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Enhancing the practical implementation of life cycle sustainability assessment – proposal of a *Tiered approach*

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A B S T R A C T

Life cycle sustainability assessment has been claimed to be one of the most common methods for assessing sustainability of products and processes. It consists of the three methods life cycle assessment, life cycle costing and social life cycle assessment. However, the life cycle sustainability assessment framework is still under development and its application is still limited. This is substantiated not only by the lack of data and experience, but also by the proliferation of indicators provided by different institutions. Although indicators are available for the three sustainability dimensions, guidance for the indicator selection is missing. The bottleneck is not the lack of good indicators, but rather the lack of a clear indicator selection process. This appears to be one of the most crucial aspects as data availability, method development and interpretation of results heavily depend on this issue. Another obstacle for the practical implementation of life cycle sustainability assessment arises with the relatively high entrance level. Whereas, for the environmental dimension sufficient data and simplified methods are usually available, e.g. carbon footprint, the social and economic dimension are lacking of similar simplifications. Within this study a *Tiered approach* has been developed providing an indicator hierarchy and proposing a stepwise implementation concept. An indicator review has been performed according to the three criteria practicality, relevance and method robustness. Afterwards the indicators have been ranked in three tiers. The first tier ('sustainability footprint') focuses on indicators, which are characterized as easily applicable indicators and as relevant for production processes and on global scales. The second tier reflects current best practice indicators already used in case studies and preferred by institutions. The last tier aims at giving a comprehensive set of sustainability indicators, even if this level may not be applicable immediately. The Tiered approach may not solve all challenges within life cycle sustainability assessment, e.g. the question of how to solve the interpretation dilemma still remains; however it does support the practical application and further development of the framework through the stepwise implementation of sustainability indicators. The application and science related benefits of the Tiered approach result from the undergone comprehensive indicator review, which seems essential as a basis for further developments within the life cycle sustainability assessment framework, and from the proposed indicator hierarchy, which provides directions for further research. The created sustainability footprint facilitates the practical implementation of life cycle sustainability assessment, as the entrance barrier was lowered without neglecting any dimension of sustainability.

1. Introduction

Sustainability and Sustainable development have been important topics in today's societies since they were promoted by the Brundtland Commission in 1987 (United Nations, 1987) and even earlier within the 'Limits to growth' (Meadows et al., 1972; The Club of Rome, 2014) and 'A blueprint to Survival' (Goldsmith et al., 1972). Sustainable development (SD) is connected to all areas of human life, even though its definition has not been unified yet. There is an ongoing discussion about the delimitation of sustainability and sustainable development as well as the achievement of sustainable development. The terms are often used as synonyms even if sustainable development can be seen as a (policy) principle and central notion, which is openly defined as "development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs" (United Nations,

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1987). On the contrary, sustainability is rather the property of a thing being sustainable (Heijungs et al., 2010).

Some argue that sustainable development rather follows the concept of weak sustainability (mostly in connection with the three-ring-model – addressing social, economic and environmental aspects), where trade-offs seem possible between the three dimensions (Giddings et al., 2002). Others by contrast state that SD goes beyond the weak sustainability concept via balancing the three dimensions (United Nations, 1987) and offers an attractive alternative to conventional growth-oriented development (Sneddon et al., 2006). Broad consensus has emerged about the contribution of social, environmental and economic aspects to sustainable development (Finkbeiner et al., 2010; Hacking and Guthrie, 2008; Heijungs et al., 2010). Additional dimensions, like cultural heritage or governance, are sometimes named, but have hardly been referred to within practical case studies. They also seem kind of irrelevant when focussing on the life cycle perspective, e.g. the proposed political-institutional (governmental) pillar is more related to organizations than to products (Burford et al., 2013). In addition, potential additional dimensions can often be covered within the social or economic dimension, e.g. cultural heritage has been mentioned as one possible pillar to measure sustainability (Burford et al., 2013), but has already been proposed as one impact category within the Guidelines of social life cycle assessment (Benoit and Mazijn, 2009). Hence, within this study the three common dimensions economy, environment and society have been selected to avoid diluting the assessment with too many side aspects (Hacking and Guthrie, 2008). The life cycle thinking concept plays an important role towards a practical implementation of sustainability aspects. Furthermore, a scientific life cycle based analysis is needed to avoid misuse of the term sustainable development (Heijungs et al., 2010). Therefore, within this study life cycle based sustainability assessment methods have been focused on.

Taking a closer look at the representation of sustainability aspects in practice it is conspicuous that most of the existing life cycle based methods still focus on only one of the three dimensions (e.g. life cycle assessment (Klöpffer and Grahl, 2014)) or are invalid from a methodological point of view (e.g. resource efficiency (Schneider et al., 2013)). However, with life cycle sustainability assessment (LCSA) a framework was established taking into account all three dimensions of sustainability, which is essential to display all resulting effects on sustainable development in a holistic way (Hacking and Guthrie, 2008). LCSA has also been promoted by the UNEP/SETAC life cycle initiative as a feasible framework to measure impacts on the three sustainability dimensions (UNEP, 2012; Valdivia et al., 2012). Within the following subsection the development and concept of life cycle sustainability assessment will be examined by pointing out the advantages and remaining challenges, which serves as a basis for the subsequent sections.

1.1. Life cycle sustainability assessment

The evolution of the LCSA framework has somehow been initiated with the development of the "Product Portfolio Analysis" (PROSA; German: Produktlinienanalyse) (Grießhammer et al., 2007; Öko-Institut, 1987). The PROSA approach was the first one considering three sustainability dimensions instead of one and can be seen as one of the initial ideas leading towards LCSA (Finkbeiner et al., 2010; Klöpffer, 2008). In addition, in the middle of the nineties the social and environmental life cycle assessment (SELCA) approach (O'Brien et al., 1996) was introduced referring to the three ring model similar to the one, which was later used within the LCSA framework. The current LCSA framework is still based on the three dimensions of sustainability economy, environment, and society and therefore takes up the structure of SD to a great extent (Giddings et al., 2002; Singh et al., 2012). It follows the triple bottom line of sustainability (Elkington, 1998) by integrating life cycle assessment (LCA) (Finkbeiner et al., 2006) to represent the environmental dimension, life cycle costing (LCC) to represent the economic dimension (Hunkeler et al., 2008) and social life cycle assessment (SLCA) to represent the social dimension (Benoit and Mazijn, 2009). Therefore, LCSA is clearly life cycle based (Klöpffer, 2008). Consequently, the three integrated methods LCA, LCC and SLCA have a similar modelling structure, following the life cycle of a certain product. The Guidelines of SLCA even state to follow the structure provided by ISO 14044, (2006) (Benoit and Mazijn, 2009). According to Swarr et al. (2011) similar accounts for LCC. Mainly this common ground was stressed to facilitate the definition and application of consistent system boundaries and functional unit for the three dimensions. However, the three methods have different target functions, which means they are looking at the same system from different perspectives (Heijungs et al., 2010; Wood and Hertwich, 2012).

The (theoretically) resulting advantage of LCSA is transparency, as it allows to identify trade-offs between the social, environmental and economic dimension (Heijungs et al., 2010). It is also often described as the most developed approach in terms of sustainability assessment (Zamagni et al., 2013). However, shortcomings exist, as LCA, LCC and SLCA do not have the same level of maturity, which hinders the broad implementation of LCSA. This is mainly substantiated by the evolutionary stage of the methods. Whereas, LCA is already a standardized method (ISO 14044, 2006) and widely used to investigate the potential environmental impacts of products and processes (Klöpffer and Grahl, 2014), LCC and SLCA are lacking of consensus and definition and thus broad practical implementation. SLCA assesses the potential social impacts of products and relates to the different stakeholder groups affected by the products, like workers, local communities and consumers (Benoit and Mazijn, 2009), but lacks proper impact assessment. LCC takes into account different perspectives (e.g. producer or consumer perspective) in order to consider the complete life cycle of a product (Hunkeler et al., 2008; Wood and Hertwich, 2012), but no impact level has been defined yet.

For LCA already broad range of well-described impact indicators is available and a common structure orientating on cause-effect chains has been developed (e.g. by the CML (Guinée, 2002) or ReCiPe (Goedkoop et al., 2009) method). Furthermore, related databases have already been established, e.g. GaBi or ecoinvent (UNEP and SETAC, 2011).

In comparison, for SLCA several impact categories have been proposed (Benoit and Mazijn, 2009; Neugebauer et al., 2014; Weidema, 2006), but they are still under discussion, as related impact pathways are lacking and the focus has so far been on the representation of stakeholder groups without bridging the gap towards impact assessment (Neugebauer et al., 2014). In addition, social data are hard to gather. Existing databases are only available on a top-down country or sector level, e.g. the Social Hotspot Database[1] (SHDB, 2013).

For LCC, similar to LCA it is possible to identify economic hotspots, which can be valuable for the decision making process within LCSA (Jeswani et al., 2010). Practical application is however lacking due to inconsistent documentation of cost sources (Wood and Hertwich, 2012) and poor data quality (Gluch and Baumann, 2004), even though some authors stated earlier that LCC is on a relatively fast track towards a comprehensive implementation

[1] The SHDB displays risk factors instead of impacts, but it is so far the only available database directly associated to SLCA.

(Hunkeler and Rebitzer, 2005). Databases for LCC are so far not available, except for the building and construction sector (Agyapong-Kodua et al., 2011; European commission, 2007), but costs are partly included in existing LCA databases (e.g. the GaBi 6.0 database) or displayed by conventional management accounting systems (Heijungs et al., 2012).

As demonstrated, indicators for all the three dimensions are available, but lacking in completeness or implementation. With this regard, Niemeijer and de Groot (2008) concluded that the bottleneck for assessments is not the lack of good indicators or good science, but rather the lack of a clear indicator selection process. Further challenges emerge as sufficient data and data sources are sometimes not or just partly available (Finkbeiner et al., 2010). Consequently, practical case studies are mostly far from being complete, as they may not cover all three dimensions, may not include the complete life cycle of products, may neglect some impacts, or may not even state the relation between indicators and impacts (Bienge et al., 2009; Heijungs et al., 2012; Heller and Keoleian, 2003; Moriizumi et al., 2010). Therewith, the representation of results within LCSA can be seen as another challenge (Ingwersen et al., 2014), as the interpretation of gathered results for the three methods goes beyond the complexity of LCA studies (Cinelli et al., 2013). Therefore, trade-offs between the dimensions must be identified with the utmost care and results must be displayed separately for each dimension (Arcese et al., 2013; Hunkeler and Rebitzer, 2005; Valdivia et al., 2012; Zamagni et al., 2013).

As a result, just a few life cycle sustainability assessment (LCSA) studies have been established (e.g. Martínez-Blanco et al., 2014; Traverso et al., 2012). Some approaches have been proposed in order to simplify LCSA. Pesonen and Horn (2012) proposed the sustainability SWOT as a streamlined tool for LCSA, which tries to identify the strengths, weaknesses, opportunities and threats of a product or process. It fails in gathering meaningful results as no indicator selection has been given beyond brainstorming about hotspots along the supply chain. Moreover, hotspots and impacts cannot be identified in any case, as user's experience is lacking or occurring impacts are still unknown. Thus, rather than a simplified tool, guidance through the existing indicators for LCSA is needed to enhance practical implementation and to support a valid identification of impacts along a product's supply chain.

1.2. Followed approach within this study

As shown within Section 1.1, four main challenges result from the above mentioned topics in connection with the LCSA framework: selection of indicators, related data availability, related method developments, and the interpretation of the indicator results (Ingwersen et al., 2014; Niemeijer and de Groot, 2008). Furthermore, transparency regarding the selection of indicators is often lacking and thus identified measures may be questionable.

In addition, challenges, which arise for any scientific tool, may as well be valid for LCSA. Crucial here seems to be the construction of a science-based theory that also contains well recognizable aspects to avoid a standstill in improvement and implementation (Heijungs et al., 2010). This appears to be especially relevant for the social and economic dimension within LCSA, as no noteworthy progress has been made since the release of the Guidelines of SLCA (Benoit and Mazijn, 2009) and the Environmental LCC book (Hunkeler et al., 2008). Thus, ways of bridging theory and practice need to be developed. Finkbeiner et al. (2010) in this context already stated earlier that there is a need to lower the entry-level into LCSA to enhance its usage. Pesonen and Horn (2012) agree with this view and state that the complexity of existing methods are the main obstacles for industry decision makers to implement life cycle based methods for assessing sustainability.

Following this argumentation, the most crucial aspect appears to be the meaningful selection of indicators, as data availability, method development and interpretation of results heavily depend on it. Therefore, within the following section, LCSA indicators in general will be discussed, leading towards the development of a new approach introduced in Section 3, which provides general guidance for LCSA studies. The benefits and remaining challenges will then be discussed in Section 4 before the contribution to science and the further enhancement of LCSA will be pointed out in the conclusions.

2. Consideration of indicators for LCSA

Indicators in general are something representing the state of a certain aspect or effect, which are used to measure a progress towards a stated goal (Parris and Kates, 2003; Turnbull et al., 2010). Within life cycle based methods the stated goal is typically defined as an area of protection (AoP). The related indicators towards this stated goal can function as variables, parameters, measures, measurement endpoints or thresholds, but are normally extended beyond measurements or values (Heink and Kowarik, 2010). Niemeijer and de Groot (2008) collected different classifications and frameworks for defining indicators. Those classifications are quite diverse; nonetheless indicators have been mostly described as an instrument to measure a causal effect. Typically, for LCA and accordingly LCSA inventory, midpoint and endpoint indicators can be differentiated describing different stages along the cause-effect-chain.[2] Accordingly, inventory indicators may be characterized as simple variables (e.g. SO_2 emissions), whereas midpoint impact indicators may be seen as parameters in the environmental mechanism network (Bare et al., 2000), which however may not account for all midpoint impacts. Endpoint impact indicators then can be seen as measurement endpoints. All this implies that indicators should be measurable, (policy) relevant, universally applicable and analytically resilient. In particular, the last two points are challenging in connection with LCSA, having regards also to the issue of data availability.

Additional challenges arise, as the three methods used for the assessment of the three dimensions have a different degree of maturity (Valdivia et al., 2012). Identical accounts for the indicators that represent the three dimensions. Furthermore, the process related nature of indicators used within the three methods LCA, LCC and SLCA show tremendous differences. Whereas within LCA, indicators are almost solely of quantitative nature and well defined within characterization models, indicators within SLCA can be qualitative, semi-quantitative or quantitative. In addition, the path from inventory towards an impact indicator can either be pursued via midpoint indicators towards an endpoint impact or unlike LCA via subcategories towards a stakeholder impact category (Parent et al., 2010; Wu et al., 2014). Although, the Guidelines for SLCA (Benoit and Mazijn, 2009) in both cases stick to the term social impacts, Parent et al. (2010) proposed earlier to use social performance for the latter one. To ensure consistency with LCA and to avoid confusion in connection with the term social impact, within this study the first approach is followed, as it has already been

[2] Detailed definitions and descriptions for cause-effect chains or impact pathways has been described earlier by Bare et al., 2000; Jolliet et al., 2004; and Kristensen, 2004. Definitions for the terms midpoint and endpoint indicator can also be taken from this sources, as e.g. Bare et al., 2000 described midpoint as “a parameter in a cause-effect chain or network for a particular impact category that is between the inventory data and the category endpoints”.

presented by Neugebauer et al. (2014). For LCC, even though the indicators are solely quantitative similar to LCA, another problem occurs, as no impact levels have been defined, yet. A similar issue accounts for the AoPs representing LCA, SLCA and LCC. Whereas, AoPs have been defined for the environmental and social dimension, there are none for the economic dimension.

Ideally, indicators of life cycle based methods should cover the complete impact pathway; however practical implementation shows a different picture. Although, LCA can be seen as the most advanced method within the LCSA framework (see Section 1.1), controversial discussions are ongoing, whether the inclusion of midpoint or endpoint impacts is expedient (Hutchins and Sutherland, 2008). Midpoint impact indicators are mostly seen as scientifically valid and easier to measure, whereas endpoint impact indicators might be more feasible due to clearer results, even though they might have shortcomings in scientific background and validity. Bare et al. (2000) concludes that midpoints and endpoints should be considered in parallel to enable coverage of the complete life cycle, but it was admitted that especially for complex models, under which LCSA can be counted, endpoint indicators are challenging due to unclear interrelations along the impact pathways.

Midpoint indicators for LCA and SLCA may impact a variety of endpoints, e.g. damage to human health, even though concrete pathways are not necessarily characterized or known (Hutchins and Sutherland, 2008). For the economic dimension not even midpoint impacts are defined and thus the consideration of endpoint impacts for the other two dimensions would lead to insurmountable divides. Building on this argumentation, for this study, midpoint impact indicators are included for LCA and SLCA. For LCC costs are considered functioning as inventory indicators,[3] as no impact level has been defined, yet. The development of method related shortcomings in connection with indicators maturity is not part of this study. However, the consideration of impacts seems reasonable, as impact indicators in contrary to inventory indicators display the relative importance of emissions, circumstances or consequences resulting from certain actions, which have been characterized into a proxy at a proceeded stage of the cause-effect-chain (Vanclay, 2002).

Due to the above mentioned challenges resulting from the different maturity levels of the three methods (LCA, SLCA and LCC), inter-linkages between the sustainability dimensions are hard to quantify, even though inter-linkages between the three dimensions do exist. However, the authors hypothesize that those inter-linkages of impact indicators (and consequently sustainability dimensions) rather arise towards the endpoint (damage) level, e.g. climate change affects simultaneously the endpoints of health and ecosystem stability or working condition may influence health damages. For the Tiered approach these inter-linkages may be acceptable, as 'only' midpoint impact indicators are considered, which instead of damages describe a state along the impact pathway.

To identify available and meaningful indicators for performing LCSA case studies, a literature review is conducted, taking into account research done by different institutions dealing with LCSA, LCA, SLCA and LCC, as well as publications and case study results addressing new aspects within the LCSA framework. In considering the practical application of LCSA, the state of the three methods in terms of indicator availability matters. For LCA, numerous indicators have already been defined and implemented. Such are included in common impact categories, like climate change or acidification. Topics, which are in this context broadly addressed are: resource impacts, biodiversity, natural environment and exhaustible resources (Pennington et al., 2004; UN, 2007; UNEP, 2012). However, some indicators are still challenging or not even addressed, like biodiversity (Klöpffer, 2008). Nevertheless, a pre-selection of indicators and impact categories has been given by several institutions, e.g. UNEP or JRC (Jolliet et al., 2014; JRC, 2011; UNEP and SETAC, 2011). All the prevailing indicators are connected to the three AoPs of LCA: ecosystem quality (also listed as natural environment), resources (also named natural resources) and human health (Goedkoop et al., 2009; JRC, 2010a). Although, human health was originally located in LCA, it has often been represented within SLCA as well. Therefore, the AoP human health, which was further addressed by Hacking and Guthrie (2008) and UNEP (2012), within this study is attributed to SLCA to avoid double-counting and to ensure an analogous allocation of indicators to the respective dimension.

For SLCA some midpoint impact categories have been proposed, but within case studies it is rather focused on subcategories than on midpoint impacts (see e.g. Martínez-Blanco et al. (2014)). However, important topics, which are considered in most of the performed case studies, are workers or working condition (including also wage levels), and health (Hunkeler, 2006; Hutchins and Sutherland, 2008; Jørgensen, 2012; Norris, 2006; Parent et al., 2010; Weidema, 2006). Moreover, education, gender equality and diversity are often mentioned, but have not been comprehensively included into SLCA practice (Hutchins and Sutherland, 2008). The defined midpoint indicators for SLCA representing these topics are: working condition, fair wage, health and education (Benoit and Mazijn, 2009; Neugebauer et al., 2014; Weidema, 2006), but are also going beyond, by addressing e.g. human rights, safety and cultural heritage (Benoit and Mazijn, 2009). Addressing the often qualitative or semi-quantitative nature of social indicators, it is worth mentioning that the characterization into impact categories is especially challenging. The most common AoP for SLCA following the Guidelines for SLCA is social or human well-being (Benoit and Mazijn, 2009), which has been also reflected in connection with social justice, prosperity and poverty (Burford et al., 2013; Cinelli et al., 2013).

For LCC no distinction has been made in inventory, midpoint or endpoint indicators. Swarr et al. (2011) therefore stated that the aggregation of costs already provides a measure of the financial impact of the product. Heijungs et al. (2012) somewhat disagreed and stated that the economic dimension goes beyond pure costs. However, classical impact categories following a cause-effect-chain, as described earlier, have not been defined yet. Therefore, LCC indicators within this study are limited to costs representing an inventory indicator level. The focus according to Hunkeler et al. (2008) should be set on such costs, which are important to assess the economic performance of products and processes. Discussions are ongoing about the inclusion or exclusion of external costs, as double-counting may occur with impacts considered in LCA (Swarr et al., 2011). Klöpffer (2008) therefore stated: if external costs are expected to be decision relevant and comprise real money flows, they must be included. In addition, double-counting is also likely to occur, when costs gathered for the different perspectives are summed up, as the purchase price already includes costs for manufacturing and needed materials (Heijungs et al., 2012). Therefore, caution is needed, when displaying the results of the LCC, by either displaying the different perspectives separately or by accounting for the resulting benefits, which are included into the purchase price. The latter requires more transparency with regard to the calculation.

Addressing the above mentioned points within this section, but also earlier within Sections 1.1 and 1.2, it appears logical to the authors of this study that focus on certain indicators is needed to

[3] Inventory indicators express single issues, e.g. pure emission factors instead of emission equivalents or salaries without relating them to fair wages.

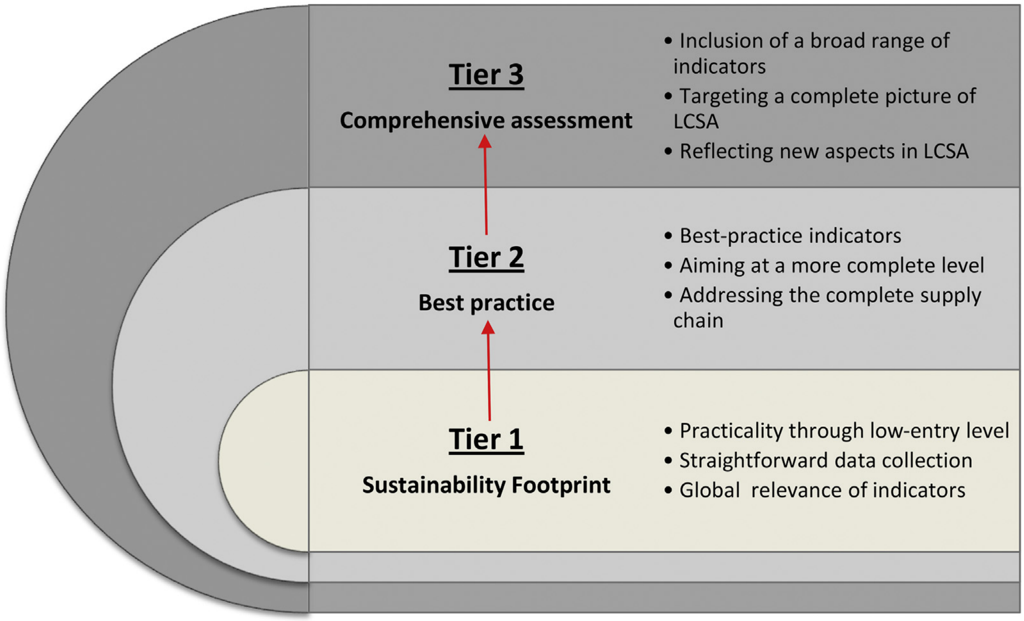

Fig. 1. Followed structure for the Tiered approach.

provide guidance and to aim at broader application and general improvements of the LCSA framework. This guidance is provided with the development of a new approach to ease the practical implementation of LCSA via including an indicator hierarchy. This *Tiered approach*, which functions as a stepwise technique through LCSA indicator implementation, is described in chapter 3. The related shortcomings and benefits when applying this approach are pointed out at the same time.

3. Tiered approach

The target of the developed Tiered approach is to enhance assessment practice towards a more holistic approach away from single dimension assessments. One assumption, which led to the development of the approach, is that assessments in any case subsist on continuity. In that sense, LCA and Carbon Footprint can serve as an example – popularity and propagation of the simplified Carbon Footprint method enhanced over time the more sophisticated LCA method in terms of practical application (Finkbeiner, 2009). Similar has been assumed during the development of the Tiered approach. By lowering the entry level and by giving an indicator hierarchy, LCSA will be simplified for the time being, to be then stepwise enhanced afterwards. Within the so-called 'sustainability footprint'[4] all three sustainability dimensions are considered from the very beginning, but just a limited number of indicators have been included (more detailed descriptions follow in the next paragraphs). Those indicators are preferably simple to implement. Afterwards, when the entrance barrier is surmounted a more comprehensive assessment is more likely to be established.

For an effective practical implementation of LCSA, three tiers have been defined starting with easy but meaningful indicators on *Tier 1* ('sustainability footprint'), proceeding with a state of the art set of indicators at *Tier 2* ('best practice') and concluding with a preferably comprehensive set of indicators measuring the sustainable performance at *Tier 3* ('comprehensive assessment') (see Fig. 1). It is assumed that the crucial obstacle for performing LCSA is the first step. Thus, after observing Tier 1 and 2 slowdowns in the implementation of additional indicators are founded in data availability or method insufficiencies, which are both difficult to overcome with increasing indicator complexity (e.g. climate change is due to data availability, public awareness and a mature method easier to assess than e.g. ecotoxicity). An additional subdivision in more than three tiers therefore seems not essential to perform LCSA in a more complete manner. Foremost, as additional indicators can be easily adapted in the provided scheme.

To be able to structure LCSA indicators into different tiers, a comprehensive research has been performed in advance, addressing the three dimensions and taking into account three key criteria to enable a reasonable indicator selection: relevance of the indicator, robustness of the related method, and practicality of the respective indicator. The criteria have been applied to a broad range of midpoint indicators for LCA, for all defined midpoint indicators for SLCA and for cost categories for LCC.[5] The criterion relevance displays the importance of the indicator for the respective method (LCA, SLCA, LCC) and the pressure behind the covered topic (Niemeijer and de Groot, 2008). Therefore, work done by international organizations and institutions has been considered. Method robustness describes the scientific dimension of the available characterization methods and their validity (see Niemeijer and de Groot (2008)). Practicality refers to data availability and the resulting societal responses. Thus, besides the awareness for the topic, also the conditions for the LCSA implementation have been considered. The indicators are ranked according to a scale of high, medium and low compliance for each of the three criteria. The

[4] In general a footprint can be described as a measure of how human activities create different kinds of burdens (Čuček et al., 2012). Outstretched on LCSA therefore the environmental, economic, and social dimension need to be included. However, it is focused on the principle followed by carbon footprint, water footprint and comparable methods, to include single indicators displaying a certain impact or problem.

[5] More information can be taken from the supplementary data. Within the supplementary data all indicators identified for the three dimensions are ranked according to method robustness, relevance and practicality. Sources are named. Further information, which is not in any detail represented in the text, can be taken from the related table.

Table 1
Proposed set of indicators for Tier 1 ('sustainability footprint') within the Tiered approach.

Indicators of Tier 1		
LCA	LCC	SLCA
Climate change *If agricultural products use Eutrophication in addition, as agricultural processes might be driven by phosphorus and nitrogen emissions (Tynkkynen et al., 2014; Velthof et al., 2014).	Production costs Including manufacturing, labour, energy, transportation & maintenance costs	Fair wages Comparison to minimum & non-poverty wage

analyzed set of indicators and the evaluation according to the three selection criteria is documented in any detail within the supplementary material.

Practicality has been rated as the most important criterion, as without it, application is unlikely. Consequently, practicality decreases from Tier 1 to Tier 3. This is not necessarily the case for method robustness or relevance. However, the general criteria fulfilment is also decreasing from Tier 1 to Tier 3, e.g. method robustness can only be considered, if a respective method is available, which is not necessarily the case for all social impact indicators considered. As least attention in terms of practical implementation and methodological progress has been paid to the LCC method, the related indicators are hardly covered within public discussions and no characterization models are available. Therefore, practicality frames the indicator selection for the three tiers (see supplementary data).

According to the ranking presented within the supplementary data, the LCSA indicators are assigned to the three tiers.[6] In addition, some further aspects are considered. For the social dimension the stakeholder groups, which were defined by the Guidelines of SLCA (Benoit and Mazijn, 2009), are considered, as one, two or all stakeholder groups might be affected by a certain impact. Similar accounts for LCC, where the different perspectives are taken into account to properly represent the (direct and indirect) costs occurring for the different stakeholders. For LCA no distinction in stakeholder groups or perspectives is needed. Generally, the descriptions for the environmental dimension are kept rather short, as for all indicators, characterization models have been defined and thus clear descriptions and definitions already exist.

3.1. Tier 1

Lowering the entrance level for LCSA and targeting applicability in the first tier of the Tiered approach, indicators with high practicality and good data availability are selected. As Tier 1 follows the idea of a 'sustainability footprint', well-known indicators are chosen to ease understanding also for non-expert practioners. For the environmental dimension the carbon footprint (midpoint category climate change or global warming potential) is included in Tier 1 (Table 1, column 1), which has become one of the most important environmental indicators, according to (Galli et al., 2012; Lam et al., 2010; Wiedmann and Minx, 2008). Several organizations identified climate change as relevant, e.g. IPCC Stocker et al. (2013), OECD (2008), WMO (2013) and UNEP (2014), and besides it is covered by the Kyoto protocol (United Nations, 1998). Consequently, the awareness and knowledge amongst stakeholder groups is supposed to be very high. The data obstacle is relatively little, as inventory data and characterization factors are widely available (Goedkoop et al., 2009; Guinée, 2002). Data and characterization factors have been implemented in common LCA software (e.g. GaBi 6.0) and carbon footprint calculators.

Although, climate change is of high relevance for utmost production processes and therefore is chosen as a generic Tier 1 environmental indicator, eutrophication might be in some cases of more relevance. For instance, agricultural processes might be driven by phosphorus and nitrogen emissions from fertilizer use (Tynkkynen et al., 2014; Velthof et al., 2014). Awareness in this context increases and eutrophication is verifiable of relevance, as it is one impact driver in agricultural production and also functions as an indication for biodiversity loss (Hodgson et al., 2014; Jolliet et al., 2014). Inventory data and characterization factors are also available (Goedkoop et al., 2009; Guinée, 2002).

For the LCC the literature according to Hunkeler et al. (2008) and Swarr et al. (2011) is followed and therefore material, manufacturing, labour, energy, transportation and maintenance costs are included in Tier 1. Accordingly, all direct production costs are covered within this tier. Heijungs et al. (2012) and Hochschorner and Noring (2011) with this regard stated that those costs are covered by the management accounting and Bovea and Vidal (2004) described them as conventional costs, which are easy to assess (Table 1, column 2).

One of the most applicable indicators considered within SLCA is Fair wage. It can be assessed by comparing the wage level of workers with minimum and non-poverty wages (e.g. Schulten (2014)) (Table 1, column 3). Fair wages are essential for satisfying workers basic needs to ensure stable living conditions (Benoît et al., 2013; Kenrick et al., 2010). Moreover, fair wages can be seen as the first step towards poverty alleviation (Worldbank, 2014), determining the time a person has to work to achieve food, housing and education (Klöpffer, 2008). Fair wage therefore describes perfectly a necessity to fulfil basic needs, as addressed earlier by Maslow with the pyramid of needs (Maslow, 1954, 1943). Data addressing wages are provided by i.a. World Bank and ILO. A first qualitative characterization model has been provided by Neugebauer et al. (2014).

Recapitulating, Tier 1 consists in total of three generic indicators representing the three dimensions within LCSA. All selected indicators are highly relevant for production processes in general, but can also be seen as crucial aspects for the related method (LCA, SLCA, LCC). However, the indicators may not be completely equal; therefore, results need to be displayed transparently and separately.

3.2. Tier 2

Reflecting the current best-practice, Tier 2 aims at including additional LCSA indicators. Indicators are included according to the suggestions of international institutions representing the state of the art for LCA, LCC and SLCA.

For LCA the recommendations of the International Reference Life Cycle Data System (ILCD) handbook are followed. Within this handbook different level of midpoint indicator maturity have been defined: level I – recommended and satisfactory; level II –

[6] The authors of this study strongly recommend the reader to take a look at the supplementary material, as a comprehensive overview of the LCSA indicators and explanation of the performed ranking have been pointed out in detail in accordance with the defined criteria.

Table 2
Proposed set of indicators for Tier 2 ('best practice') within the Tiered approach. Additional indicators compared to Tier 1 are highlighted in red.

Indicators of Tier 2		
LCA	**LCC**	**SLCA**
Climate Change	Production costs	Fair wage (comparison to non-poverty wage)
Ozone Depletion	*including manufacturing, labor, energy, transportation & maintenance costs*	*comparison to minimum & non-poverty wage*
Eutrophication	Consumer costs	Health (represented via Humantoxicity)
Photochemical oxidant formation	*including purchase prices, energy costs and costs of usage & maintenance costs*	*including health effects on workers, consumers and local communities*
Acidification		Working condition
Particulate matter		*including working hours and existence of labor laws*

recommended but in need of some improvements; level III – recommended but to be applied with caution (JRC, 2011). The set of indicators suggested for Tier 2 (Table 2, column 1) has been classified as level I and II. These indicators reflect the common best practice in LCA. Further justification for the implemented indicators can be taken from the supplementary data. All included indicators are covered within characterization models and have already been accepted within the LCA community (Jolliet et al., 2014; Pennington et al., 2004).

For the LCC further types of costs are included representing the consumers perspective. This includes purchase prices, costs for energy and usage, and maintenance (Table 2, column 2). Maintenance costs and costs of usage do not necessarily occur, but if so they need to be considered. The energy costs on the consumer side can be more difficult to assess, as they strongly depend on the user's behaviour and therefore scenario technique may need to be used.

For the social dimension additional indicators are included reflecting human health and working conditions (Table 2, column 3). Health has been broadly addressed within SLCA literature (see Section 2), within LCA literature (Jolliet et al., 2014) and by numerous institutions, like WHO or OECD. However, hardly any valid characterization method has been developed to consistently represent health issues within SLCA. Therefore, within this study it is mainly referred to Humantoxicity, wherefore a characterization method has already been provided within the Usetox model (Rosenbaum et al., 2008). In addition, direct health effects have generally been identified for workers, consumers and local communities and can therefore be relevant. Thus, whenever certain health effects are likely for specific products or processes, they should be at least qualitatively considered. Data sources, considering health issues, which go beyond toxicity, are additionally listed within the supplementary data.

Furthermore, the midpoint indicator Working condition is included in Tier 2, as numerous SLCA studies have already addressed this issue (see Section 2). It was further identified as relevant by ILO and World Bank and was represented by different trade unions. Dreyer et al. (2006) and Kruse et al. (2008) developed a first characterization model based on working hours. However, additionally to working time, compliance with labour laws is of importance to understand the prevailing circumstances, which are needed to achieve good working conditions (ILO, 2011). Data are available, but no characterization model has been provided with this regard.

To ensure delimitation of the two indicators health and working condition, which as an indicator may also affect health issues depending on the definition, health is mainly described by Humantoxicity at the midpoint level and working conditions are restricted to working hours and the existence of labour laws. Whereas inter-linkages are likely to occur at the endpoint level (e.g. both indicators may influence damages to human health), they are unlikely at the midpoint level, due to a clear demarcation (see also Section 2).

Subsuming, additional indicators have been included into Tier 2 to express a broader range of environmental aspects (e.g. ozone depletion or acidification), to give a more detailed picture about occurring costs (via the inclusion of consumer costs), and to express social impacts beyond the stakeholder group workers, which was mainly focused on within the 'sustainability footprint' (Tier 1). The resulting number of indicators for the three dimensions is uneven and different perspectives (LCC) and stakeholder groups (SLCA) have now been considered; thus it is of even greater importance than in Tier 1 that the LCA, LCC and SLCA results are displayed separately and transparently. However, a weighting of results does not seem necessary, as no quantitative comparison is performed, but rather a verbal argumentative discussion on the results. Therefore, the concrete number of indicators is not especially relevant at this stage.

3.3. Tier 3

Tier 3 aims at a comprehensive coverage of LCSA. Therefore, additional indicators are included (see Table 3); even though some indicators defined as midpoint impacts earlier are lacking proper characterization models and practical implementation. This accounts mainly for indicators of SLCA and especially LCC, but also for

Table 3
Proposed set of indicators for Tier 3 (best practice) within the Tiered approach. Additional indicators compared to Tier 2 are highlighted in red.

Indicators of Tier 3

LCA	LCC	SLCA
Climate Change	Production costs	Fair wage (comparison to non-poverty wage)
Ozone Depletion	*including manufacturing, labor, energy, transportation & maintenance costs* *including further operational cost, like waste management & taxes* *including capital, infrastructure, investment costs* *including costs due to accidents & environmental damage, if not included within LCA or SLCA*	*comparison to minimum & non-poverty wage*
Eutrophication		Health (represented via Humantoxicity)
Photochemical oxidant formation		*including health effects on workers, consumers and local communities*
Acidification		Working condition
Particulate matter	Consumer costs	*including working hours and existence of labor laws*
Ionizing radiation	*including purchase prices, energy costs and costs of usage & maintenance costs* *including further operational cost, like waste management & taxes* *including costs due to accidents & environmental damage, if not included within LCA or SLCA*	Education
Ecotoxicity		*including finished apprenticeships & university degrees, equal opportunities, literacy rate*
Land use		
Water footprint		Human rights
Resource depletion		*focus on workers & local communities* *including child labor, forced labor, discrimination, equity & autonomy*
		(Workplace) Safety
		Cultural heritage (in connection with local communities)

new methods of LCA like the water footprint method (Berger et al., 2014) (more information can be found in the supplementary data).

Within the LCA part, further indicators are added describing the state of the environment in a preferably holistic manner. This comprises midpoint indicators for ionizing radiation (JRC, 2010b), ecotoxicity (e.g. Rosenbaum et al., 2008), land use (e.g. Milà i Canals et al., 2007), water use and consumption expressed via water footprint methods, e.g. Berger et al. (2014), and resource consumption (Guinée, 2002) (Table 3, column 1). Characterization factors have already been provided, but are not always sufficient or complete (e.g. the provided characterization models for land use do not consider all relevant aspects). Impacts on biodiversity have not been directly included in the Tiered approach, as neither a characterization model has been established nor consensus has been achieved regarding its allocation to the midpoint or endpoint level (JRC, 2010b; UNEP, 2012).

The LCC is complemented by including remaining conventional costs, e.g. taxes and insurances. Further, costs for capital and infrastructure are added, which are needed to perform necessary production processes on the manufacturer's side. For capital and infrastructure costs the inclusion of discount rates was recommended by some authors, e.g. Dong et al. (2014) and therefore their inclusion might be challenging. In addition, indirect costs due to accidents or environmental damages are considered as far as the related impacts have not been reflected within the environmental or social dimension (Table 3, column 2). Hence, as long as accidents have not been covered in the social dimension e.g. in connection with health, but have already been expressed in economic terms, they should be included to ensure integrity of the LCSA model. The same accounts for the environmental damages, which have not been covered within the environmental dimension. These costs can occur on both the producer's and consumer's side; however it must be indicated clearly by whom these costs are paid. Data for these costs are partly available (e.g. capital and infrastructure costs), but the assessment of taxes and costs for accidents can be challenging, as they are not necessarily covered within management accounting systems.

For SLCA the indicators education, human rights, safety and cultural heritage are added for Tier 3 (Table 3, column 3). These indicators are typically seen as midpoint indicators, but hardly any of them have been expressed within characterization models (see also supplementary data). For education, a first characterization model has been proposed by Neugebauer et al. (2014), but no characterization factors were calculated. However, according to the provided qualitative characterization scheme, equal opportunities, literacy rate and finished degrees were focused on as a first proxy. Regardless of the current methodological shortcomings, education is of high relevance for (sustainable) development (Klöpffer, 2008; Weidema, 2006) and part of the Millennium development goals,[7] and should therefore be at least qualitatively considered within a comprehensive LCSA. Data on education are i.a. provided by ILO (2010), The World Bank (2013) and OECD (2013).

Human rights are normally expressed by different subtopics, e.g. child labour, forced labour, discrimination and equity. The topic was also often addressed within case studies (Hauschild et al., 2008; Jørgensen et al., 2009; Martínez-Blanco et al., 2014) and by several institutions, e.g. Human Rights Watch[8] and Amnesty International (1998). Nonetheless, only qualitative statements or risks have so far been evaluated, as a characterization model is missing. Qualitative data addressing the situation on human rights are provided by ILO, The World Bank and the United Nations. Moreover, human rights are hardly expressible in quantitative terms, but relevant violations of human rights should be named and listed transparently within the assessment of social impacts.

The defined social impact category safety has been mostly addressed with regard to workplaces and labour (Sakamoto, 2010; UNEP, 2010), but also in connection with food and poverty (Heller and Keoleian, 2003; UN, 2007). Nevertheless, no characterization model has been yet defined for safety and data sources are hardly provided by institutions. However, aspects on safety should be included as long as they have not been displayed within the midpoint indicator health. Further research is needed to determine, if safety shall remain as its own impact category or rather be included into working conditions and/or health.

Just a few institutions[9] addressed cultural heritage and even fewer case studies. The foremost reason for this is its limitation to local communities. Furthermore, impact definition lacks and the qualitative nature of the indicator impedes a straightforward inclusion into characterization models. However, background information has been provided by the Journal of Cultural Heritage and therefore the indicator is regarded for now within Tier 3 of the Tiered approach.

Similar can be even stronger presumed for the two indicators socio-economic repercussions and governance. Socio-economic repercussions was by literature only named in connection with climate change (IPPC), health and HIV/AIDS (Isaksen et al., 2002) and therefore should be rather included into the midpoint category health, than to be expressed in an own impact category. A clear definition is also missing for the defined midpoint category governance, which makes it nearly impossible to determine the relevance of this indicator for SLCA. Doubtless of course are the interconnections of governments and social effects (Evans, 1996), but however for SLCA it is recommended to include these effects into existing indicators, e.g. human rights, rather than to name it in a separate impact category. Therefore, within this study socio-economic repercussions and governance are not considered as own impact indicators.

As it can be taken from Table 3, Tier 3 is meant to complement the indicator selection for the three dimensions. Therefore, even indicators have been included, which are not necessarily in broad practical use. This comprises indicators, like ecotoxicity or land use for LCA; investment cost or taxes for LCC, and education or human rights for SLCA. The implementation of those indicators represents a great challenge, which should be preferably undertaken at a more advance level of LCSA. An even greater challenge can be seen in the interpretation of results at this level (comparable to the argumentation of Tier 2), as characterization models are lacking, different perspectives and stakeholder groups need to be considered and quantitative, semi-quantitative and qualitative indicators are included at the same time. Therefore, caution is needed and all indicator results must be displayed separately and transparently. Hence, also a previous weighting of results is not targeted by the authors, as no quantitative comparison is foreseen, but rather a verbal argumentative discussion on the results. Therefore, the concrete number of indicators is not especially relevant at this stage.

4. Discussion

The Tiered approach consists of a hierarchical indicator structure and guides one through LCSA orientated on the three criteria practicality, relevance and method robustness. Successively, additional indicators are implemented towards a comprehensive level of LCSA starting from the basic ‘sustainability footprint’. Targeting the enhancement of the practical implementation of LCSA, which is seen as one needed requirement to enhance further improvement of methods and science in this field, the entrance level was lowered by means of Tier 1 – the sustainability footprint. This simplification may be accompanied by lacking robustness of results and conclusions from Tier 1 to Tier 3, which can be named as one potential drawback of the Tiered approach. Contradictions in results may occur through the stepwise implementation of indicators. An option which has been identified as more sustainable within Tier 1 might turn out to be less sustainable after the complete set of indicators of Tier 2 or 3 have been applied. Thus, final conclusions based on results gathered within Tier 1 are not recommended. The same applies to carbon footprint results in comparison to full LCA, where trade-offs are likely to occur between climate change and other impacts. In addition, LCSA is seen as an iterative process (orientating on LCA) and therefore all indicators included are to be double-checked after each tier, regarding completeness and consistency.

As LCSA is still in its infancy, indicators for the economic and social dimension are often not mature. However, the Tiered approach promotes the idea of getting started instead of getting lost in perfectionism; similar has already been stated at the United Nations Conference (UNCED, 1992). Therefore, available indicators were considered and the related shortcomings were mentioned (see supplementary data). This study does however not target the further development of the characterization methods themselves, but initiates a reasonable bottom-up process by giving prioritization for different topics and indicators. Nevertheless, further research and case studies are needed to enable a verification of the chosen indicators. Furthermore, case studies are essential to revise the already made assumptions for Tier 1 regarding easy implementation and for Tier 2, which addresses the ‘best-practice’. However, the ranking for the three tiers was performed based on the defined criteria and according to best knowledge, even if transitions are often floating (see supplementary material). Consequently, additional indicators or midpoint impacts may and

[7] http://www.un.org/millenniumgoals/.

[8] http://www.hrw.org/de.

[9] Cultural heritage is e.g. addressed by *Cultural Heritage without Borders* (http://chwb.org/).

should be included, whenever new research cognitions are gained and justified.

Weighting is neither recommended nor foreseen within the Tiered approach, as at this stage only a verbal argumentative discussion of results seems reasonable. Normalization may be applied, but does not seem broadly applicable especially for LCC and SLCA, due to unclear impact and indicator definitions and missing reference quantities. More research is furthermore needed in order to claim, if and when the three dimensions are equally represented. This can be seen as one foundation to enable valuable recommendations on how to deal with the LCSA interpretation phase; foremost, as the three methods differ significantly in degree of maturity and thus an offsetting between the dimensions might lead to wrong assumptions. For the interpretation phase of LCSA, the Tiered approach does not present solutions, but it allows a transparent display of the results gathered for the single dimensions, as well as for the single indicators.

Although, the existing challenges of LCSA, which were also mentioned earlier by Klöpffer (2008) and Finkbeiner et al. (2010), have not been completely solved by means of the Tiered approach; it significantly enhances transparency within the current assessment practice and points out research needs. However, as a next step case studies need to be performed to test the approach for different fields and products. Adjustments on this basis are possible, as the Tiered approach is easily adaptable to new findings and flexible for the inclusion of additional indicators. In this context, e.g. the inclusion of a fourth tier seems useful to include endpoint impact indicators and to also display the complete impact pathway and the occurring inter-linkages within and between the sustainability dimensions.

5. Conclusions

The practical application of LCSA is still lacking due to large implementation efforts and methodological challenges. Moreover, especially SLCA and LCC seem to be stuck in a methodological vacuum. For the further development of LCSA the provision of a meaningful indicator selection appears important, particularly as method developments may depend on considered indicators. The corresponding indicator selection has been provided by means of the Tiered approach. Therefore, indicators for the three methods LCA, LCC and SLCA have been ranked according to the three criteria relevance, method robustness and practicality. The related research has been presented within the supplementary material. Accordingly, the Tiered approach may be beneficial in at least two ways for the field of LCSA. First, the included indicators have undergone a comprehensive review, which seems essential as a basis for further (methodological) developments within the LCSA framework. Secondly, the presented indicator hierarchy provides directions for data selection processes necessary to perform case studies. Furthermore, by means of the 'sustainability footprint' (Tier 1) practical implementation is facilitated, as the LCSA entrance barrier was lowered without neglecting one dimension of sustainability. LCSA may become more understandable and tangible, due to the given indicator structure. In addition, trade-offs between the three pillars will become more transparent, as all three methods have been addressed from the very beginning. Thus, the Tiered approach may enhance a more consistent way of dealing with LCSA by avoiding inconsistent approaches, which randomly include indicators into the LCA framework in order to also express social and economic performance. In addition, the Tiered approach may enhance the understanding of products and processes from a sustainability point of view, as hotspots and impacts can be identified more easily.

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List of acronyms

AoP	Area of protection
HIV/AIDS	Human immunodeficiency virus infection/Acquired Immune Deficiency Syndrome
ILCD	International Reference Life Cycle Data System
ILO	International Labour Organization
IPCC	Intergovernmental Panel on Climate Change
JRC	Joint Research Centre
LCA	life cycle assessment
LCC	life cycle costing
LCSA	life cycle sustainability assessment
OECD	Organisation for Economic Co-operation and Development
PROSA	Product Portfolio Analysis (German: Produktlinienanalyse)
SD	Sustainable Development
SELCA	social and environmental life cycle assessment
SHDB	Social Hotspot Database
SLCA	social life cycle assessment
SWOT	Strengths, Weaknesses, Opportunities, Threats
UN	United Nations
UNCED	United Nations Conference on Environment and Development
UNEP	United Nations Environment Programme
WHO	World Health Organization
WMO	World Meteorological Organization

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jclepro.2015.04.053.

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