies have been carried out in pursuit of enhancing implementation, scientific robustness, and comprehensiveness of the three methods with LCSA. In this section, some ongoing work has been selected to show the recent research progress and direction of LCSA development particularly with regard to SLCA and LCC.

4.1 Proposals of Impact Pathways for SLCA and LCC

As described in the previous sections, SLCA and LCC face numerous challenges, particularly with regard to the impact assessment stage, which hinder the implementation and methodological robustness of LCSA. This includes missing concrete impact category definitions of SLCA and LCC, missing detailed impact pathways, as well as insufficient description of the relationship between impact categories and AoPs (Bocoum et al. 2015; Chhipi-Shrestha et al. 2015; Andreas Jørgensen et al. 2008; Neugebauer et al. 2014). First steps to address these gaps were done by establishing first impact pathways for the social dimension, describing the relation between indicators and impact categories with a focus on fair wage and level of education (Neugebauer et al. 2014), and by proposing AoPs for the social and the economic dimension, such as social justice and economic stability (Neugebauer et al. 2016; Neugebauer et al. 2014). The development of the impact pathways is introduced in the following section.

4.1.1 Proposal of Social Impact Pathways: Fair Wage and Level of Education

In order to enhance SLCA and thus LCSA, impact categories need to be clearly defined. Furthermore, impact pathways linking indicators to impact categories and AoPs need to be developed.

To that end, Neugebauer et al. (2014) defined two impact categories at a midpoint level and developed social impact pathways for them. The two topics are recognised as essential aspects for Sustainable Development Goals (United Nations 2016) for mitigating poverty and enabling the achievement of higher prosperity levels. In manufacturing, fair wage is treated as an essential aspect of worker's overall living situation and well-being. Education reflects country-specific equality aspects, and measures worker's qualifications for specific sectors and countries. With the development of the two midpoint categories, three related endpoint categories (environmental stability, damage to human health, and economic welfare) and two AoPs (social well-being and social justice) were proposed to complete the impact pathways. Interrelations along the defined pathways have been introduced, e.g. the inventory indicator lowest/highest gross income affects the AoPs social justice and social well-being through the midpoint impact category fair wage and the endpoint impact categories economic welfare and damage to human health. Similar to the impact pathway for fair wage, the relation of the inventory indicators, such as access barriers to schools, to the midpoint impact level of education, was investigated.

The proposal of potential impact pathways of fair wage and level of education, serves to facilitate a more consistent and transparent assessment of social impact. However, the characterisation factors stay at a qualitative level. The next step for refining the impact pathways focuses on the identification of quantitative characterisation factors instead of purely on qualitative descriptions. Further aspects like the interpretation of social impacts have been investigated in tandem.

4.1.2 Introduction of the New Economic Life Cycle Assessment Framework

As pointed out in Sect. 2.2, LCC so far includes pure cost assessment without considering clearly defined AoPs, impact categories and corresponding causalities described in impact pathways. For this reason, some authors discuss whether LCC can actually adequately measure the economic sustainability dimension within the LCSA framework (Jørgensen et al. 2010; Heijungs et al. 2013).

Taking into account this discussion, Neugebauer et al. (2016) proposed the new Economic LCA (EcLCA) framework, which broadens the scope of the current LCC by including the impact assessment stage. As a result, two AoPs (economic stability and wealth generation), two endpoint impact categories (economic prosperity and economic resilience), and five midpoint impact categories (profitability, productivity, consumer satisfaction, business diversity, and long-term investment) are suggested and defined. The proposed midpoint impact categories can be directly linked to manufacturing. For example, profitability considers costs regarding actual economic benefits for the firms via added values instead of purely summing up costs. Furthermore, productivity is associated with human capital aspects through the whole value chains, and consumer satisfaction influences the markets and product management expenses, etc.

The suggested EcLCA framework better meets the requirements of ISO 14040 (ISO 2006a) and 14044 (ISO 2006b) adopted within the LCSA framework and describes economic aspects targeting sustainability. The next steps would be to establish measurable linkages (i.e. quantitative relation) between inventory and impact levels as well as AoPs. Moreover, trials for testing application of the new framework will constitute part of future work.

4.2 Sustainability Safeguard Star

LCSA considers the three dimensions of sustainability by combining the methods LCA, LCC and SLCA. However, there is a risk that social, environmental and economic aspects are only interpreted individually, without considering potential interlinkages between the sustainability dimensions. For instance, climate change impacts influence AoPs in both SLCA and LCA, i.e. social well-being (e.g. by affecting human health) and ecosystem quality. To address this challenge, the Sustainability Safeguard Star was designed to structure existing AoPs used in LCA into a new scheme by addressing the inter-linkages in between the three sustainability dimensions and by including additional topics of sustainability, such as social justice (Schmidtz 2006; Neugebauer et al. 2014) and economic stability (Neugebauer et al. 2016). The proposed framework is introduced in the following section.

4.2.1 Conceptual Framework of Sustainability Safeguard Star

The Sustainability Safeguard Star goes beyond the three broadly accepted AoPs from the classical (environmental) LCA human health, resource availability, and ecosystem quality (JRC 2010a), with the goal of defining common AoPs for the LCSA framework. This means that the Sustainability Safeguard Star additionally considers three complementary AoPs (i.e. safeguard subjects), which then reflect the social and economic dimension of sustainability: man-made environment, social justice, and economic stability. The six AoPs proposed for LCSA are displayed in Fig. 3.

The AoP man-made environment, which was already proposed by de Haes et al. (1999), stands for cultural value and addresses technical infrastructure, such as energy and communication networks, and the drinking water supply, indicating the living contexts of society. The AoP is, for example, concerned with the damage resulting from acidifying substances to buildings. The other AoP, social justice, takes equal opportunities and justice as core principles, like security of freedom based on a social contract (individual vs. societal). It is of high relevance to address social justice (Nussbaum 2004) issues in order to eliminate inequality, foster human rights and intergenerational equity defined as fundamental to sustainable development pursuits as defined by the Brundtland report (United Nations 1987). Last but not least, another AoP, economic stability, aims at avoiding economic crisis and promoting economic growth and employment (European Commission 2014). It is also connected to industrial diversity and multilateral trade concerns for addressing economic vulnerability (Neugebauer et al. 2016). The AoPs defined combine different aspects to consider interlinkages between the sustainability dimensions. The AoP economic stability, for example, addresses unemployment and economic prosperity, which are associated with both social and economic perspectives.

Fig. 3 Sustainability Safeguard Star: conceptual framework and relation to LCSA

Moreover, Fig. 3 shows the general conceptual framework for the potential links between micro- and macroeconomic level. The proposed AoPs reflect sustainability goals at a macroeconomic level (e.g. from sustainable development goals or strategies defined by United Nations (2016) and European Commission (2010)). These goals, for example, reducing inequality, can be assessed by defined criteria (e.g. equal access to all levels of education). With the inclusion of the proposed AoPs and their impact pathways addressing the defined criteria, LCSA can deliver the results at the microeconomic level.

4.2.2 Research Needs and Outlook

The Sustainability Safeguard Star abolishes the presumed separation of AoPs defined in three underlying life cycle methods of LCSA and in their place, suggests six common AoPs which address the inter-linkages in between the three sustainability dimensions.

Further research should focus on establishing impact pathways between defined impact categories and the proposed AoPs (see also Sects. 4.1.1 and 4.1.2) and tested in case studies. With regard to sustainable manufacturing, the newly defined AoPs of economic stability and man-made environment, can be of relevance for the purpose of reflecting the business situation of firms with the background of different production locations.

5 Conclusion

The Life Cycle Sustainability Assessment (LCSA) framework is applied to assess the sustainability performances of manufacturing products and processes. Application of LCSA can lead to the identification of product and process hotspots, and support decision-making in production development. In favour of implementation of LCSA in practice, the Tiered Approach was proposed to provide an impact and cost category hierarchy, particularly for offering guidance to practitioners in industry. This approach has already been applied in first case studies on manufacturing technologies and products, e.g. turning technologies and pedal electric cycles, and has proven its validity. Ongoing work such as the development of impact pathways for SLCA, the suggested Economic LCA, and the Sustainability Safeguard Star, serve to enhance the robustness and applicability of the LCSA. To continue enhancing currently proposed methods, future work need to focus on developing the impact pathways of economic and social aspects in the context of LCSA, and further providing quantitative measures of the pathways.

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