Enhancing Life Cycle Sustainability Assessment

Tiered Approach and new Characterization Models for Social Life Cycle Assessment and Life Cycle Costing

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By changing nothing, nothing changes!

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Abstract

Life Cycle Sustainability Assessment (LCSA) is often described as the most advanced approach for sustainability assessment, as its implementation allows for identifying trade-offs between the environmental, social and economic dimension. Yet, shortcomings for its practical implementation exist, as the three related methods – Life Cycle Assessment (LCA), Social Life Cycle Assessment (SLCA) and Life Cycle Costing (LCC) – do not have the same level of methodological and practical maturity. While LCA is widely implemented and standardized through the ISO-series 14040 and 14044, consensus on how to implement SLCA and LCC is missing.

In this context, the discussion on adopting the commonly followed structure of LCA for SLCA and LCC plays a key role. While LCA includes well defined characterization models, SLCA misses concrete impact category definitions and LCC lacks an impact level at all. This further leads to inconsistent assessment approaches for SLCA and LCC. In addition, lacking guidance on the indicators´ and impact categories´ selection creates further obstacles for practical implementation. All this impairs the achievement of methodological improvements.

Therefore, this thesis pursues a twofold approach by addressing both – the lack of guidance as well as the methodological shortcomings of SLCA and LCC. An in-depth review of existing LCSA indicators and impact categories is carried out, which builds the basis for the methodological developments addressing relevant topics of the social and economic dimension. In a first step, a criteria-based selection of impact categories and indicators is provided for the three methods – LCA, SLCA and LCC. The considered criteria are: practicality, relevance and method robustness.

The resulting Tiered approach concept includes a hierarchical structure guiding practitioners through LCSA. Therefore, the basic 'sustainability footprint' at Tier 1 provides a starting point with simple but meaningful indicators – including global warming potential for the environmental dimension, fair wages for the social dimension, and value added for the economic dimension. Consecutively, additional impact and cost categories are implemented towards a comprehensive assessment level. Tier 2 in this context broadens the assessment by including indicators suggested by relevant institutions, such as the Joint Research Centre of the European Commission. Tier 3 also includes challenging indicators worth future consideration, such as land use and cultural heritage. Although, the implemented hierarchy itself provides focus on which impact categories and indicators to consider, it hardly contains solutions for the inherent methodological challenges. Yet, the Tier 1 level provides the basis for the methodological improvements targeted within this work.

To tackle methodological differences and to align the three LCSA methods, it is focused on the different demands of SLCA and LCC. For SLCA concrete characterization models and impact descriptions are needed, while LCC requires the definition of an impact level in the first place. Accordingly, for SLCA a characterization model for fair wages is developed by also addressing the related impact pathway. With regard to the economic dimension, a new framework for economic assessments by means of Economic Life Cycle Assessment (EcLCA) is suggested defining different economic impact categories, followed by the development of a specific characterization model considering value added at Tier 1.

With the fair wage characterization model a consistent and quantitative way of determining a specific set of social impacts along a product's life cycle is presented. The inclusion of fair wages at the midpoint level allows to account for workers´ economic situation and embodies a necessary requirement for an adequate living standard. The performed case studies confirmed the general applicability of both the fair wage method and the associated database. Certain specifics of the characterization model require further investigations, such as the included inequality factor and the results´ relation to the functional unit.

With the definition of the EcLCA framework and the coherent economic midpoint and endpoint impact categories as well as economic areas of protection, a broader perspective for the economic dimension within the LCSA framework is provided. Relevant relations between the midpoint and endpoint level are displayed through the defined impact pathway, e.g. the connection between a product´s or organization's value added and an economy´s prosperity is addressed. Following on the conceptual nature of the EcLCA approach and enabling the development of concrete characterization models, a starting point is provided with a defined impact category ‘profitability’, which connects the value added indicator to an economic impact pathway. The developed characterization model allows for displaying economic impacts by means of the value added along a product´s life cycle. Therewith, the different production locations can be compared and differences and imbalances between them can be displayed. Nonetheless, the performed case studies revealed some challenges with regard to the reflection of producers far up- or downstream the supply chain. While primary data can typically be gathered for the direct producer, no economic secondary database has so far been established reflecting the up- or downstream supply chain.

Despite those challenges, the impact categories considered within the ‘sustainability footprint’ represent crucial topics of production processes, by including global warming potential representing an important environmental concern, fair wage representing the workers´ situation, and profitability addressing the organizations´ performance. Furthermore, the Tiered approach as well as the methodological developments show that an alignment of the different maturity levels of LCA, SLCA and LCC (by means of EcLCA) is possible. Moreover, it shows that quantitative and applicable characterization models can be achieved for SLCA and that impact categories as well as characterization models can be defined for the economic dimension of LCSA.

Keywords: life cycle sustainability assessment, life cycle assessment, social life cycle assessment, life cycle costing, economic life cycle assessment, tiered approach, impact pathway, impact category, characterization model

List of abbreviations

AERA	-	American Educational Research Association
Al	-	Aluminum
anod	-	anodized
AoP	-	area of protection
CTU_e	-	comparative toxic unit for ecosystems
DALY	-	disability adjusted life years
EC_{50}	-	half maximal effective concentration
EcLCA	-	Economic Life Cycle Assessment
EEA	-	European Environment Agency
EoL	-	end of life
EPA	-	Environmental Protection Agency
eq.	-	equivalents
FAO	-	Food and Agriculture Organization
FWN	-	Fair Wage Network
FWP	-	fair wage potential
galv	-	galvanized
GDP	-	gross domestic product
GNP	-	gross national product
GRI	-	Global Reporting Initiative
GWP	-	global warming potential
HC_{50}	-	hazardous concentration affecting half of the species at EC_{50} level
ILCD	-	International Reference Life Cycle Data (System)

IMF	-	International Monetary Fund
IPCC	-	Intergovernmental Panel on Climate Change
JPI	-	Joint Programming Initiative
OECD	-	Organisation for Economic Co-Operation and Development
LCA	-	Life Cycle Assessment
LCI	-	life cycle inventory
LCC	-	Life Cycle Costing
LCIA	-	life cycle impact assessment
LCSA	-	Life Cycle Sustainability Assessment
MMTF	-	modular machine tool frame
NZ	-	New Zealand
Pedelec	-	pedal electric cycle
pwc	-	powder coated
REED	-	Rural Energy Enterprise Development
R&D	-	research and development
SELCA	-	social and environmental life cycle assessment
SLCA	-	Social Life Cycle Assessment
sold	-	soldered
St	-	Steel
Ti	-	Titanium
UBA	-	Umweltbundesamt (German EPA)
UN	-	United Nations
UNECE	-	United Nations Economic Commission for Europe

UNEP	-	United Nations Environment Programme
UNESCO	-	United Nations Educational, Scientific and Cultural Organization
weld	-	welded
WHO	-	World Health Organization
WMO	-	World Meteorological Organization
WRI	-	World Resources Institute
WSN	-	wireless sensor nodes

Table of content

1 Introduction

Global recognition of sustainability started to appear with the release of the book “The Limits to Growth” (Meadows et al. 1972). Its authors were among the first to demand a shift away from today´s growth-oriented economy towards a more balanced consideration of environmental, social and economic issues. The Brundtland Commission (United Nations 1987) with its definition of *Sustainable Development* raised the points of inter-generational equity. Finally, the Rio Summit (UNCED 1992) underlined that the sustainable development concept must go beyond pure economic or environmental considerations. Since then, consensus has been achieved regarding the inclusion of three dimensions – environment, economy and society – when measuring progress towards sustainable development (Finkbeiner et al. 2010; Hacking and Guthrie 2008; Heijungs, Huppes, and Guinée 2010). This balancing of the three dimensions offers an extension to conventional growth-oriented development targets (Sneddon, Howarth, and Norgaard 2006).

However, more than 40 years later there is still an ongoing discussion on how to achieve a sustainable development and on how to exactly measure progress towards it. Especially the ‘how to measure’ gains relevance under the viewpoint of sustainable production and the assessment of products. In current assessment practice most of the existing life cycle based methods focus on one of the three dimensions only – mostly the environmental dimension by means of Life Cycle Assessment (Klöpffer and Grahl 2014) – or are insufficient from a methodological point of view, as the case with most resource efficiency approaches, which only include economic and environmental aspects (Schneider et al. 2013). In this context, the Life Cycle Sustainability Assessment (LCSA) framework has been established including the three sustainability dimensions through Life Cycle Assessment (LCA), Life Cycle Costing (LCC) and Social Life Cycle Assessment (SLCA) (Finkbeiner et al. 2010; Klöpffer 2008). The framework has also been promoted by the UNEP/SETAC life cycle initiative as a feasible framework to measure impacts on the three sustainability dimensions (Valdivia et al. 2012; UNEP 2012).

Although LCSA is often described as the most advanced approach in terms of sustainability assessment (Zamagni, Pesonen, and Swarr 2013) and its implementation (theoretically) allows to identify trade-offs between the social, environmental and economic dimension (Heijungs, Huppes, and Guinée 2010); it still harbors a number of implementation obstacles. Practical implementation is challenging and shortcomings exist, as the three related methods – LCA, LCC and SLCA – do not have the same level of maturity due to their different evolutionary stage (Valdivia et al. 2012). While, LCA is already a standardized method (ISO 14044 2006), no consensus has yet been achieved with regard to LCC and SLCA which impairs the methodological robustness. Both aspects hinder LCSA´s practical implementation and the even consideration of impacts within the three dimensions. In addition, guidance on which impact categories or indicators to include is missing, which create further obstacles for practical implementation. Niemeijer and de Groot, (2008) conclude 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. A clear selection process can also initiate the kickoff for the needed methodological improvements and is therefore seen as essential.

Therefore, five main objectives are defined for this thesis. Starting from a review of LCSA´s literature, through the development of a clear selection process, finally targeting the enhancement of LCSA´s methodological robustness and applicability. The objectives and subtargets are described as follows:

1. Review of LCSA´s status
    a. Identification of methodological and application-specific challenges
    b. Identification of relevant topics within LCSA
2. Development of a selection process by means of a conceptual approach
    a. Ranking of the relevant LCSA topics
    b. Guided selection of impact categories and indicators to enable a stepwise implementation of LCSA
3. Enhancements of LCSA´s methodological robustness
    a. Initiate methodological developments based on the guidance provided within the conceptual approach

    b. Focus on enhancing SLCA´s and LCC´s maturity

4. Refinement of the conceptual approach considering the methodological developments
5. Exemplary case studies for testing LCSA´s stepwise implementation based on the refined conceptual approach

Based on the objectives defined, the thesis contains five main parts, which can be taken from Figure 1. Four journal and three conference publications provide essential content for the core chapters of this thesis.

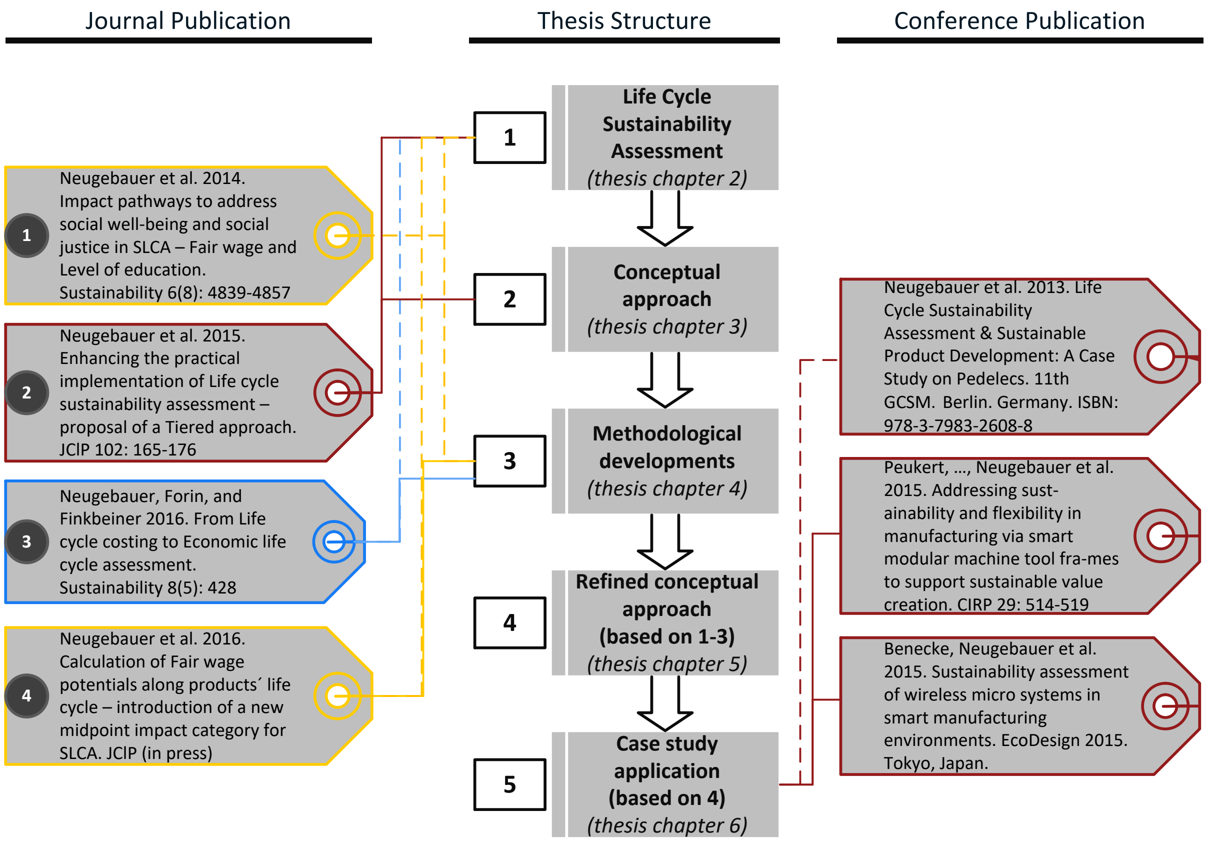

Figure 1: Thesis structure based on the defined objectives in relation to the journal publications. Yellow framed boxes relate to SLCA, red framed to LCSA and blue framed to LCC. Solid lines indicate main contributions. Dashed lines indicate supporting information used to answer the objectives of this thesis.

The content of the first and second part of this thesis is mainly taken from the second journal publication (according to Figure 1), which provides background information on LCSA and introduces the conceptual approach. Both parts are complemented by a literature review and findings in connection with the other journal publications named. In this context, three explanatory text boxes serve as an additional source of information describing the requirement of LCSA´s impact models, indicators and categories in more detail. The methodological developments of the third part of this thesis are an integral part of the third and fourth journal publication (see Figure 1), which address methodological developments in the context of SLCA and LCC. The first publication provides background information on SLCA and the methodological developments implemented. The fourth part of this thesis is based on findings of the previous parts and partly on the third and fourth journal publication. The case studies of part five are initially based on three conference publications (compare Figure 1), which are complemented and adapted based on the methodological extensions of the third and fourth part of this thesis.

Finally, the abstract, introduction, conclusion and outlook complete the thesis by providing background, summary and further research directions. The published or submitted versions of all journal publications can be found in the Annex.

2 Life Cycle Sustainability Assessment

With LCSA a framework has been established, which (theoretically) covers all three dimensions of sustainability. Practical implementation however is still lacking due to missing consensus on and unclear definitions of the impact models, categories and indicators defined. Following on the defined research objectives of this thesis, this chapter addresses the first one (‘*Review of LCSA´s status*’) and aims at comprehensively displaying the background of the LCSA framework. After an overview of LCSA´s status and its related methods (see section 2.1), general implementation challenges and available LCSA impact models (including impact categories and indicators) are introduced in section 2.2.

The findings of the four journal publications mentioned in the Introduction are displayed within this second chapter of this thesis and are supported by additional research. A comprehensive review on LCSA´s background and status has been performed within the paper of Neugebauer et al. (2015), article sections 1 and 2, to reveal the main challenges and obstacles. The findings of the cited paper are summarized; reprinted and partly adapted with permission of Elsevier B.V. (https://www.elsevier.com/about/company-information/policies/copyright). This methodological review is complemented by the introductory sections of three other journal publications, which address SLCA (Neugebauer et al. 2014; Neugebauer et al. 2016) and LCC (Neugebauer, Forin, and Finkbeiner 2016). Therefore, the LCSA background is complemented by specific background on SLCA and LCC. Furthermore, latest studies on LCSA are regarded complementing the subsections 2.1.1 to 2.1.3 to comprehensively display the status of the three related LCSA methods. In section 2.1.1 a short overview of LCA´s status and background is provided based on key literature, like Klöpffer and Grahl 2014; Finkbeiner et al. 2014; Reap et al. 2008 and others. Section 2.1.2 represents the main findings from Neugebauer et al. (2014); article section 2 (reprinted and partly adapted with permission of MDPI AG - http://www.mdpi.com/2071-1050/6/8/4839) as well as from Neugebauer et al. (2016); article section 1 (reprinted and partly adapted with permission of Elsevier B.V. (https://www.elsevier.com/about/company-information/policies/copyright). Section 2.1.3 mainly displays the findings of Neugebauer, Forin, and Finkbeiner (2016); article section 2 (reprinted and partly adapted with permission of MDPI AG - http://www.mdpi.com/2071-1050/8/5/428).

2.1 Methodological background and status

The evolution of the LCSA framework has been initiated with the development of the "Product Portfolio Analysis" (PROSA; German: Produktlinienanalyse) (Öko-Institut 1987; Grießhammer et al. 2007). Within PROSA an assessment of all three sustainability dimensions – environment, economy and society – is performed and reflected against the background of a utility analysis[1] ("Nutzenbewertung"). Therefore, the PROSA approach can be seen as key contribution leading towards LCSA (Klöpffer 2008; Finkbeiner et al. 2010). In addition, in the mid-nineties the Social and Environmental Life Cycle Assessment (SELCA) approach (O'Brien, Doig, and Clift 1996) introduced the three ring model (compare Figure 2), in connection with sustainable development (SD), expressing the three sustainability dimensions. A similar approach was and is still followed within the LCSA framework.

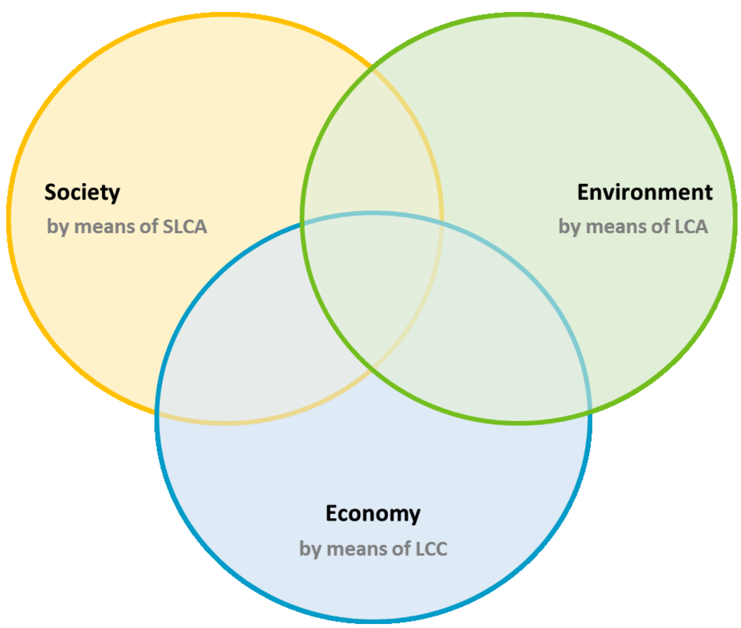

Figure 2: Three ring model commonly used in LCSA (adapted from Giddings, Hopwood, and O'Brien 2002)

[1] The utility analysis complements the sustainability assessment by including three types of utility – functional utility, symbolic utility and societal utility/public values. More details on the different types of utility can be taken from the Glossary.

With this consideration of the three sustainability dimensions the LCSA framework reflects the core concept of SD to a great extent (Giddings, Hopwood, and O'Brien 2002; Singh et al. 2012). LCSA follows the triple bottom line of sustainability (initially introduced by 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, Rebitzer, and Lichtenvort 2008) and Social Life Cycle Assessment (SLCA) to represent the social dimension (Benoit and Mazijn 2009). LCSA is clearly life cycle based (Klöpffer 2008), which leads to a similar modelling structure of the three integrated methods LCA, LCC and SLCA. The (theoretically) resulting advantage of LCSA is transparency, as it allows to identify trade-offs between the social, environmental and economic dimension (Heijungs, Huppes, and Guinée 2010).

The related methods of the LCSA framework consistently state to follow the structure of LCA, which has already been standardized by ISO 14044, (2006). The Guidelines of SLCA accordingly suggest to follow the ISO 14044, (2006) structure (Benoit and Mazijn 2009). According to Swarr et al. (2011) the same should apply to for LCC. These parallels in structure provide a common ground for the assessment of the three dimensions, such as consistent system boundaries and a uniform functional unit. However, the three methods have different target functions – e.g. environmental protection or social well-being – as they observe the same system from different perspectives (Wood and Hertwich 2012; Heijungs, Huppes, and Guinée 2010). Furthermore, the three methods do not have the same level of maturity (Valdivia et al. 2012). Considering the long history of LCA and the fact of its standardization, it is the most advanced method of the three. LCC (Hunkeler, Rebitzer, and Lichtenvort 2008) is relatively new within the sustainability assessment framework and therefore not as sophisticated as LCA, even though it has long been used in the field of business administration. The interest in SLCA (Benoit and Mazijn 2009) has been growing since its creation; however missing consensus and data hinder its comprehensive implementation (Benoît et al. 2013; Dreyer, Hauschild, and Schierbeck 2010; Jørgensen et al. 2010; Hunkeler 2006; Weidema 2006).

Background and status of the three methods – LCA, SLCA and LCC – are provided in the following subsections (see section 2.1.1 to 2.1.3). The different perspectives and objectives as well as obstacles (especially for the SLCA and LCC) are described, which lead to the general implementation challenges (addressed in section 2.2).

2.1.1 LCA – status and implementation

Since the publication of the 'Guidelines for Life Cycle Assessment: A Code of Practice' in 1993 (SETAC 1993), LCA successively attained maturity and over the years developed towards "(…) best framework for assessing the potential environmental impacts of products currently available." (European Commission 2015). With its standardization (latest version: ISO 14044 2006) last steps have been taken for reaching international acceptance and, currently, LCA is widely used to investigate the potential environmental impacts of products and processes (Klöpffer and Grahl 2014). Over the years several books and guidelines have been published guiding practitioners through LCA´s structure and fostering its implementation by also providing background information on usage scenarios (see e.g. Klöpffer and Grahl 2014; JRC 2010b; Baumann and Tillmann 2004; Guinée 2002). Broadly addressed topics in this context are: natural environment, and resource impacts (Pennington et al. 2004; UN 2007; UNEP 2012).

LCA is generally performed through a systematic evaluation of potential environmental impacts. Environmental impacts are normally determined through impact models, which are based on physical cause-effect chains (environmental mechanism) and follow a defined structure (compare Figure 3 and Box 2.1).

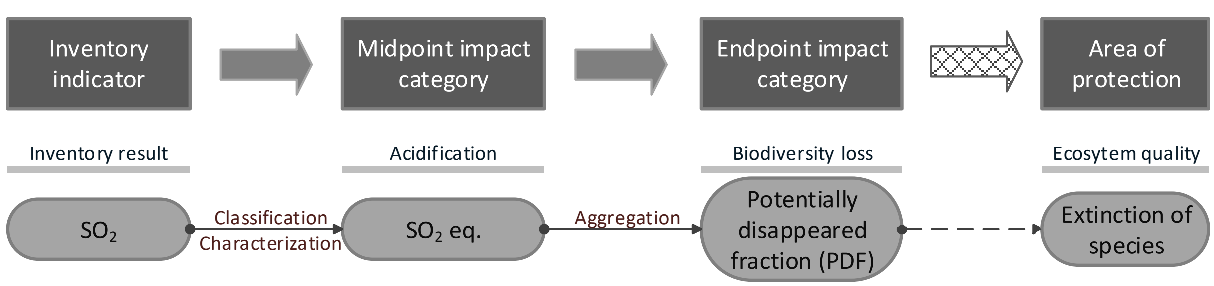

Figure 3: Exemplary impact pathway (cause-effect-chain) of LCA adopting the specifications of ISO 14044 2006; JRC 2011; and JRC 2010a

Impact models have for instance been developed by the Institute for Environmental Sciences (CML), Leiden University (Guinée 2002), or by the working group creating the ReCiPe method (Goedkoop et al. 2009). Box 2.1 describes the general structure of those impact models.

Numerous indicators relating to the impact models have been defined and implemented, determining impacts on climate change, eutrophication and acidification etc. Several institutions provide pre-selections of impact categories and indicators, e.g. UNEP or JRC (JRC 2011; UNEP and SETAC 2011; Jolliet et al. 2014).

Box 2.1: **Impact (characterization) models in LCA and LCSA**

All related methods of LCSA reportedly follow the structure of ISO 14044, (2006) (Benoit and Mazijn 2009; Swarr et al. 2011; Hunkeler, Rebitzer, and Lichtenvort 2008). Even though impact assessment is not mandatory according to ISO 14044, (2006) (except for studies, which are intended to be used in comparative assertions and/or disclosed to the public), within LCA and LCSA it can be seen as targeted. The consideration of impacts provides information on the relative importance of emissions or consequences (within social or economic considerations) resulting from certain actions at a proceeded stage of the cause-effect-chain (Vanclay 2002).

Following the suggestions of ISO 14044, (2006), the impact assessment phase shall include: impact categories, category indicators and characterization models (as stated in section 4.2.2 'Mandatory elements of LCIA' within ISO 14044, 2006). Furthermore, environmental (social or economic) mechanisms shall be represented through those impact categories, category indicators and characterization models. Therefore, in LCA usually a structure of midpoint and endpoint impact categories is adopted, which results from a continuous process supported by several authors and working groups (compare e.g. Haes et al. 2002; Jolliet et al. 2004; Klöpffer and Grahl 2014). Inventory results are therefore connected with impact categories (usually described as midpoint impact categories) and category endpoints (usually described by endpoint impact categories) (JRC 2010a). For adapting the same structure to SCLA and LCC (in the context of LCSA), social and economic mechanisms (often represented by means of impact pathways, see Jolliet et al. 2004; Jørgensen et al. 2010) should be followed. Characterization is required to aggregate inventory results within impact categories (midpoint or endpoint) to a common metric (Hunkeler 2006; ISO 14044 2006). Characterization shall be done based on scientific findings following identifiable mechanisms, reproducible empirical observations or international agreements. The resulting characterization models may, if unavoidable, contain value-choices, if those reflect *"environmental (social and economic) issues related to the product system being studied"* (ISO 14044 2006).

Furthermore, related databases have already been established, like GaBi or ecoinvent (UNEP and SETAC 2011). Most of the prevailing impact categories and indicators are connected to the three so-called areas of protection (AoPs)[2]: ecosystem quality (also listed as natural environment), resources (also named natural resources) and human health (Goedkoop et al. 2009; JRC 2010b). Human health was originally considered within LCA. However, it may rather be included in SLCA, as described by Hacking and Guthrie, (2008) and UNEP, (2012). It has further been addressed within studies determining social risks and impacts (Norris 2006; Feschet et al. 2013; Chang et al. 2015; Traverso et al. 2012). Therefore, human health within this thesis will be attributed to SLCA to avoid double-counting and to ensure an analogous allocation of topics to the respective dimension.

LCA is not perfect, even though there can be hardly any doubt about its application readiness. Some topics are still challenging, like toxicity (Reap et al. 2008), or not even addressed by impact models or indicators, like biodiversity (Klöpffer 2008). Two years ago, Finkbeiner et al. (2014) published a comprehensive analysis of remaining gaps and challenges in LCA, which relate to both scientific robustness but also implementation and preciseness. Indeed, the LCA method can still be improved. Nevertheless, the level of perfection LCA has reached by far exceeds the status of SLCA and LCC. Within this thesis, LCA will thus be considered as sufficient and focus will be set on initiating further developments for SLCA and LCC to enable coherent enhancement of LCSA.

2.1.2 SLCA – status and implementation

The topic of SLCA appeared in the mid-1990s in connection with the proposed Social and Environmental Life Cycle Assessment (SELCA) approach (O'Brien, Doig, and Clift 1996). Later in the early 2000s, social aspects in context of SLCA have been addressed by several authors (Grießhammer et al. 2006; Dreyer, Hauschild, and Schierbeck 2006; Hunkeler 2006; Labuschagne and Brent 2006; Weidema 2006; Jørgensen et al. 2008) resulting in the 'Guidelines of Social Life Cycle Assessment of products' released in 2009 (Benoit and Mazijn 2009).

[2] Areas of protection are typically understood as targets and/or objects of protection. Further information can be taken from the Glossary.

As specified by the Guidelines (Benoit and Mazijn 2009), SLCA assesses the potential social impacts of products in relation to the different stakeholder groups affected by the products´ manufacturing. Those social impacts and stakeholder groups normally relate to social AoPs. A commonly known and used AoP is human well-being[3] (Benoit and Mazijn 2009; Jørgensen et al. 2008; Dreyer, Hauschild, and Schierbeck 2006; Weidema 2006), defined as the central goal of human activity and targeting people´s happiness, satisfaction and good living standard. The earlier mentioned LCA-related topic human health is often seen as an essential part of social well-being (Dreyer, Hauschild, and Schierbeck 2006; Feschet et al. 2013; Benoit and Mazijn 2009).

With the Guidelines of SLCA (Benoit and Mazijn 2009) a first framework has been provided, defining different stakeholder groups (including related subcategories) as well as impact categories. Five stakeholder groups have been listed relating to different parts of societal systems – workers, consumers, local communities, society and value chain actors. The related subcategories per stakeholder group can be taken from Figure 4.

In addition to the stakeholder groups and subcategories, two types of impact categories have been defined either relating to the stakeholder groups or following social impact pathways based on the LCA and ISO 14044 (2006) framework. In relation to stakeholder groups, six impact categories have been defined – human rights, working condition, health and safety, cultural heritage, governance and socio-economic repercussions. In relation to social impact pathways another two types of impact categories are distinguished – midpoint and endpoint categories. At the endpoint level human capital, cultural heritage and human well-being have been named (Benoit and Mazijn 2009). At the midpoint level health, autonomy, safety, security, equal opportunities, participation and resource productivity have been mentioned (Benoit and Mazijn 2009). However, neither the stakeholder nor the pathway related impact categories have thoroughly been described or justified.

[3] Often also referred to as social well-being (Benoit and Mazijn 2009) or human dignity (Dreyer, Hauschild, and Schierbeck 2006).

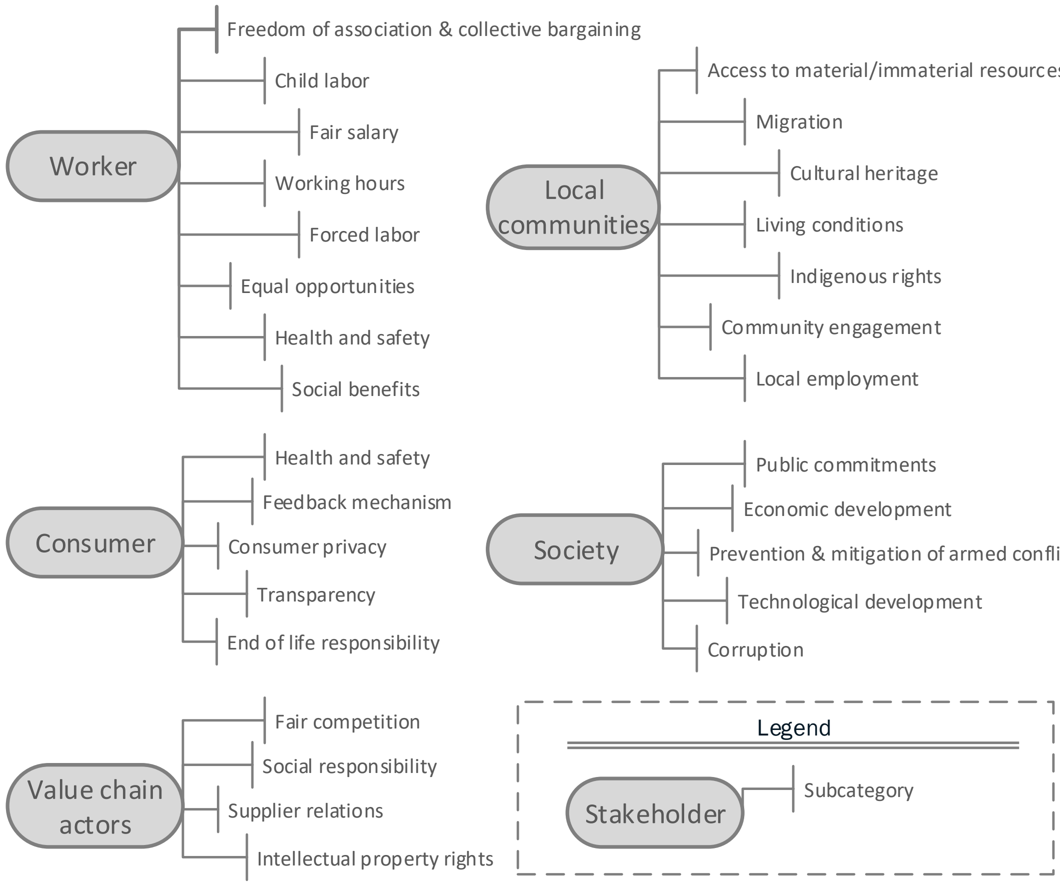

Figure 4: Stakeholder groups and related subcategories according to the SLCA-Guidelines, slightly adapted from Benoit and Mazijn (2009)

Prior and/or in addition to the Guidelines, several authors proposed impact categories or impact models (e.g. Jørgensen et al. 2008; Labuschagne and Brent 2006; Hutchins and Sutherland 2008; Jørgensen, Lai, and Hauschild 2010). Different paths have been explored trying to further develop the SLCA method. A review of SLCA studies[4] revealed that commonly three types of social impact assessment can be distinguished – termed here as Type I, II and III (see Figure 5 and Figure 6).

Type I: This approach mainly results from the stakeholder concept followed within the 'Guidelines for Social Life Cycle Assessment of Products' (Benoit and Mazijn 2009). It focuses on so-called *performance reference points* to aggregate indicator results of subcategories, which influence different stakeholder groups (Parent, Cucuzzella, and

[4] Respective references of the reviewed studies can be taken from the following paragraphs.

Revéret 2010; Wu, Yang, and Chen 2014). Those performance reference points "may be internationally set thresholds, goals or objectives according to conventions and best practices, etc." (Benoit and Mazijn 2009). The performance reference points are used within a scoring and/or weighting system, which allow for the aggregation to subcategories, impact categories or even single-score values. The Type I approach has been addressed by e.g. Dreyer, Hauschild, and Schierbeck (2010) and included in case studies by e.g. Ekener-Petersen and Finnveden 2013; Martínez-Blanco et al. 2014.

Type II: This approach follows the 'classical' LCA approach according to ISO 14044 (2006) and in the context of SLCA seeks to represent social mechanisms. It therefore follows the commonly adopted structure of LC(S)A (Parent, Cucuzzella, and Revéret 2010; Wu, Yang, and Chen 2014), as addressed in detail within Box 2.1 at the end of section 2.1.1. The adopted structure includes impact pathways as well as midpoint and endpoint impact categories, as defined by e.g. JRC 2010a; or Jolliet et al. 2004. That implies that characterization models are of quantitative character to convert inventory data into category indicator results, i.e. into social impacts. Type II approaches are therefore especially relevant in the context of LCSA for ensuring a consistent assessment practice for all related methods. This type of assessments has been adopted by Hunkeler (2006) translating labor hours into the capacity of employees to afford housing, health care, education and necessities. It can also be found in e.g. Neugebauer et al. (2014), who provide a qualitative characterization model for fair wage as a midpoint impact category, and in Kruse et al. (2009), who include different additive and descriptive indicators targeting a decent life style.

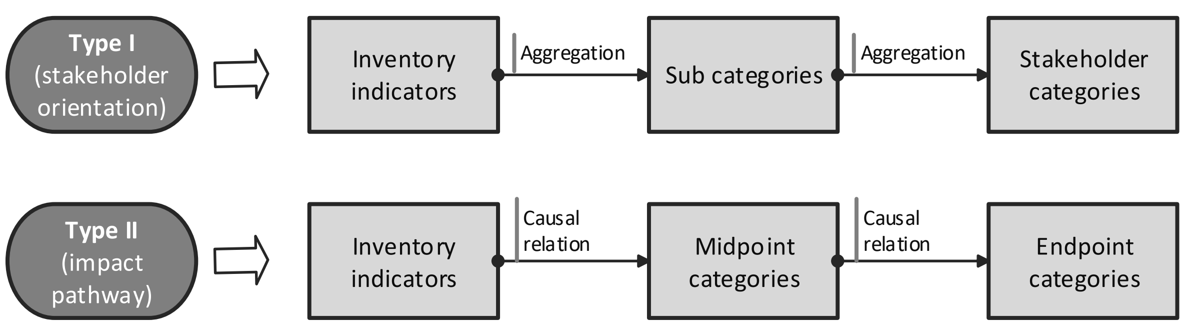

Figure 5: Type I and Type II assessment structure according to Parent, Cucuzzella, and Revéret 2010; Wu, Yang, and Chen 2014

Those two assessment types (Type I and II) have earlier been discussed by Parent, Cucuzzella, and Revéret (2010) and again by Wu, Yang, and Chen (2014). Besides the Type I and II assessment, which start from the inventory towards the stakeholder or impact category level; another type of assessment practice can be described, which is newly defined within this thesis as Type III assessment. Those Type III assessments have firstly been implemented by Norris (2006) and Hutchins & Sutherland (2008) determining social impacts on human health resulting from a change in products´ life cycles.

Type III: Social impact assessments of this type link socio-economic pathways through simplified economic modelling techniques to social endpoint impacts. Therefore, an empirical correlation between two parameters of interest is established in a first step (e.g. between income inequality and human health). In a second step, a potential social impact is predicted resulting from a *change* in a product´s life cycle (microeconomic level) that affect a national indicator of social sustainability (such as human health or social equity) based on the earlier determined empirical correlation. The approach thus contains aspects of consequential modelling and is to be differentiated from the classical attributional approach normally followed within LCSA. An example of this Type III approach has been applied by Feschet et al. (2013), who use the so-called *Preston curve* describing an empirical correlation between growth in income (measured as GDP per capita) and improvements in the health of a country's population (measured as life expectancy at birth). They then apply their impact pathway to predict the potential impact of a *change* in income levels (expressed as GDP per capita) – itself caused by a modification of the functioning of one product chain – upon the health status of the population where this *change* occurred. Another study following the same modelling type has been presented by Bocoum, Macombe, and Revéret (2015) by using the so-called *Wilkinson pathway,* which establishes a relationship between income inequality and health.

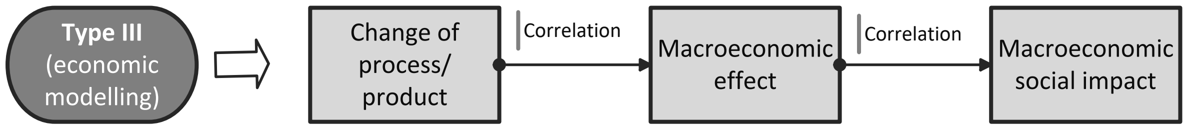

Figure 6: Type III assessment, as defined within this thesis, displaying the determination of social impacts through economic modelling

All three approaches provide benefits for different cases of application. Yet, when considering SLCA in the context of the LCSA framework, SLCA should preferably follow the commonly adopted structure of LCA (JRC 2010a; Jolliet et al. 2004) in order to maintain a certain degree of consistency and comparability among the LCSA sub-methods (LCA, LCC and SLCA). Furthermore, a product-related approach bears advantages when aiming at the quantification of social impacts along the supply chain of a product.

While, Type I assessments seem suitable to assess social risks for different stakeholder groups on a country or sectoral level; they hardly provide direct product relations and generally neglect causal relations along an impact pathway. Type III assessments with their inclusion of correlations may appear as if they provide causal relationships. However, a correlation does not necessarily equal a causal relation (to differentiate from the defined Type II approach), as it can be random, coincidental or depending on a confounding variable not included in the original correlation.[5] For instance, the correlations presented by Feschet et al. (2013) and Bocoum, Macombe, and Revéret (2015) cannot automatically be assumed causal, as they neglect control variables, such as additional socioeconomic variables e.g. education, as well as control studies.[6] Therefore, correlations can only be used for determining causal assumptions, if the bundle of studies performed is big enough, control studies[7] are performed and long-term investigations are included (Goldin 2015; Adolphus, Lawton, and Dye 2013;

[5] Further explanation and examples can be found in Goldin (2015).

[6] Picket and Wilkinson (2010) within their study on income inequality already identified education as a mediate factor influencing health. Braveman et al. 2005; and Geyer et al. 2006 in this context address the hen-egg-problem of the triangle income-education-health, which leads to the conclusion that correlations between two of those three factors cannot be investigated independently or easily. Fuchs (2004) points out that the interactions between health and other socio-economic variables must be investigated carefully and that hasty assumptions of the relation between income and health must be avoided.

[7] Control studies take into account two comparable groups or situations, which preferably differ in only one aspect, e.g. two groups of people are comparable in behavior, but contain two different sets of experience. If the results obtained through correlations are substantially different, the differences in experience may have caused the different outcome. (Goldin 2015)

Babones 2008). Another limitation of Type III assessments is that they are only useful for comparative assessments of products, which have a considerable share in the economic activity of a certain country (as e.g. explicitly stated by Feschet et al. 2013). Type II assessments, following the *traditional* LCA-inspired approach, are thus more suitable for corporate or product-related social assessments. They also target the inclusion of causal relations due to the followed social mechanisms. They allow for determining the social performance of products along the life cycle and relate inventory data on the product's life cycle to social impacts without having specific restrictions regarding the contribution of the product to the overall economy. Therefore, within this thesis the achievement of Type II approaches is targeted.

2.1.3 LCC – status and implementation

LCC[8] was first used in the mid-1960s by the United States Department of Defense. Twenty years later it was taken up by the construction industry to assess building investments (including also energy and disposal costs and setting it into an environmental context). LCC was originally developed to rank different investment options, but did for a long time not consider operating costs occurring during the product´s life time (Gluch and Baumann 2004).

A first international standard addressing LCC was published in 2008 with ISO 15686-5 that defines LCC as *"a technique which enables comparative cost assessments to be made over a specified period of time, taking into account all relevant economic factors both in term of initial costs and future operational costs"* (ISO 2008). ISO provides, despite its focus on buildings and construction assets, comprehensive guidance on how to conduct an LCC throughout a product´s life cycle, including costs for the operation and end-of-life (EoL) phase.

A similar structure has been followed within the 'manual' for LCC, the 'Environmental Life Cycle Costing' book published by Hunkeler, Rebitzer, and Lichtenvort (2008). It includes producers, suppliers, consumers and EoL actors in the assessment reflecting costs associated

[8] In literature a heterogeneous terminology is featured and LCC is inter alia referred to as Life Cycle Costing, Whole-Life Costing or Total Cost of Ownership (Settanni et al. 2014). However, within this thesis LCC is used as an umbrella term for economic life-cycle based assessment methods.

with a product´s life cycle. These life cycle related cost categories have already earlier been proposed by Grießhammer et al. (2007) differentiating different actors and/or fields.

Hunkeler, Rebitzer, and Lichtenvort (2008) differentiate between three types of LCC – *conventional* LCC, *environmental* LCC and *societal* LCC (see Figure 7). Conventional LCC sets the focus on ("real") internal costs[9], which are associated with a product´s life cycle. Environmental LCC goes beyond and includes also external costs, which are likely to be internalized in the decision-relevant future. In addition, within environmental LCC taxes and subsidies are considered and in parallel non-monetized LCA results can be included. Societal LCC goes even further by regarding all costs carried by anyone in the society, whether today or on the long-term, through the inclusion of all external costs in a monetized form (Hunkeler, Rebitzer, and Lichtenvort 2008).

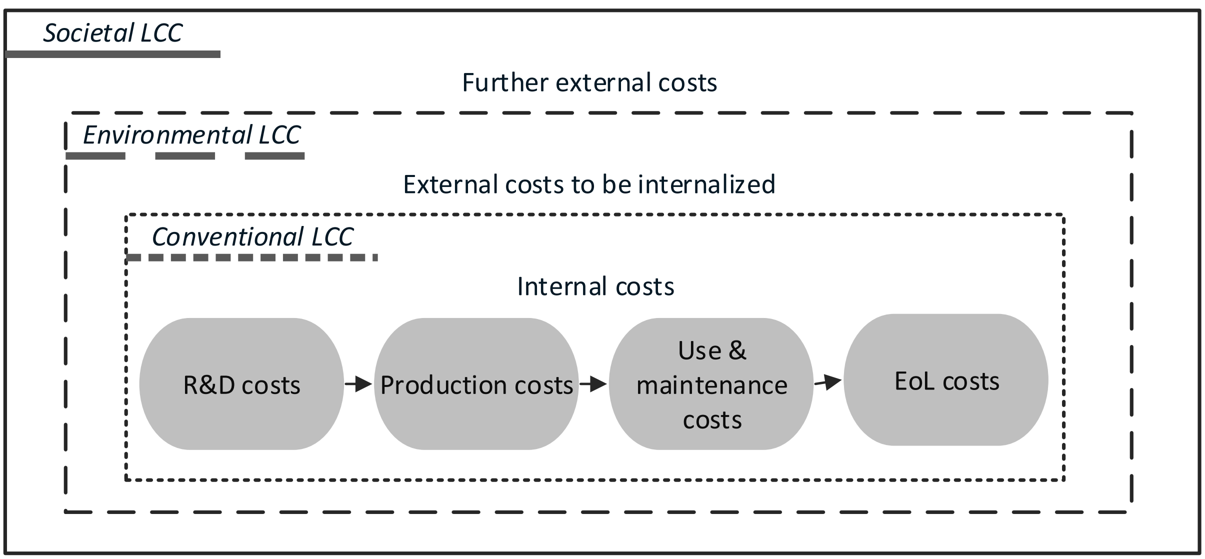

Figure 7: The three types of LCC according to Hunkeler, Rebitzer, and Lichtenvort (2008) (slightly adapted)

In practical application, LCC is performed from 'cradle to grave'; and, typically, research and development (R&D) costs, production costs, use and maintenance cost as well as end of life (EoL) costs are included (Curran, Raghunathan, and Price 2004; Hunkeler, Rebitzer, and

[9] Internal and external costs have been distinguished by Hunkeler, Rebitzer, and Lichtenvort (2008), as described in Box 2.3 in section 2.2.2.

Lichtenvort 2008; Swarr et al. 2011). Ristimäki et al. (2013) additionally mentions an interpretation phase similar to LCA, addressing significant costs and aspects of uncertainty. Although relevant costs groups have been defined by Hunkeler, Rebitzer, and Lichtenvort (2008) and others, practical implementation is not straightforward and costs and related data sources included in case studies show inconsistencies (Wood and Hertwich 2012; Gluch and Baumann 2004). Gluch and Baumann (2004) and also Bubeck (2002) in this context name several concepts, like 'total cost accounting' or 'full cost accounting', which follow very similar approaches but foster practitioner's uncertainty on which one to use. The cost term as such is not sovereign and different cost types can be differentiated, Box 2.2 gives an overview of the different types of cost and defines the cost concept commonly included in LCC.

Box 2.2: **Types of costs included in LCC**

Generally , in accordance with definition of Hunkeler, Rebitzer, and Lichtenvort (2008), 'Environmental LCC' only includes costs, which are connected to real money flows along the life cycle of a product. Therefore, the earlier mentioned external costs (compare Box 2.3) are only regarded, if those are to be internalized in the decision-relevant future. The types of cost commonly referred to in LCC can be described as financial costs (German: *pagatorische Kosten*). Financial costs clearly focus on real payments and therefore consider purchases as the solely relevant values (Bubeck 2002). Grießhammer et al. (2007) in this context mention that relevant cost data for upstream processes are hard to gather. They therefore conclude that in LCC assessments purchase prices may be used as an approximation for costs.

Within accounting practice, prices usually reflect the aggregated costs, which are based on the quantity of goods and time consumed. Those accounting costs are typically value-based and normally correspond with financial costs. However, accounting costs can also include opportunity costs, which broaden the cost concept and add a decision-oriented dimensions. Opportunity costs do not necessarily lead to expenses (e.g. when considering imputed depreciations) and can be used to evaluate the value of the best alternative (Bubeck 2002). They are therefore if at all part of societal LCC, as environmental LCC is normally limited to occurring expenses.

Generally, no impact level has been considered in current assessment practice, even though Hunkeler, Rebitzer, and Lichtenvort (2008) earlier mentioned first impact categories – namely ‘economic prosperity’ and ‘economic resilience’ in connection with GDP/GNP changes and value added. Similar to SLCA, the suggested impact categories miss further definition and description. Additionally, no impact pathway has yet been defined, which describes economic interrelations or connects economic impacts (e.g. at the midpoint level) to (not yet defined) economic AoPs (Wood and Hertwich 2012; Gluch and Baumann 2004; Neugebauer et al. 2015; Curran, Raghunathan, and Price 2004).

Addressing the lack of impact categories at the midpoint and endpoint level, some studies tried to implement a broader economic perspective compared to the restricted focus on costs. To name just a few: May and Brennan (2006) include value added as an economic indicator and relate it to wealth generation; Kruse et al. (2009) and Thomassen et al. (2009) consider value added as an (additive) economic indicator; Heijungs, Settanni, and Guinée (2012) calculate the value added for all processes within a product´s life cycle. Jeswani et al. (2010) state, that LCC allows for hotspot identification by considering the value added. Wood and Hertwich (2012) go even beyond and connect value added to GDP by using economic modelling (input output analysis) approaches and extend the classical LCC framework by drawing the connection between costs on the microeconomic level and effects at the macroeconomic level.

Despite these first approaches to broaden LCC (also often in connection with LCSA), consensus has not yet been achieved on whether and how to re-structure LCC. Discussions are ongoing if LCC´s limitation to the cost level is sufficient, especially in the context of sustainability (and LCSA). Although Swarr et al. (2011) stated that there is no need for characterization (as performed in LCA) in LCC, since costs already comprise a unit of measure; others have addressed the need for going beyond pure cost assessment. Grießhammer et al. (2007) in this context mention obstacles of this unit of measure due to different currencies and different production locations. Adding up costs across national borders does not make sense without accounting for the different economic situations or cost of living (when considering the employees´ perspective). Furthermore, the delineation between costs and other governmental pricings, such as subsidies or different rates of interest, is not trivial. Grießhammer et al. (2007) therefore stress the need for including a critical review, when performing and publishing a LCC study. Curran, Raghunathan, and Price (2004) criticize the classical LCC for ignoring causalities. Gluch and Baumann (2004) criticize the one-dimensional unit (by means of monetary values) as an insufficient assumption for expressing economic sustainability. Hall (2015) and Wood and Hertwich (2012) agree with that view and stress that the values transported by LCC are not in line with the sustainability concept, as they do not capture the complete economic dimension of sustainability, as defined by e.g. the Rio declaration (UNCED 1992)[10]. Heijungs, Settanni, and Guinée (2012) conclude that especially in the context of sustainability the limitation to costs is like "(…) narrowing the environmental analysis to waste." They add that further aspects, such as value added, growth, trade balance etc., are of higher interest in this context.

2.1.4 Concluding remarks on LCSA´s status

To summarize section 2.1, differences exist between the three methods LCA, SLCA and LCC. Those differences relate to the scientific maturity, which also influences the status of method´s implementation. Following previous statements in section 2.1.1, LCA contains no general obstacles for application; thus, is will not be further addressed within this chapter and no methodological developments are foreseen for LCA within this thesis. A different picture appears for SLCA and LCC. The main (methodological) differences of the three LCSA-methods identified in section 2.1, which serve as a basis for further investigation, can be taken from the illustration in Figure 8. To name the most important ones: Whereas LCA already contains justified impact pathways, implemented characterization models and therefore needed indicators and described AoPs; SLCA partly contains roughly defined impact categories, described AoPs and draft versions of characterization models. For LCC consensus on how

[10] Within the Rio declaration already trade liberations and a more equitable multilateral trading system were mentioned, which go beyond monetary concerns and rather focus on the establishment of non-discriminatory market situations around the globe. In chapter 33 of the declaration capacity-building and technical cooperation have been named in the context of developing countries´ equality.

and if to include an impact level is missing. It accordingly lacks defined AoPs and includes only draft versions of impact categories.

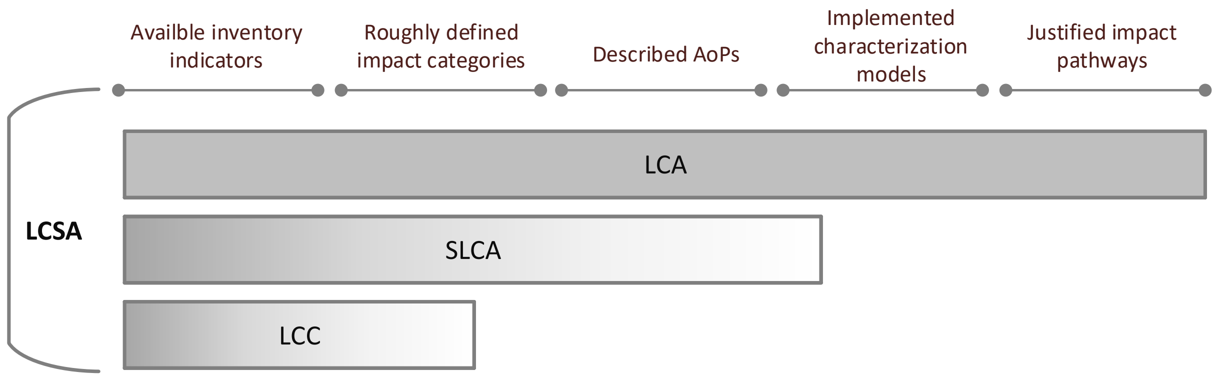

Figure 8: Methodological and implementation-related differences of the three LCSA-methods[11]

Addressing these different perspectives as well as obstacles (especially for SLCA and LCC), the following section will address the general implementation challenges occurring for the three LCSA methods.

2.2 General implementation challenges

By addressing the general implementation challenges for LCSA, this section takes up the first sub-target of the first research objective defined within this thesis (‘*Identification of methodological and application-specific challenges*’). Adding up on the differences in maturity displayed in Figure 8, the different concepts and assessment approaches led to inconsistent definitions of impact models (SLCA) or models of calculation (LCC) (as shown in section 2.1.2 and 2.1.3). The methodological shortcomings of the methods at the same time hinder their broad implementation, as they trigger uncertainties on how to use them. Furthermore, definitions has to be specified, if the requirements of ISO 14044, (2006) should be met and the commonly adopted structure of LCA should be transferred to SLCA and LCC. The earlier introduced Box 2.1 takes up this topic and addresses the steps necessary for upgrading SLCA and LCC to align

[11] Note that the figure only addresses the methodological differences of the three methods. Differences with regard to data availability will be addressed in section 2.2.

it with the common practice adopted for LCA based on ISO 14044, (2006) as well as the ILCD handbooks and others (Jolliet et al. 2004; JRC 2010c; JRC 2010b; JRC 2011).

Correspondingly, differences in practicality of LCA, SLCA and LCC result due to the amount of studies, as well as the consistency and sufficiency of application. While the standardized LCA method is widely used, the practical implementation of SLCA and LCC still appears challenging. SLCA´s lack of practical implementation mainly has two reasons: lacking consensus and unclear research directions, as indicated through the various approaches followed for SLCA (Type I, II and III – compare section 2.1.2). While different approaches also apply for LCC (e.g. total cost accounting, cost-benefit analysis), two additional reasons can be noted: Although, LCC case studies might exist on firms´ level, published studies are often missing due to confidential data and high uncertainties of related data (Grießhammer et al. 2007; Bubeck 2002). Furthermore, several authors criticized the narrow perspective of LCC as insufficient (compare section 2.1.3). As a result for both methods SLCA and LCC, no noteworthy progress has been made since the release of the Guidelines of SLCA (Benoit and Mazijn 2009) and the Environmental LCC book (Hunkeler, Rebitzer, and Lichtenvort 2008). Heijungs, Huppes, and Guinée (2010) in that context mention the importance of a science-based theory, which contains well recognizable aspects (e.g. crucial topics on the microeconomic or business level) to avoid a stalemate in improvement and implementation.

Before mitigation of methodological differences and stimulation of LCSA´s practicality can be achieved, specific implementation challenges of SLCA and LCC need to be identified. On this basis, the following subsections display challenges related to impact models and indicators for SLCA and LCC. The findings serve as the basis for section 2.3, where relevant topics of LCSA are discussed. The identified topics will then be used for setting a criteria-based hierarchy of impact categories in section 3.2.

2.2.1 Specific implementation challenges of SLCA

Following on the findings presented in section 2.1.2, two main reasons for SLCA´s deficiencies could be identified: lacking consensus on which assessment approach to implement and resulting confusion on which research direction to follow. In fact, the different approaches (within this thesis referred to as Type I, II and III) foster inconsistencies, as the results of different studies can be quite contradictory. Focus has mostly been set on the representation of stakeholder groups without bridging the gap towards impact assessment (see e.g. Martínez-Blanco et al. 2014). With regard to Type I assessments, clear definitions and relations between stakeholder groups, subcategories and impacts have so far been neglected. Thus, the proposed impact categories can only be taken as first suggestions, as they are not consistent or applicable. Furthermore, regarding the within this thesis targeted Type II assessments, impact category´s assignment to the midpoint and endpoint level remains unresolved. Impact categories and AoPs lack sufficient definition and practical indicators are missing (Neugebauer et al. 2015; Parent, Cucuzzella, and Revéret 2010; Jørgensen et al. 2008). Consequently, due to this confusion of assessment approaches, databases barely include social indicators and – if at all – include rather risk factors than to express impacts (see e.g. SHDB 2013). Databases providing secondary background data are missing; although they would be necessary for modelling supply chain impacts in relation to products´ manufacturing.

Furthermore, the selection of suitable impact categories and category indicators, which can be used to express and quantify social impacts at the midpoint and endpoint level, remains one of the major challenges of SLCA (Moriizumi, Matsui, and Hondo 2010; Heller and Keoleian 2003; Bienge et al. 2009; Jørgensen et al. 2008). The definition of such indicators is a prerequisite for developing characterization models, for designing social impact pathways linking midpoint and endpoint indicators, and for providing applicable impact assessment methods for SLCA (Niemeijer and de Groot 2008).

The deficiencies identified not only prevent a broad and consistent implementation of SLCA but also of LCSA. Especially in connection with the LCSA framework, the question of which SLCA approach to follow becomes fundamental. As earlier stated in section 2.1.2, the Guidelines of SLCA supposedly follow the structure of ISO 14044 2006. Following the earlier suggestion of Klöpffer (2008), the same holds true for LCSA. Furthermore, consistent LCSA´s results somehow require similar styles of measurement for the three related methods. Based on the assumption that LCSA and SLCA follow the ISO 14044 (2006) structure, future SLCA approaches should logically consider this structure. Thus, further development will focus on the earlier defined Type II assessments, which are based on social mechanisms or cause-effect-chains (similar to LCA), as already described in section 2.1.2. As indicated within Box 2.1, this also includes the consideration of midpoint and endpoint impact categories towards social AoPs. Nevertheless, the interrelations between the different midpoint and endpoint categories defined have not yet been clarified (Jørgensen, Lai, and Hauschild 2010; Dreyer, Hauschild, and Schierbeck 2006; Weidema 2006; Labuschagne and Brent 2006). The in section 2.1.2 identified Type III assessments, even though they do not provide causal relations as such, can be of help to determine impacts at the endpoint level, as soon as the bundle of correlations is big enough and shows consistent evidence.

2.2.2 Specific implementation challenges of LCC

Although relevant costs groups have been defined by Hunkeler, Rebitzer, and Lichtenvort 2008; and Swarr et al. 2011, the types of costs and related data sources included in case studies show inconsistencies (Wood and Hertwich 2012; Gluch and Baumann 2004). Notwithstanding these different approaches, LCC in industry is still perceived as infrequently implemented due to methodological confusion and the variety of defined concepts[12], and missing targets (Settanni et al. 2014; Hochschorner and Noring 2011; Wood and Hertwich 2012; Hall 2015; Gluch and Baumann 2004; Bubeck 2002; Hoogmartens et al. 2014). This becomes crucial with the limitation to short-term considerations (Seuring and Müller 2008; Settanni et al. 2014) as well as the discounting of future costs (Gluch and Baumann 2004; Grießhammer et al. 2007; Hochschorner and Noring 2011).

The discussion on whether or not to include external costs[13] reinforces the uncertainties. The discussion gained momentum for several reasons: the risk of double-counting, the unclear system boundary definition and the unresolved internalization approach (Rebitzer and

[12] Gluch and Baumann (2004) name several concepts, like 'total cost accounting' or 'full cost accounting', which follow very similar approaches but foster practitioner's uncertainty on which one to use. Already earlier, Bubeck (2002) in his dissertation mentioned similar challenges for the LCC concept and referred to the inconsistencies of different cost groups included depending on the approach followed. Hoogmartens et al. (2014) refer to confusions in business and policy decisions due to conflicting assessment results achieved through similar but disparate tools, like LCC and cost-benefit analysis.
[13] A distinction between external and internal costs is presented within Box 2.3.

Hunkeler 2003). Double-counting may occur when summing up costs of different perspectives. For instance, consumption costs (by means of purchase prices) already include manufacturing and material costs and therefore cannot be summed up with calculated production costs for double-counting reasons. In this context, Heijungs, Settanni, and Guinée (2012) stress that caution is needed when considering different perspectives. Caution is needed, when displaying the results of the LCC, by either displaying the different perspectives separately or by accounting for the overall value added, as suggested by e.g. Heijungs, Settanni, and Guinée (2012).

Box 2.3: **Internal and external costs in LCC**

Hunkeler et al. (2008) within the 'Environmental LCC manual' distinguish between internal and external costs. In this context, internal costs are understood as costs, which are directly linked to in the life cycle involved stakeholders. These internal costs therefore can be connected to the direct costs of business resulting from the processes involved in the product´s production. On the contrary, external costs are understood as costs, which are not directly linked to the product´s life cycle. External costs often relate to environmental and social impacts and lay typically outside the system boundary. They may therefore affect stakeholders, who have no direct relation to the product of consideration. Nevertheless, as soon as they are assumed to be internalized, e.g. due to government pricing like taxes a company has to pay, they shall be regarded in the assessment.

Double-counting may also occur in the context of LCSA, as soon as e.g. environmental burdens are accounted for in LCA but also in LCC via the inclusion of external costs. With this inclusion of external costs also an adaption of the product-related system boundaries would be needed, which can blur the transparency of the product system. Furthermore, there is no agreed practice established on how to internalize external costs in LCC, which feeds the uncertainties through inconsistent approaches.

Although some authors (Hunkeler and Rebitzer 2005) earlier stated that LCC is on a relatively fast track towards a comprehensive implementation; databases for LCC are so far not available, except for the building and construction sector (European commission 2007; Agyapong-

Kodua, Wahid, and Weston 2011). Grießhammer et al. (2007) mention the following obstacles for data availability: cost data are often confidential and not publicly available; management accounting systems are not transparent nor fully integrated in the assessment process. This further impedes LCC´s broad implementation, which partly explains the lack of published case studies in this field (Bubeck 2002; Grießhammer et al. 2007). Nevertheless, existing LCA databases (e.g. the GaBi 6.0 database) slowly start to include costs. Furthermore, management accounting systems may provide a limited basis for costs needed in LCC (Heijungs, Settanni, and Guinée 2012). In both cases, the direction of the results is not clear, as the created costs for one stakeholder embody benefits for another one. Especially in this context the definition of targets (by means of economic AoPs) would clarify the results´ direction and the perspectival confusion.

In response to all the above-mentioned challenges, the need for LCC to even exist has been discussed, especially within the LCSA framework. Jørgensen et al. (2013) and Rebitzer and Hunkeler (2003) suggest to only use LCC in the context of LCSA and to focus on the monetary gains and losses for the poor. Klöpffer and Ciroth (2011) in their answer to an editorial letter, clearly pointed out that LCC, referred to as environmental LCC, must be part of LCSA, as economic aspects have ever played and will always play a crucial role within sustainable development.

The general view to include economic aspects in the LSCA framework is supported, however a revisited form of LCC is needed to more adequately display the economic dimension of sustainability for complementing the social and environmental considerations of SLCA and LCA. Further discussions are ongoing regarding LCC´s limitation to the cost level, which has been challenged by several authors (e.g. Hall 2015; Wood and Hertwich 2012; Gluch and Baumann 2004), as already mentioned in section 2.1.3. LCC in its current form can lead to misinterpretation as it is assumed that lower costs are always beneficial and a relation to the production location is often neglected (Grießhammer et al. 2007; Bubeck 2002)[14]. This further leads to

[14] Examples can be taken from Ristimäki et al. 2013; Woon and Lo 2016; Amienyo and Azapagic 2016; Ilg, Hoehne, and Guenther 2015.

wrong assumptions when comparing the costs per life cycle stage, as it limits the results´ interpretability to the perspective of the study-executing producer. Furthermore, this narrow perspective of LCC together with its earlier addressed methodological challenges (as summarized in section 2.1.4 and the beginning of section 2.2) hinder the comparability of achieved results of the three LCSA methods. Therefore, by following the assumptions presented in Box 2.1, environmental LCC in connection with LCSA has to adopt a cause-effect-structure, which would require the definition of an impact level. The identification of relevant economic aspects plays a key role to enforce further developments, as no impact categories and AoPs have yet been defined.

2.2.3 Summary of LCSA´s challenges and further research directions

The two previous subsections displayed the challenges of SLCA and LCC in the context of LCSA´s implementation. Table 1 summarizes the main shortcomings. It is differentiated between methodological inconsistencies and insufficiencies, implementation obstacles and challenges for data availability. All identified challenges and obstacles hinder a broader practical implementation and further development of LCSA.

Table 1: Summary of challenges and implementation obstacles for SLCA and LCC in the context of LCSA

	SLCA	LCC
Methodological inconsistencies	➢ Lacking consensus on which approach to follow (within this thesis defined as Type I, II and III)	➢ Inconsistencies due to several approaches (e.g. total cost accounting, cost-benefit analysis)
Methodological insufficiencies	➢ Missing definitions of subcategories (Type I assessments) ➢ Missing definitions of impact categories (Type I, II and III assessments)	➢ Missing impact level ➢ Missing definitions of economic AoPs ➢ Unresolved internalization approach
Obstacles for implementation	➢ Inconsistent implementation of indicators and/or subcategories ➢ Missing definitions of practicable indicators	➢ Inconsistent implementation of cost categories ➢ Unclear direction of indicators due to very narrow perspective

	SLCA	LCC
Challenges for data availability	➢ Limited secondary data sources in databases ➢ Available databases rather provide risk factors	➢ Limited secondary data sources in databases ➢ Confidential data – just a few published studies

Practical LCSA case studies are often incomplete, due to the challenges and obstacles identified within Table 1. As a result, case studies may not cover all three dimensions, they may not include the complete life cycle of products, they may neglect some impacts, or may not even state the relation between indicators and impacts (similar have been observed by Moriizumi, Matsui, and Hondo 2010; Heller and Keoleian 2003; Bienge et al. 2009; Heijungs, Settanni, and Guinée 2012). Only few LCSA studies have been conducted (e.g. Martínez-Blanco et al. 2014; Traverso et al. 2012), which contain inconsistencies due to different approaches followed within SLCA and LCC. This further leads to an apparently random selection of indicators. In addition, data gaps occur, which are based on incomplete databases or missing data sources for SLCA and LCC (compare section 2.2.1 and 2.2.2). They cause further obstacles for LCSA´s implementation due to missing secondary data needed for practical assessments, as indicated by Finkbeiner et al. (2010).

Following on the in Table 1 summarized obstacles of implementation, the selection of practical indicators can be seen as a prerequisite for a successful implementation of assessments. Indicators are something representing the state of a certain aspect or effect, which are used to measure a progress towards a stated goal, within life cycle based methods typically addressed through AoPs (compare section 2.1) (Turnbull et al. 2010; Parris and Kates 2003).

Taking into account the role of indicators within LCSA as described in Box 2.4, besides the general selection of suitable indicators, the chosen level of indicators matters. Generally, inventory, midpoint or endpoint indicators can be differentiated following the rationale presented in Box 2.1. According to the identified methodological challenges, especially the comprehensive inclusion of impact indicators (by means of midpoint and endpoint indicators) requires further developments in for SLCA and LCC.

Box 2.4: **Indicators within LCSA**

Indicators in general can function as variables, parameters, measures, measurement endpoints or thresholds and go normally beyond pure measurements or values (Heink and Kowarik 2010). Niemeijer and de Groot, (2008) collected different classifications and frameworks for defining indicators, which are quite diverse. Nonetheless, indicators have been mostly described as an instrument to measure a causal effect. Furthermore, indicators should be measurable, (policy) relevant, universally applicable and analytically resilient.

Considering LCSA, challenges emerge, as the process related nature of indicators shows tremendous differences. Whereas within LCA and LCC, indicators are almost solely of quantitative nature, indicators within SLCA can be qualitative, semi-quantitative or quantitative. Particularly, the first one provides challenges when targeting impact models following the rationale presented in Box 2.1. Therefore, inventory, midpoint and endpoint categories shall be differentiated for LCSA describing different stages along a cause-effect-chain. The related category indicators express the different categories by providing concrete quantitative measures. Accordingly, qualitative indicators may not apply for this purpose.

Targeting the alignment of the three dimensions by means of methodological developments, differences between the indicator levels need to be considered. Advantages and disadvantages can be named for the different category levels. Details can be taken from the excursus presented in Box 2.5 containing a general evaluation of midpoint and endpoint impact categories, but also remarks for the approach followed within this thesis. This sets the basis for the followed direction within section 2.3 and its subsections, which also functions as a prerequisite for chapter 3.

Box 2.5: **Midpoint and endpoint categories within LCA and LCSA**

Following the commonly adopted practice of LCA (compare Box 2.1), impact categories within life cycle based methods should cover the complete impact pathway by including inventory indicators, midpoint and endpoint categories (Bare et al. 2000; JRC 2010a). Inventory indicators are defined as simple variables (e.g. SO2 emissions), whereas midpoint impact indicators are seen as parameters in the environmental (social, economic) mechanism network (Bare et al. 2000). Endpoint impact indicators are understood as measurement endpoints determining damage levels (Jolliet et al. 2004).

Nevertheless, controversial discussions are ongoing, whether the inclusion of midpoint or endpoint impacts is expedient (Hutchins and Sutherland 2008). Within LCA, midpoint impact categories and indicators are commonly understood as scientifically valid and easier to measure, but lack informative values. In contrary, endpoint impact categories and indicators display tangible aspects (damage levels) and results (concrete amount of damage), but face challenges with regard to scientific validity (Bare et al. 2000; Hutchins and Sutherland 2008; Jolliet et al. 2004; Reap et al. 2008; Grießhammer et al. 2006; Jørgensen et al. 2008).

Considering the rationale of Box 2.5 and referring to the challenges with regard to LCA, which is the most advanced method within the LCSA framework (compare section 2.1); even greater obstacles can be expected for SLCA and LCC. For complex models like LCSA, the determination of quantitative endpoint categories and indicators appears challenging due to unclear interrelations along the impact pathways (Ingwersen et al. 2014). Bare et al. (2000) in this context stress that transparency is needed regarding the proven/agreed interrelations but also the value-choices made for determining the endpoint damage level. Midpoint categories and indicators for LCSA 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; Jolliet et al. 2004). Accordingly, transparency (and knowledge) tends to be higher at the midpoint level compared to endpoint approaches, as they are closer to the activities of stakeholders (Grießhammer et al. 2006). Therefore, the research and methodological developments of this thesis focus on the midpoint level, which will be further addressed in the following section.

2.3 LCSA topics covered in impact categories and indicators

Based on the findings presented in section 2.2.3, it appears plausible concentrating on the selection and definition of meaningful midpoint categories and the development of related midpoint indicators for all three dimensions of sustainability and their respective assessment tools. Therefore, within this section the second sub-target of the first research objective of this thesis is pursued (‘*Identification of relevant topics within LCSA*’).

Prior to the development of application-oriented concepts and the promotion of methodological developments to enhance LCSA´s implementation, (inventory) indicators, impact categories and models available need to be classified. Clustering of relevant topics (e.g. global warming, education or value-added) for the three methods – LCA, LCC and SLCA – is therefore required. Especially, topics for LCC and SLCA, even if broadly discussed, are rather vague and often not covered by impact categories or indicators, e.g. no concrete indicator for assessing fair wages nor a concrete impact category for covering economic value added exist. Thus, prioritization potentially helps to identify further research directions targeting the alignment of LCSA´s related methods. The identified impact categories and indicators out of the following sections 2.3.1 to 2.3.3, will serve as the basis for the criteria-based hierarchy in section 3.2 and the Tiered approach concept developed and introduced in chapter 3, which provides guidance on indicators and impact categories and serves as the basis for the pending research demands of LCSA.

2.3.1 Addressed impact categories and indicators in LCA

Various institutions (e.g UNEP 2013; Stocker et al. 2013; WMO 2013; OECD 2008b) address environmental topics, which have already been covered in environmental impact categories. Topics in LCA normally reflect environmental concerns affecting humans, animals and plants (Jolliet et al. 2004). More specifically, topics, like human health (in this thesis and connected to SLCA – see section 2.1.2), biotic natural environment and resources (addressing the species occurrence and dynamics), abiotic natural environment and resources (including non-living materials like water and mineral resources) are addressed. Jolliet et al. (2004) further list man-made (biotic and abiotic) environments covering e.g. agricultural and mining activities.

Several sub-topics have been identified describing pollution and preventative actions and determining relevant aspects and effects of the topics listed. Those include broadly known and accepted global warming considerations, which e.g. affect humans (through impacts on human health), biotic environments (through biodiversity loss) as well as biotic and abiotic resources (through decreased availability of resources); but also consider subordinated topics like ionizing radiation, which may affect man-made environments and is especially relevant for countries depending on nuclear-power-based electricity production (Jolliet et al. 2014).

Many of these topics have been implemented in common assessment practice by means of defined impact categories. Pre-selections of impact categories and indicators have been provided by several institutions and authors, like JRC (2011), UNEP & SETAC (2011), and Jolliet et al. (2014). As most of the defined midpoint impact categories and indicators are already included in common assessment practice, their application is not challenged in the context of this thesis.[15] 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 2010b). Table 2 displays a compilation of common midpoint impact categories of LCA, which are addressed within this thesis, including related indicators and impact models.[16]

Table 2: Exemplary selection of impact categories (including related indicators and impact models) at the midpoint level of LCA

Impact level	Impact category	Indicator & Indicator results	Impact model
Midpoint impact categories of LCA	Global climate change: Global warming[a] or Climate change[b]	Increase of infrared radiative forcing[c] & global warming potential [kg CO_2 eq.][a,b]	IPCC 2007[d]
	Stratospheric ozone depletion: Ozone depletion[a,b,c]	Increase of stratospheric ozone breakdown[c] or concentration[b] & ozone depletion potential [kg CFC-11 eq.][a,b]	WMO 1999 model[e]
	Acidification[a,b,c]	Increase in base saturation[g]/proton release (H+)[c] & acidification potential [kg SO_2	Various, e.g. RAINS10 or IIASA[a], ReCiPe[b], Seppälä[f]

[15] The focus within this thesis is set on developing the assessment practice and methodological robustness of SLCA and LCC.

[16] As pointed out in Box 2.5, endpoint categories and indicators provide several challenges. Therefore, the selection and development of proper endpoint categories and indicators will not be part of this thesis.

Impact level	Impact category	Indicator & Indicator results	Impact model
		eq.][a,b] or accumulated exceedance (AE)[f]	
	Eutrophication[a]: Terrestrial and aquatic[b] eutrophication	Increase of nitrogen concentration/algae growth[g] & eutrophication potential [kg PO_4 eq.][a] / [kg P/N eq.][b] or accumulated exceedance (AE)[f]	Various, e.g. CML[a], ReCiPe[b], Seppälä[f]
	Ozone formation: Photo-oxidant formation[a] or Photochemical oxidant formation[b]	Tropospheric ozone formation[a] / concentration increase[g] & photochemical ozone creation potential [kg C_2H_6 eq.][a]/Ozone formation potential [kg NMVOC eq.][b]	Various (but similar approaches), e.g. UNECE trajectory model[a] or LOTOS- EUROS model[b]
	Ecotoxicological impacts: freshwater ecotoxicity[h]	Average sensitivity of species (HC_{50} based on EC_{50}) & Ecotoxicity potential [CTU_e][h]	Scientific consensus model: USEtox[h]
	Resource depletion: Abiotic resource depletion[a]	Decreased resource availability & Abiotic depletion potential [kg Sb eq.]	Various (due to unclear resource definition), e.g. USGS economic reserve[a]
	Particulate matter	Intake fraction for fine particles [kg PM2.5 eq.]	RiskPoll model[g]
	Water use: Water footprint[i]	Vulnerability of basins to freshwater depletion[i] & water depletion index [$m^3_{depleted}/m^3_{consumed}$][i]	Various, e.g. WAVE model[i]
	Land use	Changes in soil organic matter[j] & deficit of soil organic matter [Mg/year]	Model based on soil organic matter

[a] (Guinée 2002) [b] (Goedkoop et al. 2009) [c] (ISO 14047 2002) [d] (IPCC 2007)
[e] (WMO 2013) [f] (Seppälä et al. 2006) [g] (JRC 2011) [h] (Rosenbaum et al. 2008)
[i] (Berger et al. 2014) [j] (Milà i Canals et al. 2007)

Even though for LCA a broad range of impact categories and indicators is available, some topics have not yet been sufficiently addressed or covered within life cycle impact assessment (LCIA). Primarily, this accounts for resource, land use and biodiversity impacts (Pennington et al. 2004; UN 2007; UNEP 2012). Especially the latter lacks proper definition and coverage (Klöpffer 2008; Curran et al. 2011; Souza, Teixeira, and Ostermann 2015). Further, consensus is missing regarding biodiversity´s allocation to the midpoint or endpoint level (UNEP 2012; JRC 2010a). Unlike biodiversity, resources and land use have been covered, but the methods available do not comprehensively include all relevant aspects. Similar accounts for ionizing radiation, where a first model with regard to human health has been suggested (Frischknecht et al. 2000; JRC 2011), but ecosystems have not yet been addressed. Therefore, within this thesis ionizing radiation is solely represented in context of human health in SLCA.

2.3.2 Addressed impact categories and indicators in SLCA

Review of current SLCA studies showed, that important and often considered topics refer to workers or working condition (often by studying working hours, child and forced labor, as addressed by e.g. Hauschild, Dreyer, and Jørgensen 2008; Dreyer, Hauschild, and Schierbeck 2006; Bienge et al. 2009; Ekener-Petersen and Finnveden 2013; Jørgensen, Lai, and Hauschild 2010). In this context, wage levels (by e.g. Kruse et al. 2009; Neugebauer et al. 2014; Musaazi et al. 2015) and health[17] (Norris 2006; Dreyer, Hauschild, and Schierbeck 2006; Bocoum, Macombe, and Revéret 2015) are usually named. Moreover, education (Weidema 2006; Neugebauer et al. 2014; Labuschagne and Brent 2006) and human rights, often in connection with gender equality and diversity, as pointed out by Bienge et al. 2009; Kruse et al. 2009, are mentioned, but have not yet been included into SLCA practice (Hutchins and Sutherland 2008). Institutions, like The World Bank 2015; ILO 2008; and OECD 2008b, broadly address those topics as well, which underlines the need to consider them within SLCA.

For covering those topics within SLCA, impact models and categories are needed. Although, the Guidelines of SLCA (Benoit and Mazijn 2009) name several impact categories, such as health or working condition etc. (compare section 2.1.2), their definition is vague. The categories proposed can only be understood as first suggestions and are therefore discussed within this section, as neither concrete definitions nor further description have been pro-

[17] Health provides some challenges with regard to its assignment to the midpoint or endpoint level. It can be reflected at both impact levels (midpoint and endpoint) displaying different impact and damage levels of human health (Goedkoop et al. 2009; JRC 2010a). As defined earlier within this thesis focus is set on midpoint impact categories and indicators. Therefore, health is primarily addressed in that context. Nevertheless, connections to the endpoint level of health are mentioned in the later context of methodological developments in chapter 4.

vided. It remains undefined how to characterize midpoint and endpoint categories and indicators. Accordingly, hardly any quantitative impact model has been provided, in accordance to the requirements presented in Box 2.1.

Some of the proposed impact categories relate to crucial topics of SLCA, which suggest their further consideration. The following paragraphs will clarify, which of those impact categories qualify for further consideration. Considering the above-mentioned studies, assignment to the midpoint level (according to the definitions presented in Box 2.5) is found to be justified for the following categories: working condition (following the definitions of Dreyer, Hauschild, and Schierbeck 2010; Kruse et al. 2009), fair wage (mainly following the suggestions of Neugebauer et al. 2014), health (following common LCA metrics like e.g. Rosenbaum et al. 2008), and education (mainly following the suggestions of Neugebauer et al. 2014). Even though human rights have not been included within an impact category, it has been broadly addressed in context with equality, dignity and diversity (Bienge et al. 2009; Kruse et al. 2009; Dreyer, Hauschild, and Schierbeck 2006; Jørgensen et al. 2008). Therefore, human rights should also be covered within a separate midpoint category, as it has been identified as important by several studies.

Further impact categories, such as equal opportunities, safety, cultural heritage or governance (Benoit and Mazijn 2009) need further contemplation regarding their general consideration and allocation to the midpoint or endpoint level. Although, equal opportunities are an important aspect of social considerations, those may be inherently covered within other impact categories following the definition of Blok et al. 2013, e.g. education, fair wage or human rights. Therefore, the topic of equal opportunities is not included as a separate midpoint category.

Safety, if related to working environments, mostly describes health aspects due to accidents or hazardous materials and further aspects, such as hygiene and accident prevention. Therefore, it can better be covered within the categories working condition or health to avoid double-counting. In contrast (social) security considerations, which currently are also summarized under safety should be covered in a separate impact category. (Social) security considerations are described in the convention of the International Labour Organization (1952) and address aspects, like insurances, sickness and unemployment benefits. In accordance with the definitions of Bienge et al. 2009 and Weidema 2006, social security includes work related issues, like contracts, but also social services, like pensions and further social provisions. Therefore, it is defined as an additional midpoint impact category, even though further considerations will be necessary.

Socio-economic repercussions have been mentioned in connection with HIV/AIDS (Isaksen, Songstad, and Spissoy 2002) or climate change (IPCC 2007). Both topics, in the context of SLCA, are closely related to aspects of human health. Thus, socio-economic repercussions can be covered within the impact category health. Therefore, within this thesis no standalone impact category for socio-economic repercussions is defined.

Cultural heritage, even if broadly discussed, has only rarely been included in case studies. Yet, Ekener-Petersen and Finnveden (2013) address it within their social hotspot analysis of laptop computers. They consider connections to resource extraction, refining and recycling. Hunkeler, Rebitzer, and Lichtenvort (2008) mention cultural heritage in connection with infrastructural projects. Weidema (2006) refers to cultural heritage in connection with migration and man-made environment. Therefore, cultural heritage is included as a midpoint category for SLCA, as it describes impacts on local communities, which in its severity is not the case for any other midpoint impact category defined for SLCA.

A compilation of all SLCA midpoint categories considered within this thesis can be taken from Table 3. The table also includes available indicators and impact models. Respective sources can be taken from the table footnotes.

Table 3: Exemplary selection of impact categories for SLCA (including available indicators and impact models) at the midpoint level

Suggested midpoint impact category	Potential (quantitative) indicators	Impact models available	Impact pathway definition
Health[a]	Various, e.g. Humantoxicity potential [CTU_e][b] or Ionizing radiation potential [man*Sv][c]	Various, e.g. Ionizing radiation model[c] or scientific consensus model USEtox[b]	Various, e.g. ReCiPe[c] or LIME[d]

Suggested midpoint impact category	Potential (quantitative) indicators	Impact models available	Impact pathway definition
Fair wage	Relative indicator comparing lowest/highest wage with minimum wage and living wage[e] or absolute fair wage value depending on expenses to be covered[g]	Relative scaling model[e]	First qualitative impact pathways[e,f]
Education	Absolute sub-indicators determining different levels of education[e] or correlation-based necessity indicator expressed in working hours needed[h]	Qualitative impact model[e]	First qualitative impact pathways[e]
Working condition	Descriptive indicators describing societal values related to working conditions[g] or labor rights and indicators reflecting issues like overtime, benefits etc.[i,j] are available	None	None
Human rights	Qualitative indicators referring to discrimination, forced labor etc.[j]	None	Exemplary consideration of human right aspects within impact pathways, e.g. by means of equality or discrimination[j]
(Social) security	None	None	None
Cultural heritage	None	None	None

[a] As described in the previous section, but also in section 2.1.2 human health aspects are included in SLCA. Earlier developed LCA-based impact categories can in this context serve as first approximations, as long as no comprehensive SLCA-based impact categories will have been achieved.
[b] (Rosenbaum et al. 2008) [c] (Goedkoop et al. 2009) [d] (Pennington et al. 2004)
[e] (Neugebauer et al. 2014) [f] (Jørgensen 2010) [g] (Kruse et al. 2009)
[h] (Hunkeler 2006) [i] (Dreyer, Hauschild, and Schierbeck 2010) [j] (Jørgensen et al. 2008)

Unlike the midpoint categories defined within LCA, which have been defined in characterization models and addressed in case studies, most of the named midpoint impact categories within the SLCA Guidelines (Benoit and Mazijn 2009) have never been defined in detail nor have they been mentioned by SLCA case studies. Therefore, within this thesis these suggested midpoint categories (resource productivity, autonomy, participation and governance) are neglected. Resource productivity has been excluded, as resource aspects should rather be covered within LCA or LCC (see section 2.3.1 and 4.2.3.1). Autonomy according to Guidelines of SLCA (Benoit and Mazijn 2009) relates to human rights and should thus be indirectly covered within this impact category. Participation, even though it is relevant for workers' motivation on the corporate level; its relevance and modelling aim remain unclear. So far, participation has only been connected to the representation of stakeholder positions but not yet to any social impacts (Grießhammer et al. 2007). Therefore, participation is not regarded as an additional impact category within this thesis. The same applies to governance, which has neither been included in existing SLCA studies nor have related assessment targets or scope been defined. Following the description within the methodological sheets (Benoît et al. 2013) governance can be either regarded within the impact category 'working condition', but may also apply to the economic dimension of LCSA.

2.3.3 Addressed cost categories and indicators in LCC

Unlike LCA and SLCA, impact categories have not yet been defined for LCC nor implemented in common assessment practice. Instead, different cost categories are generally considered in LCC practice (compare section 2.1.3). Those cost categories can reflect different life cycle stages and different perspectives addressing the different stakeholders within the supply chain. Commonly included in LCC (e.g. by Ristimäki et al. 2013; Martínez-Blanco et al. 2014; Traverso et al. 2012) are: production costs (often including material, manufacturing and labor costs), consumer costs (commonly including usage and maintenance costs) and EoL costs (including dismantling cost and costs for further treatments). Further costs, such as R&D or investment costs may not as frequently be included. Yet, published case studies exist, which include R&D costs, e.g. as shown by Ilg, Hoehne, and Guenther (2015). The same applies to costs, like subsidies or capital costs, which have been included, e.g. by Woon and Lo (2016). Furthermore, the consideration of internalized external costs in case they are expected to be decision relevant (e.g. taxes), as stressed by e.g. Klöpffer (2008), has been performed by e.g. Bovea and Vidal (2004). Yet, in current assessments implementation of these costs remains unclear due to inconsistent definitions. In addition to those common cost categories, several authors included value added as an additive economic indicator broadening the view of LCC

(Kruse et al. 2009; May and Brennan 2006; Heijungs, Settanni, and Guinée 2012; Thomassen et al. 2009; Jeswani et al. 2010; Wood and Hertwich 2012). Value added in this sense could be understood as a first impact indicator, also following the definition of Hunkeler, Rebitzer, and Lichtenvort (2008) and the understanding of Wood and Hertwich 2012; and May and Brennan 2006. Even though no impact level or categories have officially been implemented for LCC, economic resilience and economic prosperity have been already named as economic impacts by Hunkeler, Rebitzer, and Lichtenvort (2008) (see Table 4). The same can be said of economic target functions, as May and Brennan (2006) described wealth generation as a target for economic assessments.

Table 4 summarizes the cost categories used, and impact categories and target functions named for LCC and ranks them according to their status of implementation. Due to the different approach of LCC in comparison to LCA and SCLA, a different structure is presented within this table. While LCA already includes sufficient impact categories and characterization models and SLCA contains different proposals for impact categories, LCC is limited to different cost categories included in common assessments. Therefore, the table provides the cost categories commonly regarded within assessments, as well as first proposals of impact categories and target functions for future reference, which will again be taken up within the methodological developments in chapter 4.

Table 4: Representation of cost and impact categories and one target function for LCC

	Implemented within assessments	Proposed for future reference
Cost category[a]	Production costs, normally including material, manufacturing and labor costs[b]	
	Consumer costs, normally including usage and maintenance costs[c]	
	EoL costs[d]	
	R&D costs[e]	
	Further costs (including subsidies, capital costs etc.)[f]	
	Internalized external costs (e.g. through taxes)[g]	
	Value added[h]	

	Implemented within assessments	Proposed for future reference
Potential impact category		Economic resilience[i]
		Economic prosperity[i] (GDP/GNP changes)
Potential target function		Wealth generation[j]

[a] The cost categories considered follow the structure of Hunkeler, Rebitzer, and Lichtenvort (2008).
[b] Broadly considered e.g. by Ristimäki et al. 2013; Kruse et al. 2009; Amienyo and Azapagic 2016; Martínez-Blanco et al. 2014; Traverso et al. 2012
[c] Addressed e.g. by Ilg, Hoehne, and Guenther 2015; Ristimäki et al. 2013; Kruse et al. 2009.
[d] Addressed e.g. by Ilg, Hoehne, and Guenther 2015; Amienyo and Azapagic 2016
[e] Addressed by e.g. Curran, Raghunathan, and Price 2004; Ilg, Hoehne, and Guenther 2015
[f] Considered e.g. by Martínez-Blanco et al. 2014; Woon and Lo 2016
[g] Considered e.g. by Bovea and Vidal (2004), and somehow addressed e.g by Erlandsson and Borg 2003; Hofstetter and Müller-Wenk 2005
[h] Suggested by Kruse et al. 2009; May and Brennan 2006; Heijungs, Settanni, and Guinée 2012; Thomassen et al. 2009; Jeswani et al. 2010; Wood and Hertwich 2012
[i] Hunkeler, Rebitzer, and Lichtenvort (2008) proposed the two impact categories, without providing further description or definition.
[j] Wealth generation in context of LCC has been mentioned by May and Brennan (2006).

2.3.4 Concluding remarks on LCSA´s covered topics

After identifying LCSA´s implementation challenges and summarizing specific obstacles of SLCA and LCC in Table 1 of section 2.2.3, such as lacking consensus on the common approach or inconsistent implementation of indicators, the thorough selection of indicators has been identified as an important step towards LCSA´s enhancement. By means of a thorough selection of impact categories and indicators, the entrance level of LCSA can be lowered, which has been identified as an important aspects for its practical implementation (Finkbeiner et al. 2010; Pesonen and Horn 2012). Finkbeiner et al. (2010) state that there is a need for simplifying the access to LCSA for increasing its usage. Pesonen and Horn (2012) agree with this view and stress that the complexity of existing methods is the main obstacle for industry decision makers to implement life cycle based methods for assessing sustainability.

On this basis, section 2.3 served as a prerequisite by displaying available or described impact categories for LCA and SLCA as well as cost categories for LCC. The identified impact/cost categories and indicators serve as the basis for the criteria-based hierarchy in section 3.2 and the Tiered approach concept developed and introduced in chapter 3, by which suggestions are provided on how to lower the entrance level of LCSA.

3 Tiered approach concept

After introducing the idea and concept of the Tiered approach, a criteria-based indicator hierarchy is presented based on the identified impact and cost categories of section 2.3. Therefore, within this chapter the second research objective of this thesis (‘*Development of a selection process by means of a conceptual approach*’) is addressed. A prioritized selection of categories and indicators and is presented in section 3.2 functioning as a prerequisite for the indicator hierarchy. Therewith, the first sub-target of the second research objective (‘*Ranking of relevant LCSA topics*’) is pursued. The LCSA impact/cost categories and indicators are then assigned to three tiers, by which means the second sub-target (‘*Guided selection of impact categories and indicators to enable a stepwise implementation of LCSA*’) is addressed. At the end of this section, remaining methodological challenges are named, introduced by Neugebauer et al. (2015) and others, laying the foundation for the methodological improvements of chapter 4.

The Tiered approach concept is part of the publication of Neugebauer et al. (2015), article section 3. The findings of the cited paper; reprinted, partly adapted, updated and complemented with permission of Elsevier B.V. (https://www.elsevier.com/about/company-information/policies/copyright); are summarized in this chapter. The achieved results are based on the original article complemented by new findings in accordance to latest studies published.

3.1 Idea and development of the Tiered approach concept

With the Tiered approach concept and its indicator hierarchy in three tiers, a first step in solving the dilemma of indicators´ selection in LCSA can be undertaken. Therewith, the Tiered approach allows for a structured implementation of LCSA, which can lead to a more consistent and quicker implementation-related and methodological-wise enhancements. A thorough selection of topics representing the three dimensions and considering defined impact categories, indicators and data available appears to be crucial in the context of those enhancements. Assuming that at least (inventory) indicators are available for all three dimensions, the judgement of Niemeijer and de Groot, (2008) appears valid, who conclude that the bottleneck for assessments is not the lack of good indicators or good science, but rather the lack of a clear selection process. This selection process should also include consideration of available data sources, as needed data are sometimes not or only partly available (Finkbeiner et al. 2010).

In accordance with the second research objective of this thesis, the two main targets of this section are:

1. To provide a thorough selection of impact categories and indicators for LCSA representing the three dimensions, and
2. To ensure data availability for the selected impact categories and indicators.

The currently occurring lack of focus on certain (most relevant) aspects leads to shortcomings in target oriented method development (Niemeijer and de Groot 2008). The prioritization in three tiers subsequently to the impact/cost categories´ selection allows for this focus, which indicates directions for further methodological-wise enhancements. Therefore, a subordinated target, which is linked to but goes beyond the Tiered approach and relates to the third objective of this thesis (see Introduction), can be defined:

3. Initiate related method developments with regard to impact and characterization models.

Following on the first and second target, the Tiered approach strives to enhance LCSA´s assessment practice towards a more holistic approach and away from single dimension assessments. Under the assumption that assessments subsist on continuity, a stepwise approach such as the Tiered approach allows for a simplified access into LCSA. Similar could been observed for LCA. Popularity and propagation of the simplified Carbon Footprint method promoted LCA by lowering the entrance level and by providing incentives for the consideration of further environmental aspects (Finkbeiner 2009). Afterwards, the achieved simplification can serve as a starting point for stepwise methodological enhancements.

Therefore, the differentiation in three tiers was found suitable for achieving the above-mentioned targets. The tiers are defined starting with easy but meaningful indicators on *Tier 1* (‘sustainability footprint’), proceeding with a state-of-the-art indicator set at *Tier 2* (‘best practice’), concluding with a comprehensive set of indicators at *Tier 3* (‘comprehensive assessment’) (see Figure 9). Accordingly, Tier 1 assessments are the easiest to implement, Tier 2 already provides some challenges and Tier 3 cannot be applied without further efforts to tackle data gaps and prevalent drawbacks of the LCSA framework. To provide an example: global climate change is easier to assess within an LC(S)A study than ecotoxicity impacts, due to its high data availability, high public awareness and the maturity of its characterization method

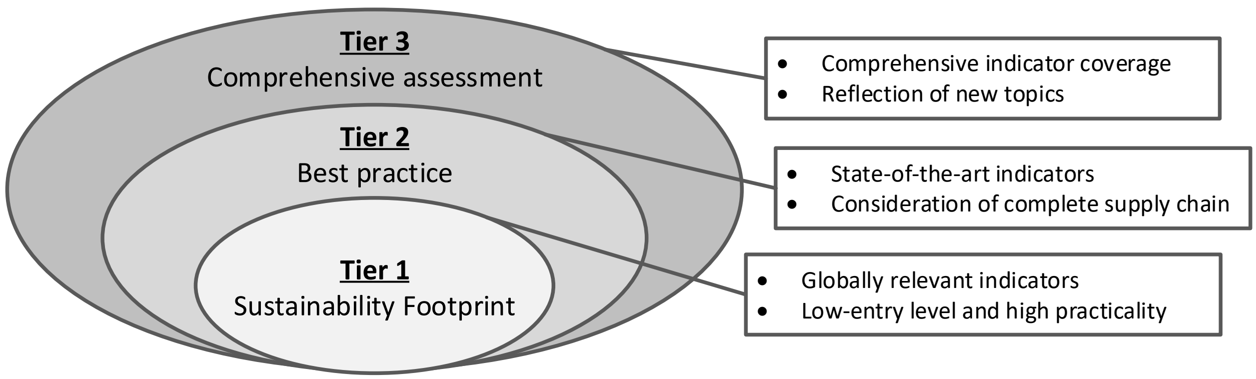

Figure 9: Tiered approach structure including significant characteristics of the three tiers

The so-called ‘sustainability footprint’[18] considers all three sustainability dimensions by including a limited number of indicators (more detailed descriptions follows in section 3.3). The ‘sustainability footprint’ targets the inclusion of highly practical indicators to ensure its implementation. After the first step in LCSA has been mastered, Tier 2 and 3 successively complete the assessment by adding more indicators.

The next section provides a criteria-based indicator hierarchy. Thereafter, the identified indicators and respective impact categories are classified in three tiers in accordance to the criteria-based evaluation. Based on this guidance methodological developments (if needed) can

[18] In general a footprint can be described as a measure of how human activities create different kinds of burdens (Čuček, Klemeš, and Kravanja 2012). Enlarged for LCSA, the environmental, economic, and social dimension need to be included. Accordingly, for the sustainability footprint it is focused on the principle followed by the carbon footprint approach: Simple but valid and applicable indicators should be included.

be initiated, which then allows for a stepwise implementation of LCSA. Based on the definition of the three tiers a discussion and critical reflection of the concept is applied, followed by the identification of further research needs to enable LCSA´s implementation.

3.2 Criteria-based hierarchy of impact and cost categories

The criteria-based indicator hierarchy embodies the heart of the Tiered approach concept. The impact categories and indicators identified in section 2.3 are ranked through a criteria-based ranking. Focus is set on midpoint categories, or respectively cost categories for LCC, following the rationale of Box 2.5. For enabling a meaningful ranking and subsequently reasonable assignment to the three tiers within the Tiered approach concept, three criteria are included:

1. Practicality of the indicator representing the impact category
2. Relevance of the impact category
3. Method robustness of the impact category and/or indicator

Similar criteria have already been proposed by Jolliet et al. (2014) within their 'Global guidance on environmental LCIA indicators (…)'. Therein, they define the criterion *Applicability* (here named *Practicality*) by considering if inventory data are available. *Relevance* is described through the importance of overall (environmental) impacts. The criterion *Scientific validity* (here called *Method robustness*) describes the maturity of science behind the method.

In the context of this thesis, those criteria are now applied to the LCSA context, going beyond LCA. Therefore, *Practicality* refers to data availability and/or the societal awareness of the method. *Relevance* describes the relative importance of the impact category (additionally considering the suggestions of Niemeijer and de Groot 2008), which can be measured by the citation of topics by international organizations and institutions. *Method robustness* evaluates the scientific validity of the impact and characterization models available. The ranking of the impact categories and indicators is performed by determining the general fulfillment of the criteria. Three degrees of fulfillment are defined: high, medium and low accordance.

As the practical implementation of LCSA has been described as a major target, 'practicality' embodies the most important criterion.[19] As social and economic topics are not comprehensively covered within impact models, the measuring of 'method robustness' includes shortcomings. The same applies for 'relevance' criterion in the context of LCC. LCC´s relevance and methodological improvements is difficult to determine, as impact models are missing and related topics are rarely discussed. Therefore, focus is set on the practicality of the different cost categories identified. The focus according to Hunkeler, Rebitzer, and Lichtenvort (2008) is to be set on such costs, which are important to assess the economic performance of products and processes. Generally, the impact categories´ and indicators´ practicality decreases from Tier 1 to Tier 3. The same does in general apply for the other two criteria *Method robustness* and *Relevance*.

The following subsections display the criteria-based indicator ranking respectively for the LCA, SLCA and LCC. The findings are mainly based on the supplementary material presented in the study of Neugebauer et al. (2015). The results can be taken from the following tables (Table 5 to Table 7). Further and more detailed descriptions are provided within the sections 3.3 to 3.5.

3.2.1 Criteria-based ranking of impact categories in LCA

This section contains the hierarchy of impact categories for LCA, which was first presented within the supplementary material of Neugebauer et al. (2015). The criteria-based ranking is performed through a colored gradation. Green coloring shows a high correspondence; light green coloring indicates a lower correspondence. Blue coloring shows a medium correspondence, light blue coloring lower medium correspondence and so forth. Table 5 displays the ranked LCA midpoint impact categories starting with the most important ones.

[19] Note that impact categories rated with high practicality do not automatically contain mature methods (which is rated under method robustness), but rather promising conditions data-wise. Thus, for performing a consistent assessment, in accordance with the description of Box 2.1, still some methodological improvements are necessary.

Table 5: Criteria-based indicator hierarchy for the LCA midpoint impact categories

Impact category	Practicality[a]	Relevance[a]	Method robustness[a]
Global climate change	Overall high awareness, e.g. through carbon footprint approaches Data and LCI in many LCA software tools available	Addressed within the sustainable development goals[b] Confirmed relevance due to Kyoto protocol[c] Classified as highly relevant by e.g. UNEP[d], OECD[e], WMO[f], WRI[g], EEA[h], EPA[i], UBA[j]	Overall consensus about IPCC2007[k] model Ranked as Level I by the ILCD handbook[l]
Stratospheric ozone depletion	Broad awareness, e.g. due to UBA[j] campaigns Data and LCI in many LCA software tools available	Confirmed relevance due to Montreal protocol[m] and Gothenburg protocol[n] Classified as relevant by e.g. WMO[f], UNEP[d], OECD[e], EPA[i], EEA[h]	Overall consensus about WMO1999[o] model Ranked as Level I by the ILCD handbook[l]
Ozone formation	Broad awareness, e.g. due to UBA[j] campaigns and seasonal information (summer smog) Data and LCI in many LCA software tools available	Confirmed relevance due to Gothenburg protocol[n] Represented within air quality indices (compare Kyrkilis et al.)[p] Classified as relevant by e.g. WHO[q], UNEP[d], UNECE[r], EPA[i], EEA[h], UBA[j]	Different but similar characterization models available (compare Table 2 and ILCD handbook[l]) Ranked as Level II by the ILCD handbook[l]
Eutrophication	Increasing awareness according to Rönnberg, Selman and Greenhalgh, and Carvahlo[s] Data and LCI in many LCA software tools available	Confirmed relevance due to Gothenburg protocol[n] Classified as relevant by e.g. UNEP[d], OECD[e], WRI[g], UNECE[r] Identified as relevant for agricultural processes by e.g. Tynkkynen et al, Velthof et al. and Khan[t]	Characterization models available, but no consensus (compare Table 2) Ranked as Level II by the ILCD handbook[l]
Acidification	Awareness due to past acid rain cases (EPA[i], EEA[h]). Data and LCI in many LCA software tools available	Confirmed relevance due to Gothenburg protocol[n] Implemented in the Directive on “Ambient Air Quality and Cleaner Air for Europe”[u]	Characterization models available, but no consensus (compare Table 2) Ranked as Level II by the ILCD handbook[l]

Impact category	Practicality[a]	Relevance[a]	Method robustness[a]
		Classified as relevant by e.g. OECD[e], UNECE[r], EPA[i], EEA[h]	
Particulate matter	Increasing awareness according to EPA[i] and UBA[j] Few data and LCI in LCA software tools available, but with uncertainty	Defined air quality limits by i.a. the European Commission[u] Identified as relevant by e.g. EPA[i], EEA[h], UNEP[d]	Characterization models available, but no consensus (compare Table 2) and a certain inherent uncertainty Ranked as Level I by the ILCD handbook[l]
Ecotoxicological impacts[v]	Lacking awareness due to missing assessment practice Data are partly provided within LCA software, Risk of neglecting substances	Part of the Reach program and the Basel Convention[w] Identified as relevant by e.g. EPA[i], EEA[h], UNEP[d], UBA[j]	Somehow consensus on USEtox model[x], even though the model contains a certain inherent uncertainty Ranked as Level II to III by the ILCD handbook[l]
Land use	Lacking awareness due to missing assessment practice Data are partly provided within LCA software, Risk of neglecting substances	Indirectly addressed within the sustainable development goals[e] Addressed by Kyoto protocol[c] Part of the REED programme[y] Identified as relevant by e.g. UN[z], FAO[aa], EEA[h]	First (inconsistent) (characterization) models (e.g. Mila i Canals et al.)[bb] Ranked as Level III by the ILCD handbook[l]
Water use	Increasing awareness due to the efforts of the water footprint network (Hoekstra et al.)[cc] Data are partly provided within LCA software	Identified as relevant by e.g. UN[z], FAO[aa], OECD[e], UNEP[d], UBA[j], EPA[i], UNECE[o].	Characterization models available (e.g. Berger et al.)[dd] WULCA consensus model in progress[ee]
Resource depletion	Data are partly provided within LCA software, Risk of neglecting substances	Adressed within the ProgRess program[ff] Forest, fishery and energy resources identified as relevant by OECD[e], UNEP[d]	Unclear impact category definition and consideration of different resource types (compare ILCD handbook[l]) Ranked as Level II by the ILCD handbook[l]

[a] Criteria gradation in high, medium and low correspondence through coloring including nuances.
[b] (UN 2016a) [c] (United Nations 1998) [d] (UNEP 2012; UNEP 2013) [e] (OECD 2008b)
[f] (WMO 2013) [g] (Watson et al. 2005) [h] (EEA 2005) [i] (EPA 2012)
[j] (Schwermer 2007; Graff et al. 2014) [k] (IPCC 2007) [l] (JRC 2011)
[m] (UNEP 2007) [n] (UNECE 2012) [o] (van der Voet, De Bruyn, and Tukker 2009)
[p] (Kyrkilis, Chaloulakou, and Kassomenos 2007) [q] (Mücke 2008) [r] (UNECE 2016c)

[s] (Rönnberg and Bonsdorff 2004; Selman and Greenhalgh 2009; Carvalho and Moss 1995)
[t] (Tynkkynen et al. 2014; Velthof et al. 2014; Khan and Mohammad 2014) [u] (EC 2005)
[v] Humantoxicological impacts are included in SLCA, as the display impacts on human health.
[w] (Basel Convention 2011; European Chemicals Agency 2016) [x] (Rosenbaum et al. 2008)
[y] (UNEP 2016) [z] (United Nations 2012) [aa] (FAO 2014) [bb] (Milà i Canals et al. 2007)
[cc] (Hoekstra et al. 2009) [dd] (Berger et al. 2014) [ee] (Boulay et al. 2016) [ff] (UBA 2012)

3.2.2 Criteria-based ranking of impact categories in SLCA

This section contains the hierarchy of impact categories for SLCA, first presented within the supplementary material of Neugebauer et al. (2015). The criteria-based ranking is performed through a colored gradation. Green coloring shows a high correspondence; light green coloring indicates a lower correspondence. Blue coloring shows a medium correspondence, light blue coloring lower medium correspondence and so forth. Table 6 displays the ranked SLCA midpoint impact categories representing the social dimension of LCSA.

Table 6: Criteria-based indicator hierarchy for the SLCA midpoint impact categories

Impact category	Practicality[a]	Relevance[a]	Method robustness[a]
Fair wage	Overall high awareness, e.g. through Sweat free communities and Wageindicator Foundation[b] Data are provided by e.g. ILO, The World Bank, and WSI[c] Applicability is straightforward, as wage assessment consists on a limited number of values.	Indirectly addressed within the sustainable development goals[d] Addressed by e.g. the Fair Wage Network[e] Identified as relevant by e.g. The World Bank (2014), ILO (ILO et al. 2012), UNEP/SETAC (2009)[f]	Qualitative characterization model available (compare Table 3)
Health	High awareness, but missing consensus on which health aspects to consider Data are partly provided by LCA software and UNECE, World Bank and WHO[g] High risk of neglecting health aspects	Addressed within the sustainable development goals[d] Identified as generally relevant by e.g. WHO, OECD, UBA[h] Identified as relevant in connection with safety & health and working environments by ILO[i]	LCA-based characterization models available (compare Table 3); however, those mostly contain uncertainties e.g. Humantoxicity
Education	High awareness, but missing consensus on how to determine education	Addressed within the sustainable development goals[d] Identified as relevant by e.g. The World Bank, ILO,	Qualitative characterization model available (compare Table 3)

Impact category	Practicality[a]	Relevance[a]	Method robustness[a]
	Data are provided by e.g. UNESCO, The World Bank, OECD, ILO[j] Relation to functional unit seems challenging	OECD, UNESCO, UNECE, AERA[k]	
Working condition	High awareness, but missing consensus on how to determine working condition Data are mostly limited to working hours and are provided by ILO and The World Bank[l] Aspects, like child labor, forced labor or accidents tend to be randomly considered.	Addressed within EUROFOUND[m] and UN Global compact[n] Identified as relevant by e.g. ILO, The World Bank and OECD[o]	No characterization model available, but first indicators relating to working condition and labor rights (compare Table 3)
(Social) security	Awareness due to governmental actions (e.g. social security administration of the USA)[p] Partly, data can be taken from e.g. ILO[q] Relation to functional unit seems challenging	Indirectly addressed by UNECE within the protocol of civil liability[r] Addressed by ILO via safety at work and social security and by World Bank via social protection and labor[s]	No characterization model available (compare Table 3)
Human rights	High awareness, but various aspects to be considered, which may also be based on value choices Labor related data can be taken from e.g. ILO[t] Relation to functional unit seems challenging	Addressed within UN Global compact[n] Identified as relevant by Human Rights Watch and Amnesty International and the UN[u]	No characterization model available (compare Table 3)
Cultural heritage	Awareness appears to be low (from a European point of view) Data sources are hard to determine Relation to functional unit seems challenging	Addressed in programs like JPI Cultural Heritage[v] Addressed by governmental organizations, e.g. Ministry for Cultural heritage NZ and by UNESCO[w]	No characterization model available (compare Table 3)

[a] Criteria gradation in high, medium and low correspondence through coloring including nuances.
[b] (University of Amsterdam 2014; SweatFree 2013) [c] (ILO 2010c; Schulten 2014; The World Bank 2015)
[d] (UN 2016a) [e] (FWN 2016) [f] (ILO et al. 2012; The World Bank 2014b; Benoit and Mazijn 2009)
[g] (The World Bank 2016b; WHO 2016; UNECE 2016c) [h] (UBA 2016; WHO 2016; OECD 2016)
[i] (ILO 2011b) [j] (ILO 2010a; UNESCO 2011; OECD 2012; The World Bank 2013)

[k] (AERA 2016; UNECE 2016b) [l] (The World Bank 2016a; ILO 2011b)
[m] (Eurofound 2013) [n] (UN 2016b) [o] (OECD 2008b) [p] (United States 2016)
[q] (ILO 2016b) [r] (UNECE 2016a) [s] (The World Bank 2016d)
[t] (ILO 2016a) [u] (Human Rights Watch 2016; Amnesty International 1998; UN 2016b)
[v] (JPI Cultural Heritage 2016) [w] (UNESCO 2016b; UNESCO 2016a; NZ Government 2016)

3.2.3 Criteria-based ranking of cost categories in LCC

This section contains the indicator hierarchy, which was first presented within the supplementary material of Neugebauer et al. (2015). The criteria-based ranking is performed through a colored gradation. Green coloring shows a high correspondence; light green coloring indicates a lower correspondence. Blue coloring shows a medium correspondence, light blue coloring lower medium correspondence and so forth. Table 7 displays the ranked LCC cost categories representing monetary aspects of the economic dimension of LCSA. The two criteria 'method robustness' and 'relevance' are hard to determine or more specifically are not applicable, as no impact level has been included and no justification has been provided by the scientific community, yet. An exception is provided by the earlier mentioned value added (compare sections 2.1.3 and 2.3.3), which has a certain relevance in connection with economic performance (compare e.g. May and Brennan 2006; Wood and Hertwich 2012). It is thus additionally included, even though it has not been part of the original article of Neugebauer et al. (2015). The change will be further justified in section 3.3, where also the value added term is described in more detail.

Table 7: Criteria-based indicator hierarchy for the LCC (impact) and cost categories

Impact category	Practicality[a]	Relevance[a]	Method robustness[a]
Value added	Data are provided by management accounting practice[b] and partly by The World Bank[c]	Economic values are e.g. addressed by the Global Reporting Initiative and the International Monetary Fund[d]	No characterization model available, but first (impact) indicators for value added have been proposed (compare Table 4, section 2.3.3).
Production cost (including e.g. material, manufacturing and labor costs)	Data are provided by management accounting practice[b]	Not applicable	Not applicable
Consumer costs	Data are available through purchase prices; however, price volatility can provide challenges[e]	Not applicable	Not applicable

Impact category	Practicality[a]	Relevance[a]	Method robustness[a]
EoL costs	Data may be available through waste management and recycling management documents, but are usually not included in the price[f]	Not applicable	Not applicable
R&D costs	These costs are not directly related to the production and thus assumedly harder to assess[g]	Not applicable	Not applicable
Further costs (including subsidies, capital costs etc.)	These costs are not directly related to the production and thus assumedly harder to assess (compare Table 4) Relation to functional unit seems challenging	Not applicable	Not applicable
Internalized external costs (e.g. through taxes)	These costs are not directly related to the product (e.g. taxes) and thus assumedly harder to assess (compare Table 4) Relation to functional unit seems challenging Risk of double-counting may occur	Not applicable	Not applicable

[a] Criteria gradation in high, medium and low correspondence through coloring including nuances.
[b] (Bovea and Vidal 2004; Heijungs, Settanni, and Guinée 2012)
[c] (The World Bank 2016c)
[d] (Global Reporting Initiative 2013; Bems and Johnson 2015)
[e] (Heijungs, Settanni, and Guinée 2012)
[f] (Klöpffer 2008)
[g] (Rebitzer and Hunkeler 2003)

3.3 Tier 1

Following the findings of the previous section and the targets defined in section 3.1, Tier 1 of the Tiered approach concept targets to lower the entrance level of LCSA and should consider impact categories or at least (inventory) indicators for all three dimensions. A lowering of the entrance level is likely to be achieved by focusing on the applicability of impact categories and indicators. Thus, indicators with high practicality (according to the criteria-based hierarchy presented in section 3.2.1) and good data availability are to be selected. Accordingly, the 'sustainability footprint' includes well-known impact categories and indicators also easing the understanding for non-expert practitioners. The indicator hierarchy presented in section 3.2.1 provides the necessary basis for choosing suitable impact and cost categories.

Global climate change as a midpoint impact category was found suitable for representing the environmental dimension within Tier 1. The impact category ‘global climate change’ showed high correspondence with all three criteria, as shown in section 3.2.1. Especially, practicality can be rated as high through broadly applied carbon footprint methods (compare e.g. Wiedmann and Minx 2008 or Dalgaard et al. 2014), but also relevance, as indicated by the Kyoto protocol (United Nations 1998) and others (e.g. IPCC 2013).

According to Wiedmann and Minx 2008; Galli et al. 2012; Lam, Varbanov, and Klemeš 2010, climate change has become one of the most important environmental topics and indicators. In addition, the sustainable development goals (UN 2016a) define climate change as a global challenge underlining the pressing need to consider it within assessments. This need is further emphasized by various organizations, such as the Intergovernmental Panel on Climate Change (IPCC 2013), the World Meteorological Organization (WMO 2013), the Organisation for Economic Co-Operation and Development (OECD 2008a), or the United Nations Environment Programme (UNEP 2014). Correspondingly, high awareness (and also knowledge) across stakeholder (groups) underpins the good applicability of global climate change indicators. Inventory data and characterization factors for those indicators are widely available (Goedkoop et al. 2009; Guinée 2002) and have already been implemented in common LCA software (e.g. GaBi 6.0) and carbon footprint calculators (e.g. provided by the WWF)[20].

Even though the general importance of global climate change is convincing, some cases can require additional considerations. Agricultural processes are for instance rather driven by phosphorus and nitrogen emissions through fertilizer use (Velthof et al. 2014; Tynkkynen et al. 2014). Thus, ‘eutrophication’ as an impact category may be more suitable for such cases instead of climate change and should be additionally considered at Tier 1. Although eutrophication’s practicality and method robustness lies beneath that of global climate change, gen-

[20] The calculator can be accessed under http://footprint.wwf.org.uk

eral awareness of its risks and causes have been generally increasing in recent years. Eutrophication is one impact driver in agricultural production and also functions as an indication for biodiversity loss (Hodgson et al. 2014; Jolliet et al. 2014). Applicability is ensured through common LCA software tools. Inventory data and characterization factors for related indicators are also available (Goedkoop et al. 2009; Guinée 2002).

Fair wage as a midpoint impact category appears to be suitable for representing the social dimension within Tier 1. It showed high compliance with two of three criteria[21] (compare section 3.2.2), which is the highest ranking of the social midpoint impact categories considered. Especially, for practicality reasons the midpoint category provides benefits, as fair wages can be calculated by using quantitative measures and by including a limited number of values (compare Neugebauer et al. 2014). Furthermore, fair wages have a certain relevance for poverty alleviation, as indirectly stated by the sustainable development goals (UN 2016a) and indicated by The World Bank (2014).

Through ‘fair wage’ the wage level of workers can be set in context to the required minimum, living or non-poverty wage (e.g. Schulten 2014). Fair wages thus play an essential role in satisfying the workers´ basic needs, such as stable living conditions (Kenrick et al. 2010; Benoît et al. 2013). Although, the idea of wages enabling an individual or a family to have an adequate living standard is not new (Anker 2011), a uniform definition or comprehensive coverage in SLCA is still missing. However, the wage discussion has gained new momentum and is increasing in relevance due to widening wage inequalities and low paid work situations (Bennett 2014).

An respective midpoint impact category would allow for determining the time a person has to work to secure food, housing and education (Klöpffer 2008). Therefore, ‘fair wage’ goes well in line with Maslow´s pyramid of needs (Maslow 1954; Maslow 1943), describing the fundamentals of prosperity. Wage related data are provided by i.a. The World Bank and ILO.

[21] As shown in the sections 2.1.2, 2.2.1 and especially 2.3.2, social impacts have only conceptually been covered within impact models and characterization models are broadly missing. Thus, the criterion ‘method robustness’ somehow lacks foundation.

A first qualitative characterization model to include fair wages in SLCA studies has been provided by Neugebauer et al. (2014).

Following on the findings of 3.2.3, the two criteria ‘method robustness’ and ‘relevance’ are not applicable for current LCC cost categories. Those cost categories are hardly reflected within local or global discussions and there are no specific characterization models available for their calculation. Some may argue this simplicity is beneficial from a practical point of view; however, it also prohibits drawing conclusions on the sustainability performance of products due to unclear relevance and missing targets (compare section 2.2.2). Addressing the findings of section 2.1.3 and 2.3.3[22], only value added considerations partly allow for a criteria-based classification. Therefore, value added is chosen as an indicator for Tier 1 by representing a slightly broader perspective of LCC towards economic impact assessment.[23]

Value added as an indicator has already been mentioned by Hunkeler, Rebitzer, and Lichtenvort (2008) in the context of production costs. Value added in economic considerations is typically determined through revenues, costs and benefits, as e.g. defined by Thomassen et al. 2009; Figge and Hahn 2004; Azapagic and Perdan 2000. The value added can be calculated per unit, process, company or even country. This allows for determining the value added for different producers along the supply chain as well as for the complete life cycle as displayed by Wood and Hertwich 2012; Heijungs, Settanni, and Guinée 2012. On the corporate or product level the value added can be used as a measure for determining the business success and thus the economic performance (Ingwersen et al. 2014; Azapagic and Perdan 2000), which broadens the scope of LCC.[24] It can therefore function as an indicator to set costs into perspective when assessing products along their life cycle (Thomassen et al. 2009; Figge and Hahn 2004). Heijungs, Settanni, and Guinée (2012) and Hochschorner and

[22] The value added has already been taken up as an extension of LCC by several authors (e.g. Kruse et al. 2009; May and Brennan 2006; Wood and Hertwich 2012).

[23] In the original manuscript (Neugebauer et al. 2015) ‘production costs’ have been included representing LCC within Tier 1. However, considering further studies, value added appears to be a good option for initiating economic impact assessment. Data-related requirements have to be fulfilled, so that no shortage in practicality is expected.

[24] Wood and Hertwich (2012) in this context stress that the consideration of life cycle cost alone can never serve this purpose of determining economic well-being.

Noring (2011) point out that the data requirements for value added calculations do not significantly differ from those of LCC, which qualifies the indicator for the Tier 1 level, as Bovea and Vidal (2004) describe these costs as conventional costs, which are easy to assess.

The described midpoint categories of LCA and SLCA, and respectively the cost category included for LCC, representing Tier 1, can be taken from Table 8.

Table 8: Proposed set of impact and cost categories for Tier 1 ('sustainability footprint') within the Tiered approach.

Impact and cost categories of Tier 1		
LCA	**SLCA**	**LCC**
Global climate Change **if assessing agricultural products use Eutrophication in addition*	Fair wages *comparison to minimum, living & non-poverty wages*	(economic) value added *including e.g. expenses for manufacturing, labor & maintenance*

To summarize, Tier 1 consists of three categories representing the three sustainability dimensions but also reflecting different perspectives of production processes. Therefore, value added addresses the producer's perspective complementing the environmental perspective (by means of global climate change) and the social (worker´s) perspective (by means of fair wage). Furthermore, the selected indicators are generally relevant for production processes. However, the indicators representing the three categories do not yet follow comparable modelling approaches; therefore, the indicator results must be displayed transparently and separately.

3.4 Tier 2

Tier 2 broadens the 'sustainability footprint' defined at Tier 1. Accordingly, Tier 2 includes a broader variety of impact and cost categories reflecting current state-of-the-art assessment practices. Therefore, suggestions of international institutions and common guidelines are considered representing the state of the art for LCA, LCC and SLCA.

For LCA the handbook of the International Reference Life Cycle Data System (ILCD) describes different assessment stages by including different levels for midpoint impact categories (JRC 2011). Three levels are distinguished: level I – recommended and satisfactory; level II – recommended but in need of some improvements; level III – recommended, but to be applied with caution. The defined impact categories on level I and II go well in line with the criteria-based hierarchy of section 3.2.1. Therefore, the transition between level II and III serves as a cut-off between Tier 2 and 3.

Tier 2 accordingly includes midpoint impact categories classified as level I and/or II. Common assessments normally include these indicators. They reflect the common best practice in LCA (Rebitzer et al. 2004). Through the extension further environmental aspects can be considered going beyond the globally relevant climate change and including also locally relevant impacts, such as acidification and eutrophication, or seasonal ones, like ozone formation (summer smog). All included impacts are covered within characterization models and have widely been accepted within the LCA community (Pennington et al. 2004; Jolliet et al. 2014).

For SLCA no handbook is available providing a clear order on which impact categories to include. However, the criteria-based ranking in 3.2.2 reveals implementation potentials for the impact categories identified. According to this ranking, health, education and working condition appear to be more likely implemented than (social) security, human rights and cultural heritage. For the former three (qualitative) characterization models (health and education) or concrete indicators have been suggested. Furthermore, data are available due to international organizations (compare section 2.3.2 and 3.2.2). Hence, the social pillar of Tier 2 additionally includes the midpoint categories health, education and working condition. Health has been broadly addressed within SLCA literature (compare sections 2.1.2 and 2.3.2), within LCA literature (Jolliet et al. 2014) and by numerous institutions, like WHO (2016) or OECD (2016). An impact and characterization model comprehensively covering health aspects in SLCA is still missing. Therefore, as indicated in section 2.3.2, health is considered through two midpoint impact categories originally located within the LCA framework. Humantoxicity, as introduced by (Rosenbaum et al. 2008) within the Usetox (UNEP/SETAC) toxicity model, allows for determining toxicity-related health impacts of cancer and non-cancer effects. In addition, ionizing radiation (JRC 2010a) may be considered, if required due to relevant circumstances like high dependencies on nuclear power. Furthermore, ionizing radiation can be of importance in the context of mining processes, as e.g. uranium miners face an increased risk of different types of cancer due to radioactive radiation (Zaire et al. 1997; Möhner et al. 2006).

Just as health, education has been broadly addressed within SLCA and LCSA literature (compare sections 2.1.2 and 2.3.2). Weidema 2006 and Klöpffer 2008 describe education as relevant for future sustainable development. The United Nations recently addressed it within the sustainable development goals (UN 2016a). Therefore, education should be considered within SLCA studies. A first (qualitative) characterization model has been proposed by Neugebauer et al. (2014). Even though no quantitative characterization has been performed, it includes qualitative inventory indicators as a first proxy addressing equal opportunities, literacy rate or finished degrees. Data on education are provided by different organizations, e.g. ILO (2010), The World Bank (2013) and OECD (2013).

Working condition as a midpoint category is also included in Tier 2, since numerous SLCA studies have considered aspects formally related to working conditions (compare sections 2.1.2 and 2.3.2). ILO 2011 and The World Bank 2016a already earlier addressed several of those aspects, so do different trade unions (e.g. Ver.di 2016). ILO (2011) mainly defines good working conditions through working time and compliance with labor laws. First descriptive indicators, included by Dreyer, Hauschild, and Schierbeck 2006; Kruse et al. 2009; Jørgensen et al. 2008, take up those points by regarding societal values related to labor rights and reflecting issues like overtime or benefits. Relevant data are provided by ILO (2011).

For LCC no handbook is available providing a clear guidance on which cost categories to include. LCC´s exclusion of impact categories provides further challenges, which hinder a sound evaluation of relevant topics. However, as an immediate remedy of those shortcomings is unlikely, as already indicated in section 2.2.2, an alternative approach is needed. Therefore, it is proposed to at least cover different perspectives, when applying LCC. Therefore, Tier 2 additionally includes consumer and EoL costs. It is assumed that production costs are already covered within the value-added considerations; thus, this cost category (as included in Table 7) is not additionally considered, as it would lead to double-counting. Consumer costs and

EoL costs have already been included in LCC studies and implementation is quite straightforward (compare section 2.3.3). Consumer costs normally include purchase prices[25], costs for energy and usage, and maintenance. Energy costs can be difficult to assess, as they strongly depend on the user's behavior. EoL costs include monetary expenses for final waste and recycling treatments.

The described midpoint categories for LCA and SLCA, and respectively the cost category included for LCC, representing Tier 2, can be taken from Table 9.

Table 9: Proposed set of impact and cost categories for Tier 2 ('best practice') within the Tiered approach. Additions to Tier 1 are highlighted in red.

Impact and cost categories of Tier 2		
LCA	**SLCA**	**LCC**
Global climate change	Fair wage	(economic) value added
Stratospheric ozone depletion	*comparison to minimum, living & non-poverty wages*	*including e.g. expenses for manufacturing, labor & maintenance*
Ozone formation	Health	Consumer costs
Eutrophication	*considering Humantoxicity impacts and Ionizing radiation impacts*	*including e.g. purchase prices, energy, usage costs*
Acidification	Education	EoL costs
Particulate matter	*addressing e.g. equal opportunities, literacy rate or finished degrees*	*including monetary expenses for final waste and recycling treatments*
	Working condition	
	including e.g. working hours and existence of labor laws	

To summarize, Tier 2 represents a broader view on LCSA topics by including additional impact and cost categories. Those allow for a more detailed picture on environmental, social and

[25] Caution is needed in this context, as purchase prices inherently cover production costs. Therefore, the costs included for the different perspectives cannot be summed up.

economic aspects representing different concerns (e.g. local vs. global environmental impacts), stakeholder groups (e.g. workers and society member), or perspectives (e.g. producer vs. consumer perspectives). Yet, as not the same number of categories is considered and still different modelling principles are followed, a transparent and separate consideration of indicator result remains important.

3.5 Tier 3

Even though with the inclusion of Tier 2 a broad coverage of topics and perspectives have been reached, some topics remain unconsidered. These topics contain an inherent complexity (e.g. in case of land use or toxicity impacts), missing consensus (e.g. in case of resource depletion) or missing definition (e.g. in case of human rights). Therefore, with the inclusion of those categories into Tier 3 incentives for further developments are provided. Accordingly, Tier 3 also provides methodological and data related challenges for practitioners; since, it aims at a comprehensive coverage of relevant topics within LCSA.[26]

With regard to LCA, environmental issues at Tier 3 should be presented in a preferably holistic manner. Correspondingly, the additionally included midpoint categories address (eco-)toxicity aspects (e.g. Rosenbaum et al. 2008), land use (e.g. Milà i Canals et al. 2007), water use (e.g. Berger et al. 2014), and resource consumption (e.g. Guinée 2002). All named impact categories face challenges in scientific validity, even though characterization models have been established. Those models tend to be limited to certain aspects, e.g. the model on land use of Milà i Canals et al. (2007) solely focuses on soil organic matter. At the same time, those topics contain a certain relevance, as indicated in section 3.2.1, for current, but also future generations. Therefore, they are included in Tier 3 of the Tiered approach concept.

Similar to the environmental dimension of LCSA, SLCA impacts at Tier 3 should ensure a rather holistic perception of the social dimension. Building on the findings of the sections 2.3.2 and 3.2.2, human rights, (social) security and cultural heritage are added to the social dimension

[26] The coverage of impact/cost categories and indicators orientates on the identified ones, which have been listed in the sections 2.3 and 3.2. This thesis therefore does not raise a claim on absolute completeness, but targets the reflection of crucial topics for all three sustainability dimensions.

of Tier 3; even though, comprehensive impact or characterization models have not yet been defined. Within SLCA Human rights normally address subtopics, like child labor, forced labor, diversity, discrimination and equity (compare e.g. Jørgensen et al. 2010; Martínez-Blanco et al. 2014; Hauschild et al. 2008). Institutions, like Human Rights Watch [27] and Amnesty International (1998), further underline the relevance of human right considerations. Targeting the inclusion into future SLCA practice, the qualitative indicators or risk potentials randomly considered (compare section 2.3.2) can serve as a basis for further developments. Data can be taken from ILO (2010c), The World Bank (2014a) and the United Nations (UN 2016c).

The same goes for (social) security considerations. To achieve practical impact models, the (qualitative) indicators, e.g. described by Bienge et al. 2009 and Weidema 2006, can serve as a basis for further developments. Considerations addressed by several governmental institutions (e.g. United States 2016) and data provided by e.g. ILO (2016b) may also be helpful.

The inclusion of cultural heritage into future SLCA appears even more challenging. Even though it has often been mentioned qualitatively in the SLCA context, neither a clear outline nor a concrete definition has been agreed upon. However, a strong relation to local communities and different societal groups is commonly implied (compare section 2.3.2). Just a few institutions[28] addressed cultural heritage in detail, and even fewer case studies. Nonetheless, background information can be taken from the Journal of Cultural Heritage, which can serve as a basis for a clearer impact definition.

In addition to the different perspectives covered within Tier 2, Tier 3 targets the coverage of rarely considered cost categories, which contribute to significant monetary expenses in certain cases. Thus, costs for research and development (R&D), capital and infrastructure are added.[29] In addition, internalized external costs should be considered, which relate to accidents or environmental damages and which have not been considered within social or environmental assessments. For instance, as long as e.g. health impacts have not been regarded

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

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

[29] In this context, also the inclusion of discount rates can be relevant, as indicated by e.g. Dong et al., (2014). Choosing the "correct" discount rate is however controversial. Further information can be taken from the Glossary.

within SLCA, they should be expressed in monetary terms if possible to ensure integrity of the LCSA model. Here the earlier mentioned unresolved internalization approach (Rebitzer and Hunkeler 2003) should be part of further research directions. Data for these costs categories are harder to gather, as they are not easily available within management accounting systems.

The described midpoint categories for LCA and SLCA, and respectively the cost category included for LCC, representing Tier 3, can be taken from Table 10.

Table 10: Proposed set of impact and cost categories for Tier 3 ('comprehensive assessment') within the Tiered approach concept. Additions to Tier 2 are highlighted in red.

Impact and cost categories of Tier 3		
LCA	**SLCA**	**LCC**
Global climate change	Fair wage	(economic) value added
Stratospheric ozone depletion	*comparison to minimum, living & non-poverty wages*	*including e.g. expenses for manufacturing, labor & maintenance*
Ozone formation	Health	Consumer costs
Eutrophication	*considering Humantoxicity impacts and Ionizing radiation impacts*	*including e.g. purchase prices, energy, usage costs*
Acidification	Education	EoL costs
Particulate matter	*addressing e.g. equal opportunities, literacy rate or finished degrees*	*including monetary expenses for final waste and recycling treatments*
Ecotoxicological impacts	Working condition	R&D costs
Land use	*including e.g. working hours and existence of labor laws*	Capital & infrastructure costs
Water use	Human rights	*including also e.g. subsidies*
Resource depletion	*including e.g. diversity, forced labor and discrimination*	(Internalized) external costs
	(Social) security	*including e.g. taxes*
	including e.g. contracts, pensions and further social provisions	

	Cultural heritage *including e.g. aspects of migration and man-made environment relations*	

In summary, Tier 3 complements the impact and cost categories addressed within LCSA. Therefore, even categories are included, which contain shortcomings with regard to applicability. As the implementation of those categories likely provides challenges, they require advanced practitioners and/or method developers. With Tier 3 an even broader consideration of different impacts and aspects would be achieved; however also greater uncertainty in results can be assumed. The differences in maturity between the different categories increased for both within and between the methods. Furthermore, given that not the same number of categories is considered and still different modelling principles are followed, a transparent and separate consideration of indicator result remains important.

3.6 Discussion of the Tiered approach concept

The Tiered approach concept provides a hierarchical structure guiding practitioners through LCSA. Successively, additional impact and cost categories are implemented towards a comprehensive assessment level starting from the basic ‘sustainability footprint’. With this simplification of LCSA by means of the ‘sustainability footprint’ (Tier 1), deficiencies in results´ robustness may occur, as results at Tier 1 potentially contradict with results at Tier 3. Thus, an as beneficial identified product option at Tier 1, might turn out less sustainable after the Tier 2 or 3 assessments. Conclusions therefore must consider these potential uncertainties.[30] A straightforward solution to this challenge cannot be provided, as simplified approaches are often accompanied by a lack of informative value or at least contain limitations, as indicated by e.g. European Commission 2009; Pesonen and Horn 2012; Jolliet et al. 2003; Milà i Canals et al. 2007. Yet, correlations between different indicator results can minimize shortcomings which come along with simplified approaches, as shown by Berger and Finkbeiner (2011).

[30] Similar has broadly been recognized within LCA practice, as carbon footprint results may be as well contradictory in comparison to full LCA results.

The Tiered approach promotes the idea of getting started instead of getting lost in perfectionism. The same principle has already been stated at the United Nations Conference (UNCED 1992). For facilitating this practical orientation of the Tiered approach concept, Tier 1 includes impact categories, which do not require an exorbitant amount of data, which embody relevance in the respective dimension and which (even if not consistently) have already been included in case studies. At the same time, shortcomings in methodological maturity are accepted, which mainly apply for impact and cost categories within SLCA and LCC. While the LCA impact category global climate change assigned to Tier 1 has reached consensus and is scientifically substantiated, the two indicators fair wage (identified for the social dimension) and value added (representing the economic dimension) have not yet reached the same sufficiency, but indicate benefits in data requirements and case study appliance.

Naturally, the practicality decreases for Tier 2 and 3 and several challenges occur, such as problems in delineating between the different impact categories. For instance, health and working condition may contain overlaps, if their scope is not carefully defined. The same applies to equity, as it can in its different manifestations be relevant for education (as indicated by Neugebauer et al. 2014), but also has a certain linkage to human rights (according to e.g. Bienge et al. 2009). Further research therefore must also focus on the clear differentiation of the different impact categories defined.

Furthermore, impact categories´ relation to the functional unit can be challenging especially for Tier 3 categories. Especially, SLCA and LCC include topics with societal relevance, but rather limited product relevance, e.g. social security and internalized external costs. The extent to which this obstacle can be solved need to be part of further research by considering also new approaches, such as organizational LCA (Martínez-Blanco, Finkbeiner, and Inaba 2015) and Social organizational LCA (Martínez-Blanco et al. 2015).

Although, the criteria-based ranking has been performed according to best knowledge; further research and practical case studies are needed to enable verification of the chosen impact categories and indicators. Additionally, the transitions between the tiers are not very strict and require confirmation of practical case studies. By this means adjustments are possible, considering that the Tiered approach concept allows for adapting new findings and inclusion of additional impact categories. Consequently, additional impact categories and indicators are to be included, whenever new research findings are made and confirmed.

The differences in maturity further provide some obstacles for LCSA´s interpretation, as offsetting or compensation of results within the different dimensions is not expedient. The Tiered approach concept, even though it does not present solutions for the interpretation challenges, allows for transparently displaying the results gathered within the three methods.

3.7 Conclusion and critical reflection of the Tiered approach concept

The criteria-based hierarchy of the Tiered approach concept strives to enhance practical implementation and further developments of the LCSA framework. The Tiered approach therefore functions as a prototypical selection procedure towards integrated LCSA focusing on practicality by means of data availability and readiness of implementation. Nevertheless, (methodological) challenges within the LCSA framework remain and need to be tackled, if a thorough and consistent assessments practice is targeted (compare Box 2.1). Those challenges have conceptually been addressed within section 2.2 and mainly result from the differences in maturity of LCA, SLCA and LCC (Niemeijer and de Groot 2008; Pesonen and Horn 2012). Solving those challenges is however not aimed at by means of the Tiered approach, as it is rather focused on initial guidance and selection of LCSA topics.

Explicitly, the Tiered approach concept assists in:

- Provision and ranking of relevant topics in LCSA
- Performance of simplified LCSA assessments by means of the ‘sustainability footprint’ at Tier 1
- Implementation of additional indicators through a step-by-step guidance

By means of this simplification and guidance, methodological shortcomings (e.g. with regard to impact assessment) and research needs (e.g. with regard to delineation and definition of impact categories) can be identified. Yet, the Tiered approach does not target:

- Tackling of those methodological shortcomings,

- the provision of solutions for the research needs identified,
- the presentation of solutions for the interpretation challenge of LCSA.

Therefore, further research focuses on those last three bullet points. Relevant research directions will be identified within the next section.

3.8 Identified research directions

Based on the findings in the previous section, tackling of the methodological shortcomings within SLCA and LCC seems to be a logical next step. It appears fundamental for this purpose to achieve first impact models for SLCA and LCC for aligning the assessment practice of the three dimensions (Hacking and Guthrie 2008). The focus of the following chapter 4 is therefore laid on the implementation of advanced social and economic impact models not only covering risk factors or cost categories, but considering interrelations along impact pathways. Indicators, which have already been part of practical case studies and which contain a certain applicability appear to be a promising basis for developing such impact models. Therefore, the indicators identified in section 3.3 at the Tier 1 level are selected following on the discussion in section 3.6. They can assist in dissolving the methodological vacuum, in which SLCA and LCC seem to be trapped.

The different demands of SLCA and LCC are considered (as shown in the previous sections, mainly 2.1, 2.2 and 0). Whereas for SLCA impact categories and first impact pathways are available, LCC lacks both and only provides first concepts for including impacts, such as value added. Accordingly, different approaches are followed for aligning the LCSA methods. Developments in SLCA primarily concentrate on the achievement of concrete impact definitions and characterization models (focusing on Tier 1). Developments with regard to LCC have to previously focus on aligning its structure to the rationale of Box 2.1. Therefore, impact pathways for displaying economic mechanisms should be included together with suitable impact categories in accordance with ISO and ILCD. Concrete impact definitions and characterization models (also focusing on Tier 1) will then be the next step.

Being specific, in context of the Tiered approach concept SLCA developments within this thesis initially focus on developing a practical but also substantiated method for determining fair wage impacts based on previous work, mainly presented by Neugebauer et al. (2014). In contrast, LCC developments initially concentrate on proposing a new structure for economic assessments in LCSA and the achievement of an economic impact pathway and related impact categories, before a suitable Tier 1 impact category can be defined, focusing on the identified indicator value added.

4 Methodological developments supporting the Tiered approach concept

Building on the presented Tiered approach concept providing structure for LCSA topics, different methodological developments will be initiated in the following sections fostering LCSA´s implementation and aligning LCA, SLCA and LCC. As indicated in the previous section 3.8 the methodological challenges are quite different for SLCA and LCC. Whereas for SLCA an initial classification of topics has already been achieved, LCC still faces the discussion on whether and which impacts categories to define. Therefore, the followed approach in the subsequent sections is different for the two methods. Accordingly, three main targets can be defined for this chapter:

1. Fostering SLCA´s implementation through selected quantitative characterization models for assessing fair wage impacts
2. Adapting LCC´s structure for alignment with LCA and SLCA
3. Fostering LCC´s implementation through selected quantitative characterization models for assessing value added impacts

Therewith, the third research objective of this thesis (‘*Enhancements of LCSA´s methodological robustness*’) and the related sub-targets (‘*Initiate methodological developments based on the guidance provided within the conceptual approach*’ and ‘*Focus on enhancing SLCA´s and LCC´s maturity*’) are taken into consideration. Focus is set on the first tier for two reasons – firstly, the included impact and cost categories are promising for a straightforward implementation, and secondly, methodological improvements are favored due to previous work and studies addressing fair wages and value added. As soon as those methodological improvements are achieved, the provided indicator hierarchy of the Tiered approach concept will be refined in chapter 5. The newly defined characterization models of the refined Tier 1 are then tested within the exemplary case studies in chapter 6.

As LCA has already reached a valid and application-ready state not only for the impact category identified within Tier 1 (global climate change), but also for various others, broad implementation and investigation of different products and processes is enabled (compare section

2.1.1). Therefore, LCA is not further addressed within this chapter and focus is set on methodological developments of SLCA and LCC.

4.1 Methodological developments for SLCA

Following the Tiered approach hierarchy by particularly addressing 'fair wage' and displaying its importance, a section on the history of 'fair wage' within the SLCA context is included prior to the impact category development, to consider the related impact pathway and to define a suitable characterization model. The impact category 'fair wage' and its accompanying methodological developments have been investigated within the journal publication of Neugebauer et al. (2016). The main findings are presented in subsection 4.1.1, reprinted and slightly adapted with permission of Elsevier B.V. (https://www.elsevier.com/about/company-information/policies/copyright).

Following from a detailed definition and description of the 'fair wage potential' as the social indicator included at the Tier 1 level, a outlook is presented addressing the latest status and further research needs of social impact categories for Tier 2 and 3. Therefore, the findings of the subsection 4.1.2 are partly based on the journal publication of Neugebauer et al. (2014); sections 4.2 and 5.2, reprinted and slightly adapted with permission of MDPI AG (http://www.mdpi.com/2071-1050/6/8/4839). Subsection 4.1.2 further considers research from other authors relating to health and working condition. Section 4.1.3 is complemented by displaying latest research results within the field of SLCA addressing (social) security, human rights and cultural heritage.

4.1.1 Tier 1 assessment – A new characterization model for Fair wage

This section introduces a new midpoint impact category and characterization model for fair wages. The considerations and requirements are therefore displayed regarding general understanding of different wage classifications used within literature and the achievement of first approaches within SLCA. Later a first *qualitative* impact pathway is presented connecting the proposed midpoint category to potential endpoint impacts. Although, endpoint modelling is not part of this thesis (as stated in chapter 2), the identification of endpoint categories was found relevant for reflecting comprehensive impact models. Therewith, potential linkages can be indicated between the developed characterization models at the midpoint level and the endpoint level as well as AoPs. Yet, the considerations are limited to the identification of *qualitative* linkages, as a quantitative coverage of endpoint indicators would require further methodological improvements. Even for LCA still not all interrelations towards the endpoint level are qualified or known. Therefore, the development of *quantitative* endpoint categories and indicators will not be part of this thesis.

4.1.1.1 Relevance and classification of wages in the context of SLCA

Wages, income and salaries have already been mentioned by several authors and institutions in connection with SLCA (e.g. Anker 2011; Bennett 2014; Guzi and Kahanec 2014; Benoit and Mazijn 2009). In this context, the terms ‘non-poverty’ and ‘living wages’ have been broadly discussed. A ‘non-poverty wage’ guarantees living at a basic level of economic security above the poverty line, including low cost nutrition and minimum non-food necessities (Guzi and Kahanec 2014; Anker 2006).

The living wage concept goes beyond that by including aspects of human dignity, as well as by covering not only the worker’s needs, but also basic necessities of his or her family (Anker 2011; Benoît et al. 2013; ILO 1970). The idea of the living wage concept enabling an individual and his/her family to achieve an adequate living standard is not new. It has already been mentioned in 1894 by Ada Nield Chew, a working class mother, and was taken up again by the International Labour Organization (ILO), who addressed ‘living wages’ in their Constitution of 1919 (Bennett 2014; Anker 2011). A century later, a uniform definition is still missing; yet the living wage discussion has gained new momentum due to widening wage inequalities and low paid work situations (Bennett 2014). Broad consensus has been achieved that living wages should ensure a decent life style. Dreyer, Hauschild, and Schierbeck (2006) state in their study that “at least three important prerequisites for a good and decent life can be identified, ‘human health’, to live a healthy and naturally long life; ‘human dignity’, to (…) enjoy respect and social membership; ‘basic needs fulfillment’, to have access to food, water, clothes, medical care (…)”. Some even state that living wages should enable the healthy and educational development of related children and a decent participation in the community

(Anker 2011; Guzi and Kahanec 2014). According to Anker, (2011) the level of living wages required varies significantly depending on the country of interest and the time of inquiry. This is because living costs and minimum living standards are influenced by the economic development status within a given region, as well as by prevalent societal values, such as intensity of consumption.

In connection with SLCA, it is often referred to the term ‘fair wages’ or ‘fair salaries’ (Parent, Cucuzzella, and Revéret 2010; Klöpffer 2008; Benoit and Mazijn 2009).[31] Similar to living wages, fair wages are often understood as essential for satisfying a worker´s and his/her family´s basic needs to ensure stable living conditions (Kenrick et al. 2010; Benoît et al. 2013). The World Bank, (2014) declares fair wages as a prerequisite to poverty alleviation. Much like living wages, the value of fair wages is highly variable and strongly dependent on a country’s situation, but also on the situation within a sector and/or organization (Neugebauer et al. 2014).

All three wage concepts – non-poverty, living and fair wages – can be classified by means of Maslow´s pyramid of needs. Living wages and fair wages go beyond non-poverty wages by not only fulfilling the physiological needs of workers and their families (e.g. shelter, water, food), but also addressing aspects of safety (see Figure 10).

[31] Even though the Guidelines of SLCA referred to ‘fair salary’, within this thesis the term ‘fair wages’ is used to avoid confusion. The term ‘wages’ is commonly used in connection with labor and often understood as an "umbrella" term for employees´ monetary compensation. Salary sometimes only covers the compensation agreed on for a weekly/daily work independent from time actually worked. Wages instead are often related to pieces or hours (Anker 2006).

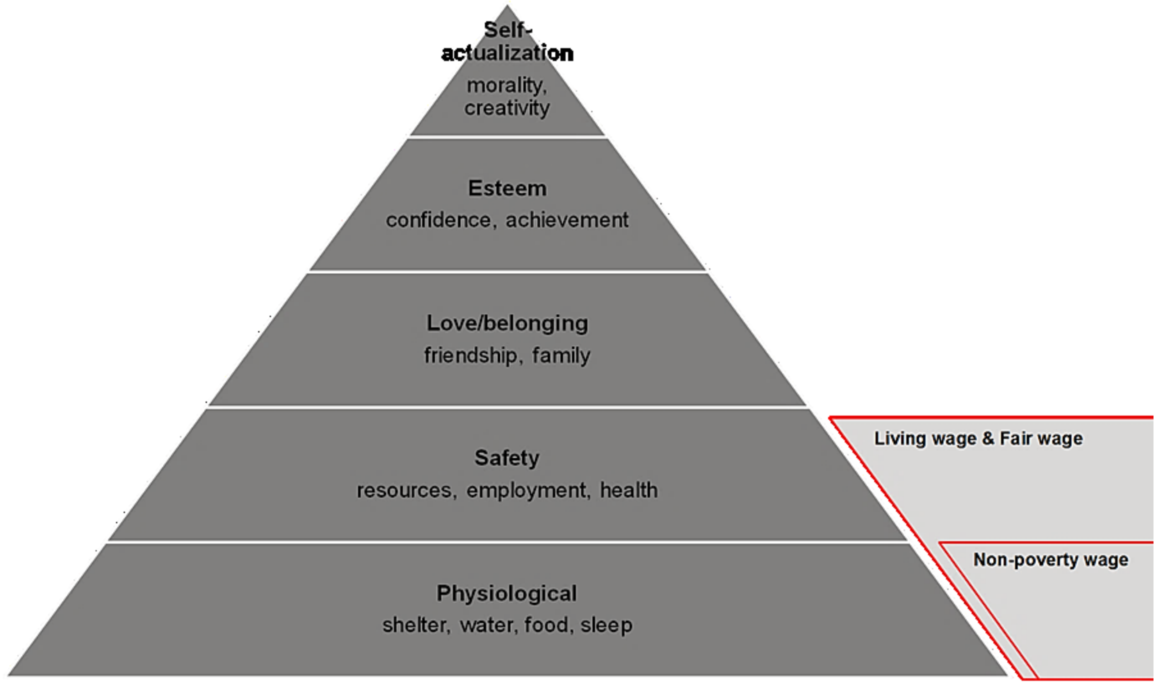


Figure 10: Classification of wages based on Maslow´s Hierarchy of Needs (Maslow 1943)

The delineation between living wages and fair wages is not as straightforward, because both concepts consider similar aspects of what guarantees a decent living. Consequently, both terms are often used synonymously. Yet, SLCA literature makes a clear distinction between both concepts. According to 'The Methodological Sheets for Sub-categories in SLCA' (Benoît et al. 2013) and other studies (Anker 2011; Giddings, Hopwood, and O'Brien 2002; Akerlof and Yellen 1990; Neugebauer et al. 2014; Musaazi et al. 2015; Bennett 2014) the fair wage concept should consider working time and equal remuneration in addition to living wage values. Working time or the (overtime) hours worked have a certain relevance in the fair wage context, as it is often the case that workers in developing countries work longer hours without being sufficiently compensated for the additional work (Anker 2011). Many studies, considered within the comprehensive review of Anker (2011), concluded that a living wage should be earned within the *normal* working time.

Summarizing the findings of this section the different wage concepts can be ranked as displayed in Figure 11.

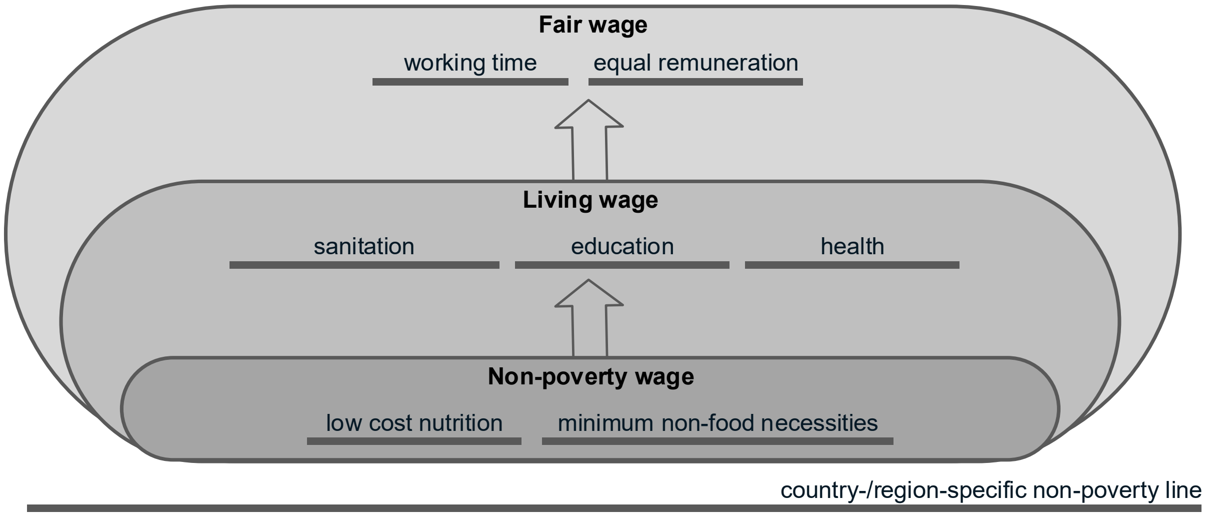


Figure 11: Interlinkage between different wage concepts

Assigning income or wages to a specific impact category within SLCA provided some challenges. No consensus has so far been achieved on whether fair wages should be classified as an inventory result or ascribed to a midpoint impact category (Norris 2006; Hauschild, Dreyer, and Jørgensen 2008; Jørgensen et al. 2008). First approaches considering 'wages' within SLCA have previously been mentioned by Neugebauer et al. (2014) and Kruse et al. (2009). Further approaches considering income levels include that of Feschet et al. (2013) with their cross-sectional empirical relationship between growth in income (measured as GDP per capita) and improvements in the health of a country's population (measured as life expectancy at birth) to design their "impact pathway" for social impact assessment. Yet, the effect of income on population´s total health differs depending on the location of consideration. While the found correlation is strong for developing countries with a comparably low level of average income, a similar increase in health cannot be observed for developed countries, where the average income is generally higher (Fuchs 2004). Extending the work of Feschet et al. (2013), Bocoum, Macombe, and Revéret (2015) used the so-called *Wilkinson pathway,* which establishes a relationship between income inequality and health, describing an additional pathway for SCLA.

Following on the earlier classification in Type I to III assessments (see section 2.1.2), the above mentioned approaches are quite different. Neugebauer et al. (2014) or Hunkeler 2006; Weidema 2006; and Kruse et al. 2009 represent the Type II approach by including social impact pathways and social impacts in their considerations. Within this thesis the mentioned approaches of Feschet et al. (2013) and Bocoum, Macombe, and Revéret (2015) have been classified as Type III approaches. Summarizing the argumentation in section 2.1.2, Type II assessments follow the *traditional* LCA-inspired approach. They target the inclusion of causal relations for SLCA by considering social mechanisms and they determine the social performance of products along their life cycles and relate inventory data to social impacts. Therefore, the Type II approach is followed for defining a new impact category and characterization model for fair wages quantifying impacts at the product or corporate level in section 4.1.1.2. In addition, *potential* social impacts towards the endpoint along an impact pathway are discussed in section 4.1.1.3. While the first step embodies the core of this impact category development, the second step rather provides tasks for further research, as quantifying impacts at the endpoint level is not the aim of this chapter. The basis for both – a characterization model for fair wage and a related impact pathway – has been provided by Neugebauer et al. (2014). The presented impact pathway includes two endpoints (economic welfare and human health) and two AoPs (social well-being and social justice). This pathway functioned as the conceptual basis for their *qualitative* characterization model developed. The characterization model includes several cost categories, e.g. costs for housing or food, which are then used to calculate a living wage value. Different 'performance ranks' were defined, which relate living wage values with minimum wages and the lowest and highest income paid to the workers. The qualitative approach of Neugebauer et al., (2014) provides the conceptual basis for the work done here, which aims to develop a quantitative characterization model.

4.1.1.2 Quantitative fair wage characterization at the midpoint level

To transfer the initially proposed *qualitative* midpoint impact from Neugebauer et al. (2014) into a *quantitative* one, a new characterization method, by means of 'fair wage potentials' (FWP), is proposed within this section. The method is proposed following on the methodological classification of section 4.1.1.1. It includes the relevant factors of a given product, which affect the FWP, according to the categorization of wages presented in the previous section. Possible links between corporate decisions at the micro (midpoint) level (e.g. workers' remuneration) and social damage factors at the macro (endpoint) level (e.g. damage to human health) are shortly discussed in section 4.1.1.3 introducing first aspects for a comprehensive (qualitative) impact pathway.

Following on the wage categorization in the previous section and Figure 11, determination of fair wages mainly depends on three country/region-specific and/or product-specific parameters: 1) living wages, 2) working time and 3) income (in-)equality. For developing a characterization model, characterization factors for these parameters have to be operationalized and included in a formalized relationship. Thereby remuneration aspects of the inventory along a product's life cycle (inventory data) can be transformed into FWPs. For each process n of the respective production location regionalized characterization factors have to be calculated representing a country´s and/or sector´s situation. The three parameters identified have been operationalized as follows:

1) **Minimum living wage**: Living wages can only apply, if they are tailored for the respective situation in a certain country or region. Therefore, *minimum living wages* (MLWs) are defined describing the country-/region-specific minimum level of remuneration required to enable a decent life style for the worker and/or his/her family. Those MLWs ensure that costs for housing, food, health and education and further necessities can be covered. To determine the underlying MLWs, mainly two sources are considered (Guzi and Kahanec 2014; City and County of San Francisco 2014) which both cover various country situations setting a basis for the fair wage characterization.
2) **Working time**: For operationalizing working time, it has to be distinguished from unpaid overtime in order to relate time paid to time worked. Through the inclusion of different aspects of working time, excessive unpaid or unrewarded working hours or overtime can be accounted for if occurring on a regular basis. Regionalized or sector-specific time factors allow for expression of the product-specific situation. Therefore, the *normal* contracted working time follows statutory regulations, which are depending on countries, regions or sectors (Anker 2006).
3) **Income equality**: Income-related inequalities at the workplace are addressed by describing unequal pay with regard to gender or race, but also considering the total in-

come inequality within an organization, sector or country. For this characterization factor the organizational perspective is added, as inequality can e.g. occur on a sectoral level, but not on an organizational level and vice versa. Ideally, this factor should function as a measure for income inequality on an organizational[32] or sector level. If those specific measures for income inequality are not available, the income related Gini coefficient – available for various countries – can be used as a proxy reflecting the country-specific income distribution.

The above considerations led to the definition of the following equations to calculate the 'fair wage potential' (FWP) expressed in 'fair wage equivalents' ($FW_{eq.}$). In Equation 1 the regionalized characterization factors (CF_{FW}) are multiplied with the inventory results (by means of real wages (RW_n) and real working time (RWT_n) per process). Equation 2 provides an overview of the characterization factors considered for calculating the 'fair wage equivalents'.

Equation 1: $$\boldsymbol{FWP_n = \frac{RW_n}{RWT_n} \times CF_{FW,n}}$$

Equation 2: $$\boldsymbol{CF_{FW,n} = \frac{1}{MLW_n} \times CWT_n \times (1 - IEF_n{}^2)}$$

Boundary condition: ($1-IEF_n{}^2$) is only considered, if $RW_n \leq$ average wage per country or sector

FWP_n – Fair wage potential [expressed in $FW_{eq.}$] representing process n within a product´s life cycle taking place at a defined location

RW_n – Real (average) wage [€/month calculated over one year], which are paid to the worker employed in process n

RWT_n – Real working time [hours/week] of workers performing process n (including vacation days and unpaid overtime)

$CF_{FW,n}$ – Fair wage related characterization factor [month/€] for process n representing the country, region, or sector specific conditions

[32] The organizational level included in this characterization factor has not been regarded for the factors 1) and 2) for the following reasons: MLWs are dependent on the country or regional situation, but are independent from the organizational situation; the statutory working time should be regarded on a sector or country level and is therefore independent from the organizational policy.

MLW_n – Minimum living wages by country, region or sector [€/month], which have to be paid to the worker to enable an adequate living standard for an individual and/or family in the respective country or region, where process n is performed

CWT_n – contracted working time [hours/week] for workers performing process n (including vacation days)

IEF_n – (squared) inequality factor [expressed in percentages] of the organization, region or country where process n is performed

With Equation 1 and 2 the above mentioned factors for determining the FWP are set in a formal relationship. Inventory results relating to the actual (average) remuneration and working time for the unit process n are therefore multiplied with the regionalized characterization factor CF_{FW} of the same unit process. Each process-specific CF_{FW} is threefold consisting of the living wage (MLW_n), which characterizes the real wage (RW_n); the contracted working time (CWT_n) characterizing the inverse fraction of real working time RWT_n; and a squared income inequality factor (IEF_n), which independently from remuneration and working time accounts for great differences in income. The first (MLW_n) and second (CWT_n) characterization factor embody a self-evident relation to fair wage, as both characterization factors ensure the very basis of a fair wage, as discussed in detail within the previous section. For instance Anker (2011) in his investigations already pointed out the importance of minimum living wages, which depend on the country´s situation, as well as working time, by means of *normal* working time contracted. Yet, the relation between the third characterization factor (IEF_n) and fair wages is not as straightforward and rather of normative character based on ethical values that suggest a wage significantly higher or lower than a societal norm is perceived as unfair. Based on the normative character, those inequalities only play a subordinated role within the fair wage considerations; therefore, they are squared to avoid exaggerated influence on the total result.

Remuneration levels along the supply chain are set in relation to the characterization factors (CF_{FW}), which allow for determining the distance from the required fair wage. Hereby, FWP values greater than one are superior over values below one. An accumulation of FWP values lower than one within a certain region or sector may indicate regular cases of underpayment per year in those regions or sectors. Thus, the determined distance from fair wage can function as a suitable category indicator for the impact category 'fair wage' (compare Table 11). Excessive working hours and high inequalities in wages function as additional factors complementing the fair wage considerations (like indicated in section 4.1.1.1). Excessive working hours may additionally contribute to the cases of underpayment through time lost to replace the lack of income. Great income inequalities may foster the imbalance between richer and poorer society members. Both working time and inequality aspect lead to a downwards correction of the total FWP. Especially the IEF should only be applied, if the real wage paid to the worker is equal or below the average wage (also following on the argumentation above). Therewith punishment of companies paying better than their competitors is avoided. Further weaknesses of these parameters as measures of the different factors considered in the definition of fair wages will be discussed in section 4.1.1.4.

Equation 1 and 2 orientate on the "classical" characterization procedure of life cycle impact assessment (LCIA) like defined within ISO 14044 (2006): *"Characterization models reflect the (environmental) mechanism by describing the relationship between the LCI results, category indicators and, in some cases, category endpoint(s)."*

This logic is transferred to SLCA by establishing a relationship between real wages at the social life cycle inventory (SLCI) level and fair wages at the midpoint level expressed in units of $FW_{eq.}$ (category indicator result) in accordance to the rationale presented in Box 2.1. Therefore, Equation 1 and 2 aim to express midpoint related consequences of wages, present a numerical indicator result by means of $FW_{eq.}$ and provide a method to carry out social impact assessment. In addition to the general LCIA requirements and recommendations, a *regionalized* characterization model is proposed, which is essential in the context of wages especially MLWs.

Summarizing the developed characterization model, Table 11 provides an overview of the proposed midpoint impact category 'fair wage' for SLCA.

Table 11: Clarification and classification of terms for the proposed 'fair wage' midpoint category

Impact category	Fair Wage
Inventory result	Real (average) wages paid to the workers per month and year and real working time per worker
Characterization model	Proposed model within this thesis and the related publication of Neugebauer et al. 2016
Category indicator	Distance from fair wage
Characterization factor	Fair wage potential (FWP) for each group of workers per process [FWeq / group of worker]
Category indicator result	Fair wage equivalents per process and/or functional unit
Category endpoint	Social well-being by means of Social Equity, Economic welfare, Human Health (qualitative relations are introduced in section 4.1.1.3)
Social relevance	The cases of underpayment function as a proxy for poverty alleviation and a decent life style.

The presented impact category and the introduced FWP may serve as a measure of the social sustainability performance of a product and/or company. Thus, FWPs can provide a decision support with regard to social impacts on workers along a product´s life cycle. With the FWPs, hotspots along a product´s life cycle can be identified. By averaging the single FWPs of the different worker groups and life cycle stages, the fair wage impact of product A can be compared with the one of product B.

The developed characterization model will be tested in three exemplary case studies in chapter 6 addressing tomato production, pedal electric cycles and modular machine tool frames. The in the original article of Neugebauer et al. 2016 (see Annex) included comprehensive database allows for the calculation of regional characterization factors (CF_{FW}) and includes secondary wage data. Thus, the FWPs for the three case studies can be calculated along their life cycles. The included data tables can be downloaded under https://www.see.tu-berlin.de/menue/forschung/ergebnisse/fair_wage_aequivalente/.

4.1.1.3 Qualitative fair wage characterization towards the endpoint level

To provide *qualitative* relations between the introduced midpoint category and the social mechanisms towards the endpoint level, a qualitative impact pathway is introduced. By this means interlinkages to social endpoint categories as well as AoPs are provided to *qualitatively* address important impacts, which may result from unfair/insufficient wage levels. This linkage between midpoint impacts and endpoint damages is especially in SLCA not straightforward as no social mechanisms (equivalent to environmental mechanisms in LCA) have yet been defined. However, the earlier introduced Type III models (e.g. Hutchins and Sutherland 2008; Norris 2006; Feschet et al. 2013; Bocoum, Macombe, and Revéret 2015), which consider empirical relations focusing on social aspects, may be used for developing such social mechanisms. In addition, relevant studies on fair wages are included as well as socio-economic studies which add up on the discussion within the SLCA community. It is important to point out, that the aim hereby is not to present a finalized social pathway and an aggregation model which translates midpoint impacts into social damages at the endpoint level. The concrete determination of those social damages as well as the concrete aggregation will be part of further research. The aim of this section is to suggest and discuss *possible* (endpoint) effects which may result from the midpoint impact category 'fair wage' and to present a conceptual qualitative social mechanism that could serve as a basis for future impact model development.

Hutchins and Sutherland (2008) underline the general relevance of (fair) wages within the societal context by referring to the UN division on sustainable development, which also released the sustainable development goals (UN 2016a). Those include social considerations on poverty, living conditions, nutritional status, and life expectancy etc., which all to a certain extent depend on the economic resources available to a family and, thus, on the wage that the working family members receive. Flows, such as employees' wages are therefore linked to social sustainability indicators at the endpoint level (Hutchins and Sutherland 2008). According to the suggestions of Neugebauer et al. (2014) and the findings of sections 4.1.1.1, three potential endpoint categories and two areas of protection (AoPs) were found relevant for the impact pathway originating from the midpoint indicator fair wage potential: human health, economic welfare, and (social) equity as endpoint indicators; and social well-being and social justice as AoPs (see Figure 12).

Human health as an endpoint indicator has been part of the LCSA framework for a long time (compare section 2.1.1 and 2.1.2). It is one of the classical three endpoints evaluated in environmental LCAs and for consistency reasons, several authors have suggested to instead consider it within SLCA. In this context, A close connection between social well-being and human health has been determined by several authors (e.g. Norris 2006; Dreyer, Hauschild, and Schierbeck 2006). The relevance of fair wage appears straightforward, as insufficient wages determine the nutritional status and the life expectancy, which can negatively influence population´s health (Neugebauer et al. 2014). Hutchins and Sutherland (2008) draw first empirical relations with regard to SLCA, indicating that changes in corporate supplier decisions e.g. with regard to labor equity (using wages and compensation packages as a unit of measure) influence populations health on a broader scale (using infant mortality as a unit of measure). A similar approach has been followed by Bocoum, Macombe, and Revéret (2015), who link income distribution/inequality and population´s health status through a simplified empirical regression model based on the Wilkinson pathway (Picket and Wilkinson 2010). They more specifically determine how changes in a product's supply chain can result in changes in the income distribution of the affected population, and in return, in its health status.

Neugebauer et al. (2014) propose economic welfare as a second endpoint category addressing the interlinkage between social and economic topics. They indicate a connection between fair wages and welfare mainly through the work of Atkinson 1970; De Maio 2007; Zieschank and Diefenbacher 2012; Talberth, Cobb, and Slattery 2007; and Costanza et al. 2004, who all conclude that the level of income and its distribution should be part of welfare considerations. For instance, Zieschank and Diefenbacher (2012) find that the more unequal the income distribution the lower the National Welfare Index (NWI) (if all other conditions remain the same). The German Enquete Commission on growth, wealth and life quality (Deutscher Bundestag 2013) defines the NWI as a complementing measure of welfare. With the enlarged GDP, the Commission addresses the need to broaden the common GDP indicator and its classical focus on absolute income and growth. Still the average gross income determines the material prosperity, yet it is complemented by nine sub-indicators addressing different socio-economic, economic and environmental concerns, e.g. income inequality determining societal participation. In fact, according to the Commission, the distribution of income is of greatest importance, as it significantly influences the standard of living and therewith populations´ health and education as well as crime rates (which was also investigated by Picket and Wilkinson 2010). Earlier, Akerlof and Yellen (1990) within their study on fair wages address the connection of fair wages and equity and point out that work efforts and quality correlate with equal remuneration. They therewith underline the influence of fair wages on economic welfare, as a drop in work efforts and quality may also lead to a decrease in welfare in the long-term. Economic welfare can also be interpreted in the context of prosperity, which to a certain degree depends on economic resources available to a family and thus on fair wages, as indicated by Hutchins and Sutherland (2008). If Pradhan and Ravallion (2011) are right and the poverty line or respectively the fair wage considerations are indeed a measure of individual´s economic welfare, then it should be possible to determine an impact on the macro-level resulting from the earlier presented FWP. Therefore, economic welfare would be (beside other factors as addressed by German Enquete Commission) influenced by the absolute level of income, the inequality in income, but also the time spent for generating this income, which are all factors regarded within the FWP.

Extending the work of Neugebauer et al. (2014), (social) equity is proposed as an additional AoP following on the principles of the Brundtland Commission (United Nations 1987) and the Rio Summit (UNCED 1992). Even though both sources did not directly link equity and income, they call for fairer distribution of income and for considering the poverty line when determining an individual´s remuneration. In the social sustainability context, Hutchins and Sutherland (2008) take up on that by connecting poverty and income inequality to the defined endpoint indicator equity. In the fair wage and SLCA context, Musaazi et al. (2015) address the call for re-considering distribution by designing a cause-effect relation between workers´ wages and social equity impacts. Giddings et al. (2002) define five equity principles, in which procedural equity addresses fair treatment of people including also wage levels. Anker (2011) adapts this view to the living wage concept and mentions equity in the context of overall repercussions on country´s employment. Therefore, (social) equity may be influenced by the absolute level of income, the inequality in income, but also the region of income, which is all regarded within the FWP.

These potential endpoint categories, identified within this section, indicate a certain relevance for the different AoPs defined for SLCA. Human health has already been connected to social well-being (compare e.g. Dreyer, Hauschild, and Schierbeck 2006). (Social) equity indicates a certain relevance in the context of social justice, which has been proposed as an AoP for SLCA by Neugebauer et al. (2014) and includes aspects like equal opportunities, security and freedom. ILO (2008) in this context underlines that social justice is essential for “universal and lasting peace (…)”. Earlier Nussbaum (2003) referred to social justice in connection with equality and gender equity. Economic welfare as an endpoint may potentially influence both AoPs, as it applies to aspects of prosperity and well-being but also equity and distribution.

Figure 12 displays the potential interlinkages of the defined midpoint category representing fair wages with the indicated endpoint categories along the *qualitative* impact pathway. Those endpoint impact categories and AoPs are neither exclusive nor quantitatively defined. To enable an aggregation of the midpoint indicator ‘fair wage potential’ to useful and meaningful endpoint indicators further research is needed. However, those investigations are not part of this thesis.

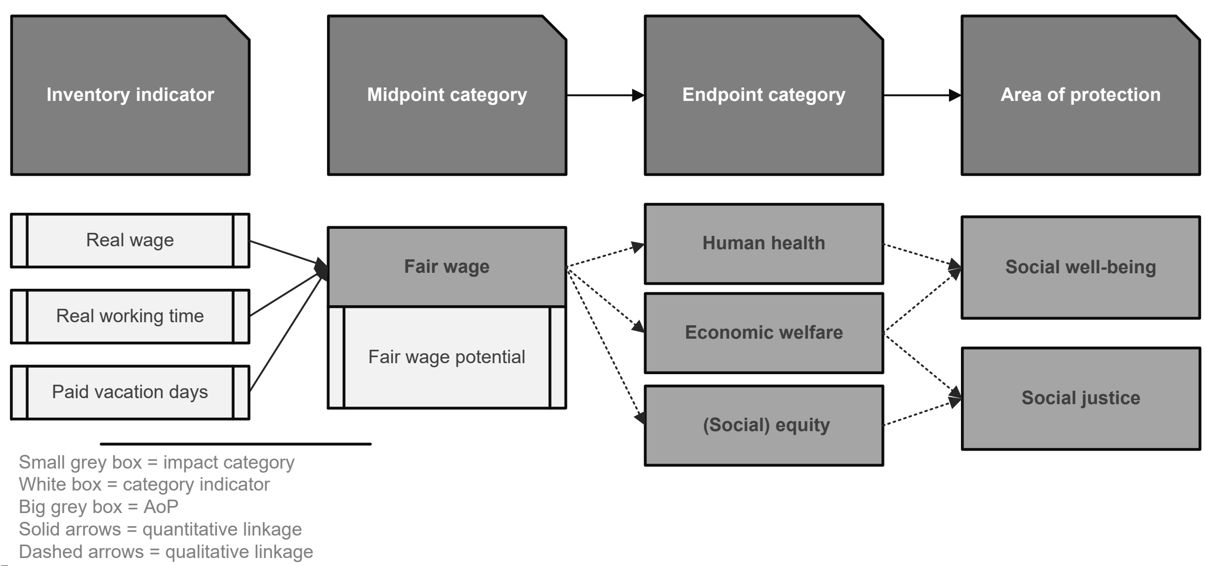


Figure 12: Impact pathway originating from the midpoint impact category ‘fair wage’

4.1.1.4 Discussion and critical reflection of the fair wage characterization model

A consistent and quantitative way to calculate FWPs along a product´s life cycle has been presented enabling the determination of social impacts along a product's life cycle. Furthermore, it allows for independent non-comparative conclusions, as the $FW_{eq.}$ values alone indicate insufficient remuneration levels of processes in relation to the product considered. Therewith, hotspots along the life cycle can be determined, which makes the fair wage approach beneficial for improving a product's social sustainability by indicating optimization potentials e.g. target upstream suppliers paying a fair wage. With the fair wage characterization, a way of determining corporate social impacts along a products supply chain has been introduced following a similar path than the earlier proposed social organizational approach of Martínez-Blanco et al. (2015). A direct relation to the functional unit was not (yet) provided for two reasons: 1) remuneration of workers is initially independent from the product produced and rather depending on the country, sectoral and/or organizational situation, 2) a relation to the functional unit e.g. by multiplying the FWPs with the process working time may distort the results, as it attributes higher relevance to the processes requiring more working time. Therefore, further research will be performed to find a suitable relation to the functional unit and/or to explore the social organizational approach further.

In addition to the challenge of FWPs relation to the functional unit, the expression of an aggregated FWP over the product's life cycle needs further consideration. The initial suggestion of averaging the single process-specific as well as working group-related FWPs over the product´s life cycle enables a comparison basis between different products. Yet, by unifying the single FWPs negligence or underestimation of the different groups of workers may occur. For instance, if the overall workforce is dominated by laborers, who tend to earn lower wages, averaging of the overall FWP displays a more balanced view. On the contrary, if the workforce is dominated by service providers, who tend to be overpaid, underpaid workers along the supply chain face the risk to be disregarded. Therefore, when aggregating the single FWPs, sensitivity analyses emphasizing the different groups of workers should be applied for guaranteeing an equitable perspective.

For the method development, a midpoint category was defined, which sets workers' remuneration into context with the working situation and the required living standard within the region of consideration. From an organizational point of view, the informational value of FWPs may be more important and helpful than the determination of an endpoint damage. Nevertheless, ways on how conditions at the product or corporate level – expressed as fair wage potential – cause broader social impacts at the endpoint level along a social impact pathway have been postulated. The earlier mentioned approaches of Hutchins and Sutherland 2008; Feschet et al. 2013 and Bocoum, Macombe, and Revéret (2015) may help to determine *quantitative* endpoint (damage) levels for SLCA.

Even though the composition of the characterization model itself has been justified through the findings presented in the section 4.1.1.1, single aspects such as the practical inclusion of the Gini-coefficient as an inequality measure may be discussable. The Gini-Index has been utilized to indicate the income inequality for a certain country/region for two reasons: 1) it is commonly known as a measure for income inequality of countries; 2) the data for worldwide Gini-coefficients are readily available. Accordingly, the Gini values have mainly been used for practical reasons. Nonetheless, it is well-recognized that using a national-level indicator of income inequality to calculate a midpoint indicator at the product or corporate level represents an inconsistency. For future studies, a company-specific income inequality measure is proposed that better serves the purpose but will require higher data collection efforts. A potential approach has earlier been introduced by Hutchins and Sutherland (2008), who use the ratio of the average hourly labor cost (including benefits and taxes) to the total compensation package (converted to an hourly measure) for the company's highest paid employee. They conclude that the closer this ratio is to one, the greater the compensation equity within the company. The Gini-coefficient can serve as a secondary indicator of income inequality, if primary company-specific data are not available. In that specific cases, the calculated FWPs must be interpreted with caution as the used inequality measures does not purely represent a product or corporate perspective. Yet, considering the boundary condition defined with regard to the IEF, future research should also investigate, if there is an optimum level of income equality and what are potential targets in this context. While there is little doubt on the fact that a more equal distribution of income in most societies will foremost have positive impacts, from a certain point on an absolute equality of income might also create reverse effects. In this context, it can also be recommended to consider different inequality measures in a sensitivity analysis, in order to determine the order of magnitude. There is a broad range of inequality measures available, which are more sensitive to changes at the bottom or top of the income spectrum, e.g. the Palma ratio (Cobham and Sumner 2013), the Atkinson index (Atkinson 1970), the Theil index (Bellù and Liberati 2006), the Kakwani progressivity index or the Robin Hood Index (De Maio 2007). Additional inequality factors, which e.g. address discrimination of gender or certain groups of society can also be possible and necessary and will be part of further development of the fair wage impact category.

Going beyond the composition of the characterization model at the midpoint level, in addition, the interrelations along a *qualitative* impact pathway have been indicated to also address the potential effects on category endpoints and AoPs. The mentioned combination Type II and Type III approaches show some potential for quantifying complete impact models. Simplified empirical relations however may not in any case solve the challenges of determining valid social mechanisms, as those contain some shortcomings regarding the artificial disentanglement of normally interlinked aspects or the negligence of reverse causalities. For instance, higher per capita income does not only result in better health (as stressed by Feschet et al. 2013) but also the other way around, as e.g. discussed by Bloom and Canning (2007). In addition, focus on detached interlinkages, like performed by Bocoum, Macombe, and Revéret (2015) with regard to the Wilkinson pathway must be considered with caution, as further important factors (e.g. unequal opportunities) named in the original book publication (Picket and Wilkinson 2010), are neglected. Thus, for establishing a thorough connection between fair wages at the midpoint level and health at the endpoint level further research is needed. The additional consideration of social determinants through sociology, politics and history may be helpful in this context.

4.1.2 Outlook Tier 2 assessment – Health, Education and Working condition

Even though focus of this chapter 4 is set on a suitable and practical midpoint characterization model for the social impact category identified within Tier 1, a brief outlook with regard to

Tier 2 is provided for the sake of completeness. Yet, the remarks and explanations presented in the following subsections are neither mature nor do they provide a final solution. They rather indicate possible and future research directions. In accordance to section 3.4 of this thesis, Tier 2 assessments include health, education and working condition as impact categories for SLCA.

4.1.2.1 Health

Assessing human health impacts at the midpoint level is not straightforward. First and foremost, health-related impacts are difficult to assess because they are relevant on different levels – worker, community, society. While the societal level can be expressed at the endpoint level using DALYs, worker´s and community member´s health can also be affected by different incidents, e.g. accidents or chronical diseases, which are better assessed at the midpoint level. Humantoxicity (which has been suggested by Neugebauer et al. 2015) as a first approximation does not cover all midpoint related health aspects. Impact categories like ionizing radiation or particulate matter also apply to assess health impacts at the midpoint level, as indicated in section 3.4. Furthermore, Finkbeiner et al. (2014) with their review on LCA, identified several fields of research with regard to health, such as direct health effects (e.g. addressed by Henderson et al. 2012) or nanomaterials (e.g. addressed by Birnbaum and Jung 2011). Despite these attempts within the LCA framework, health considerations within SLCA are mostly covered by displaying risk instead of impacts, as shown by the Social Hotspot Database (SHDB 2013). In her work about sustainability assessment along automotive supply chains, Karlewski (2015) determined rather health risk than impacts. She indicates several fields of relevance relating to health aspects of products, which may be helpful for developing additional characterization models accounting for health impacts, such as addressing the severity of accidents or the impacts resulting from indoor emissions.

Summarizing the findings, health is not easily coverable in one midpoint impact category, as the fields of relevance as well as aspects are quite diverse. Proper characterization models are so far missing, e.g. for expressing health impacts resulting from accidents, direct or indoor emissions. Further research is needed to enable a sufficient coverage of health at the midpoint level, which can partly be based on the existing studies. Once a suitable coverage of health aspects at the midpoint level is ensured, the aggregation to DALYs at the endpoint level will become more convincing and informative.

4.1.2.2 Education

Education, even though broadly discussed within SLCA, has not yet been covered within a quantitative midpoint impact category. Hunkeler (2006) defines education as a midpoint impact and proposes to determine education, health care and housing, through working hours needed to afford it. Labuschagne and Brent (2006) name access to education without specifying concrete measures. Neugebauer et al. (2014) provide a qualitative characterization model considering inventory indicators with regard to primary, secondary and tertiary education levels, which are then categorized and linked to defined endpoint categories, such as economic welfare. They further consider aspects of gender discrimination, literacy rate or access barriers.

However, even though the study of Neugebauer et al. (2014) provides a basis, further research is needed for establishing a quantitative characterization model to include education into SLCA studies. Socioeconomic studies on human capital and education, e.g. presented by Blundell et al. 1999; and Montenegro and Patrinos 2014, can help to bridge the gap towards quantitative characterization models, as they provide correlations between years of schooling and returns to schooling (by labor market earnings) for 160 economies. Further studies with regard to child development e.g. presented by Chang, Schneider, and Finkbeiner (2015) may help to address children's needs in connection to education.

4.1.2.3 Working condition

Working condition embodies one of the core concerns within SLCA and has been broadly mentioned by several studies (compare sections 2.3.2 and 3.4). The considerations are however limited to a qualitative level through the inclusion of descriptive indicators, included e.g. by Dreyer, Hauschild, and Schierbeck 2006; Kruse et al. 2009; Jørgensen et al. 2008. No characterization model is available, partly because consensus on the scope of the impact category is missing as 'working condition' are not easily separated from other impact categories. For instance, accidents are often covered under working condition, but could also be covered within the impact category ‘health’. In the same way that working condition is difficult to distinguish from human health, the boundary between working condition and human rights is also unclear, as both address aspects like child or forced labor.

Therefore, further research should focus on a clear delineation between the different categories. For instance, only cover clearly working environment related aspects under working condition, such as contract and employment situations, labor rights and regulations. Those aspects could then be characterized by setting it in relation to specific minimum standards, like indicated by Seuring (2013).

4.1.3 Outlook Tier 3 assessment – Human rights, (Social) security, and Cultural heritage

Even more challenging than the development of characterization models for Tier 2, is the definition of characterization models at Tier 3. A brief outlook with regard to Tier 3 is provided. Yet, the remarks and explanations are to be taken as a first indication of possible research directions and do not provide a final solution.

4.1.3.1 Human rights

Similar to the challenges identified in connection with the impact category ‘working condition’, Human rights provided severe challenges due to unclear definitions, qualitative nature of indicators and a great number of other aspects. Nevertheless, the qualitative indicators or risk potentials considered already in some SLCA studies (compare section 2.3.2) serves as a basis for further developments targeting the future design of characterization models. Focus should be set on aspects like equality, dignity and diversity (as mentioned by e.g. Bienge et al. 2009; Kruse et al. 2009; Dreyer, Hauschild, and Schierbeck 2006; Jørgensen et al. 2008). Of assistance in this context can be the considerations of Anand and Sen 2000 and Diener and Seligman 2004 in connection with welfare and well-being determinations, as well as the minimum standards defined for companies by Amnesty International (1998).

4.1.3.2 (Social) security

(Social) security considerations broaden the impact category working condition and cover additional aspects, such as social services, pensions and further social provisions (e.g. maternity benefits). To achieve practical characterization models, the (qualitative) indicators, e.g. described by Bienge et al. 2009 and Weidema 2006, serve as a basis for further developments. For achieving a quantitative characterization model or at least quantitative indicators the comprehensive database of ILO (2016b) provides relevant information and aspects. Further the ILO convention No. 102 can be of assistance for setting a minimum standard for social needs regarded within the characterization.

4.1.3.3 Cultural heritage

Cultural heritage is considered a quite specific topic within SLCA, which may or may not be of great relevance for specific studies. For instance, considering a newly build production location in the Peruvian Amazon, which may threaten the local indigenous population. Such conflicts are not expected for the same production location in the German *Ruhr area*. It has been qualitatively addressed by Ekener-Petersen and Finnveden (2013) within their social hotspot analysis of laptop computers. Weidema (2006) refers to cultural heritage in connection with migration and man-made environment. As not even concrete qualitative indicators have yet been defined, further research should focus on these aspects, prior to the development of complete characterization models. Of assistance could be the institutions, which deal with issues of cultural heritage, such as *Cultural Heritage without Borders*[33] or the UNESCO (2016a).

4.2 Methodological developments for LCC

The previous chapters and especially section 2.1.3 and 2.2.2 displayed the current status and challenges for LCC, which have been summarized in Table 1. The often criticized limitation of LCC to the financial cost level (e.g. by (Grießhammer et al. 2007; Curran, Raghunathan, and Price 2004; Heijungs, Settanni, and Guinée 2012; Hall 2015; Wood and Hertwich 2012; Gluch

[33] http://chwb.org/

and Baumann 2004) is accompanied by further challenges, such as missing targets (by means of economic AoPs) and lacking definition of economic impact levels. Therefore, two paths will be followed in this section. Prior to a detailed definition and description of a suitable midpoint impact category for Tier 1 (by means of value added, as identified in section 3.3), a new structure for LCC is proposed, which provides a basis for impact assessment in LCC (following the definition presented in Box 2.1). This new structure includes suggestions for economic AoPs, a comprehensive economic impact pathway and impact categories on the midpoint and endpoint level. Therewith, the original focus of this thesis on midpoint impact categories is broadened in order to also indicate the potential linkage to the endpoint level. Yet, the development of *quantitative* endpoint categories and indicators goes beyond the scope of this thesis (compare also section 4.1.1). Subsequently, those developments are then transferred to the earlier developed Tiered approach.

The redefinition of LCC within the LCSA context has been investigated by Neugebauer, Forin, and Finkbeiner (2016). The main findings are presented in the following subsections, reprinted and slightly adapted with permission of MDPI AG (http://www.mdpi.com/2071-1050/8/5/428).

4.2.1 *From LCC to Economic Life Cycle Assessment*

Following on the previous argumentation, it appears important to redefine LCC, as economic activities have a wide range of positive and negative consequences. Those consequences may affect the other dimensions of sustainability that cannot be represented by means of monetary values only (Hall 2015; Singh et al. 2012). Therefore, a redefinition should broaden the current view especially in the context of LCSA (compare Box 2.1) and may also provide alternatives to conventional growth-oriented development targets (Sneddon, Howarth, and Norgaard 2006). The redefined economic assessment approach should include already named economic impacts, such as value added and economic resilience, as well as aspects, which are generally perceived important, such as the stability of economic systems (European Commission 2014; IMF 2015; Jackson 2011). In this relation, within this thesis a new framework by means of Economic Life Cycle Assessment (EcLCA) is proposed going beyond the classical LCC approach to more comprehensively represent the economic pillar of LCSA by also including non-monetary values and going beyond the narrow comparison of costs and benefits. Environmental LCC is considered as the basis for further developments. The re-structuring process towards EcLCA will presented in the following section.

4.2.1.1 Introducing Economic Life Cycle Assessment

An adaption of the economic pillar in LCSA requires, following on the rationale presented in Box 2.1 and the challenges summarized in Table 1, the inclusion of economic mechanisms, which represent a causal chain by means of economic impacts and AoPs. LCC in its current form does not fulfill this purpose, due to the missing impact level and its limited perspective, as pointed out by e.g. Hall 2015; Wood and Hertwich 2012; Gluch and Baumann 2004. Therefore, linking of product-specific (inventory) data to microeconomic categories and, in the following step of the impact pathway, connecting those categories to macroeconomic "damages" is proposed.[34] Thus, enhancements focus in the first instance on:

(i) identifying relevant economic categories for broadening the scope within LCSA's economic pillar (also considering the ones suggested in former studies, see section 2.3.3);

(ii) defining relevant economic target functions (by means of AoPs);

(iii) defining relevant impact categories and interlinking them within an economic pathway.

Further considerations should be taken into account, in addition to the aspects named under the points (i) to (iii). Wood and Hertwich 2012; Boons et al. 2013; and Zamagni et al. 2013 in this context require a comparison between the user´s targets (typically minimization of costs) and broader socio-economic goals (e.g. maximization of value added). Furthermore, Settanni et al. (2014) propose to put the customer point of view more into focus by defining products as value deliverables. Wood and Hertwich (2012) additionally differentiate between short-term economic cost and long-term economic sustainability by identifying aspects, like investments, labor productivity, and geographical specifications as influencing factors for economic strength. The aspect of human resources can also play an important role in contradicting the pure profit view. Some authors (Hill, Wial, and Wolman 2008; Ștefănescu-Mihăilă 2015) even

[34] The differentiation in micro- and macroeconomic considerations will further be justified in the following section.

state that growth, mostly measured in terms of GDP, cannot be the only goal or factor within economic assessments.

With the proposal of the new EcLCA, aspects mentioned in former studies are considered, like value added or productivity, but also economic impacts defined earlier, such as ‘economic prosperity’ or ‘economic resilience’. In addition, input output (I/O) approaches like the one presented by Wood and Hertwich (2012), can assist in relating aspects on the microeconomic (e.g. productivity) with aspects on the macroeconomic level (e.g. contribution to GDP), similar to the Type III approaches in SLCA, which may be of help for the determination of endpoint impact categories. Yet, beyond the *qualitative* linkage of the microeconomic to the macroeconomic level, input output analysis is not significant in the context of this thesis. As pointed out by e.g. Majeau-Bettez et al. (2016), input output analysis is more a top-down than a bottom-up method, including highly aggregated date and considering effects on the macro level rather than considering product-related issues. Therefore, the general usefulness of input output analysis with regard to LCSA and EcLCA can be questioned. From a microeconomic life cycle perspective, it appears to be more logical to start from the process level. In this thesis, the design and implementation of impact pathways is therefore targeted in order to relate microeconomic activities to macroeconomic consequences and economic targets (by means of economic AoPs).

4.2.1.2 Economic impact pathway

When describing economic activities, the classification into micro- and macroeconomic aspects is broadly supported within economic research (Hill, Wial, and Wolman 2008; Bleaney 1996; Briguglio et al. 2009; OECD 2001). Generally, microeconomic actions (striving to improve market efficiency) to a certain extent determine the macroeconomic performance, which leads to an increased or decreased economic stability and wealth (OECD 2001; Malizia and Ke 1993; Oxenburgh, Marlow, and Oxenburgh 2004; Simmie and Martin 2010; Vargo and Lusch 2008). Consequently, one of the core questions is: How do microeconomic activities and macroeconomic effects influence each other and how can those effects be measured? Within this thesis, this question is answered on a conceptual level through the identification of relevant micro- and macroeconomic categories and their interrelation. Therefore, a consideration of microeconomic effects at the midpoint level and macroeconomic effects at the endpoint level are proposed and discussed for future use in the new EcLCA approach.

The influences of small components like product systems on the functionality of an economic system are hard to grasp (Wood and Hertwich 2012). Nevertheless, micro- and macroeconomic studies, which will be presented in the subsequent sections, determine crucial factors connecting the corporate or organizational level with economy-wide effects. On this basis, an impact pathway is developed, which strives to better represent the economic dimension within LCSA. Therefore, economic aspects like financial costs should be connected to resulting impact and damage categories (see Figure 13). The linkage between an economic midpoint impact and endpoint damage level can succeed by considering the micro- as well as the macroeconomic level. The defined midpoint categories therefore describe important aspects for microeconomic market efficiency. The endpoint (or damage) categories aim at the determination of impacts on the macroeconomic level, which are interlinked with the defined midpoint categories. Additionally, two economic areas of protection have been defined, describing target values by which economic activities are assessed.

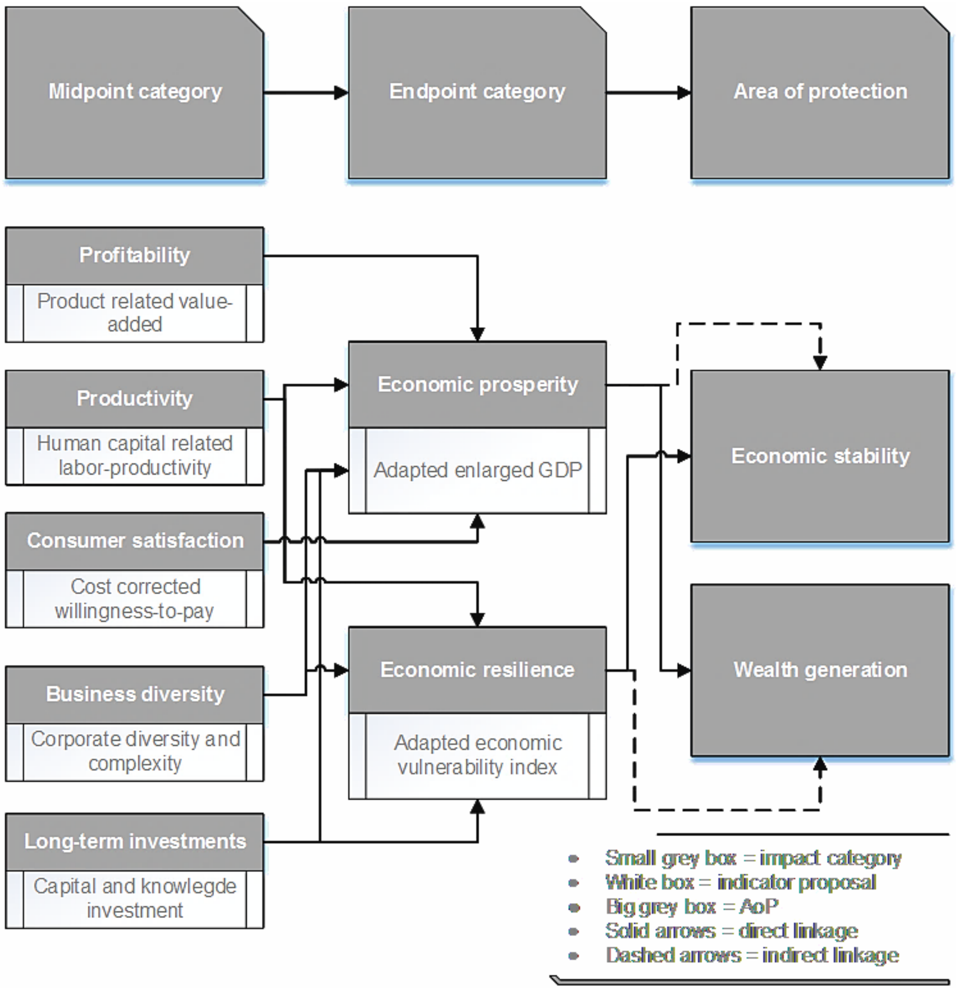


Figure 13: Impact pathway representing the economic dimension of sustainability within LCSA

To summarize the findings displayed in Figure 13: 'economic stability' and 'wealth generation' are essential targets for today's economic systems (IMF 2015; European Commission 2014; Wood and Hertwich 2012; Anand and Sen 2000; Felipe and Hidalgo 2015; Offer 2007). They appear therefore suitable to be defined as economic areas of protection. While the latter rather represents the classical orientation on growth and prosperity, the first adds an additional perspective by bringing in aspects, which go beyond the growth concept, such as the resilience of economic systems. Accordingly, two crucial aspects affecting the two areas of protection are: 'economic prosperity' and 'economic resilience'. The latter describes the shock resistance and long-term functionality of an economic system, which influences its stability (Hill, Wial and Wolman 2008; Briguglio et al. 2009; Simmie and Martin 2010). The former is more oriented towards the classical economic growth paradigm generating a macroeconomic 'value added', which affects wealth (Curran, Raghunathan and Price 2004; Ștefănescu-Mihăilă 2015; Blok et al. 2013). These two endpoint categories are determined by several midpoint categories describing microeconomic activities and targets. Within this thesis the microeconomic activities and targets identified as relevant for economic impact assessment at the midpoint level are: *profitability*, understood as microeconomic value added (Settanni et al. 2014); *productivity*, understood as output in connection with employee participation and human development (Blundell et al. 1999); *consumer satisfaction*, representing a product's utility from a consumer perspective (Jonkman, van Gelder, and Vrijling 2003); *business diversity*, understood as region-specific corporate diversity (Simmie and Martin 2010); and *long-term investments*, determining the long-run success and survival in the market (Ștefănescu-Mihăilă 2015) and including dependencies on different types of capital (The World Bank 2011). Microeconomic aspects like profitability, productivity, consumer satisfaction, and long-term investments have earlier been addressed within the Oxfam Poverty Footprint (Oxfam International 2009). Thus, the defined midpoint categories are not only relevant for developed economies, but also for the developing world.

To follow the Tiered approach presented in chapter 3, core considerations within this thesis are limited to midpoint impact categories and more specifically to the Tier 1 level. The same applies for the developments in connection with EcLCA. Consequently, detailed descriptions of the related endpoint impact categories as well as the AoPs can be taken from the original article included in the Annex, but are not further addressed within this thesis. The defined midpoint categories are in more detail described in the following sections 4.2.2 to 4.2.4. As the focus is set on the definition of a characterization model for Tier 1, value added, as defined within section 3.3 and included within the midpoint category 'profitability', plays a key role in the following considerations.

With the pathway and the new EcLCA approach the reality of economic systems may better be accounted for in economic assessments. It was initially focused on achieving a conceptual framework addressing possible and considerable interlinkages between the micro- and the macroeconomic level. Relations between economic activities and resulting consequences have been displayed going beyond the narrow perspective of LCC.

4.2.1.3 Utilization of the defined EcLCA approach within the Tiered approach

Within the Tiered approach, presented in chapter 3, classical LCC has been considered by ranking different cost categories. With the development of the EcLCA approach, those cost categories are replaced by the newly defined midpoint categories described in the related article of Neugebauer, Forin, and Finkbeiner (2016) in order to align the economic assessments practice with LCA and SLCA. Considering the followed approach of section 3.2 the suggested impact categories are ranked as shown in Table 12. Therefore, the criterion 'practicality' is again treated as superior compared to the other two.

Table 12: Criteria-based indicator hierarchy for the EcLCA impact categories

Impact category	Practicality[a]	Relevance[a]	Method robustness[a]
Profitability	Data are available through management accounting practice[b] and partly by The World Bank[c]	Economic values are e.g. addressed by the Global Reporting Initiative and the International Monetary Fund[d]	No characterization model available, but concrete indicator proposals for value added are available - compare section 4.2.2. Linkage to the endpoint level seems possible - compare section 4.2.2.
Productivity	Data are available through management accounting systems[b] and others[e]	Productivity is addressed by e.g. OECD and The World Bank[f]	No characterization model available, but concrete indicator proposals are available - compare section 4.2.3.1.
Customer satisfaction	Data are partly available through management accounting systems[b]	Customer satisfaction is commonly part of the Balanced scorecard[g]	No characterization model available, but concrete indicator proposals are available - compare section 4.2.3.2.
Business diversity	Data may be available through management documents; however secondary data sources are required for assessments.	Relevance in connection with economic resilience and stability identified by several authors[h]	No characterization model and no concrete indicator proposed. First coverage within the Product complexity index[i]

Impact category	Practicality[a]	Relevance[a]	Method robustness[a]
Long-term investments	Data may be available through management documents; however concrete data requirements are not clear at this point.	Identified as relevant by e.g. The World Bank and the GRI[j]	No characterization model and only qualitative indicator[k] proposed.

[a] Criteria gradation in high, medium and low correspondence through coloring including nuances.
[b] (Bovea and Vidal 2004; Heijungs, Settanni, and Guinée 2012)
[c] (The World Bank 2016c)
[d] (Global Reporting Initiative 2013; Bems and Johnson 2015)
[e] Psacharopoulos 1994 and Montenegro & Patrinos 2014
[f] (OECD 2001; The World Bank 2011)
[g] (Hansen and Schaltegger 2016)
[h] (Felipe et al. 2012; Hausmann et al. 2013)
[i] (Hausmann et al. 2013)
[j] (The World Bank 2011; Global Reporting Initiative 2013)
[k] (Zadek and Tuppen 2000)

A detailed description of the single midpoint categories can be taken from the subsequent sections. Justification for the ranking can also be found in the following subsections.

4.2.2 Tier 1 assessment – A characterization model for profitability by means of value added

Following on the findings of the earlier sections 2.1.3 and 2.2.2 and the specifications of the Tiered approach concept as well as the EcLCA framework, 'profitability' measured by means of value added is set on Tier 1. Through the value added determination different purposes can be served (compare section 3.3), as it typically includes revenues, costs and benefits and provides linkage to the broader economic performance. Those purposes will be discussed in the following sections including a concrete proposal for a characterization model and providing linkage to the endpoint level. The general relevance of the value added concept is investigated in the next section. The considerations presented within the related article (Neugebauer, Forin, and Finkbeiner 2016) are complemented by additional definitions to provide an applicable characterization model.

4.2.2.1 Relevance and classification of value added and profitability

Most firms and organizations still have a strong focus on profit margins, which is mainly substantiated in current market situations and growth-driven economic systems. Two terms are broadly used when assessing products and services: profitability and/or value added. Those product values are usually described as a mix of value creation, revenue, costs, and benefits (Aspromourgos 2013; Boons et al. 2013). Referring to the findings of section 2.1.3 and 2.2.2, the value added term has already been taken up by several authors, mainly with the target to extend the current LCC practice. While Hunkeler, Rebitzer, and Lichtenvort (2008) already mention value added in the context of LCC and suggest to also include benefits in addition to costs, practical LCC studies often omit benefits´ inclusion (compare e.g. Hochschorner and Noring 2011; Woon and Lo 2016; Ilg, Hoehne, and Guenther 2015).[35] Hunkeler, Rebitzer, and Lichtenvort (2008) refer to limitations in practicality as the main reason for frequently neglecting revenues within LCC. Moreover, the broader perspective transported with the inclusion of valued added, as e.g. indicated by Heijungs, Settanni, and Guinée (2012) with their supply chain related value added, is often neglected. In addition, although value added has already been identified as relevant for LCC (compare section 3.3), only few studies provide a linkage to the broader economic perspective, as e.g. indicated by Wood and Hertwich (2012). Hardly any study differentiates between inventory, midpoint, or endpoint (damage) levels (as required for the adaption of LCC following on the rationale in Box 2.1).

With the introduction of the new EcLCA approach, a clear assignment of different economic aspects to midpoint and endpoint impact categories has been conducted according to the presented impact pathway in the previous section. With this regard, value added as a category indicator is now assigned to the midpoint level, as it describes an important part of firms' efforts to succeed in microeconomic markets. Addressing the profit but also the operating efficiency, which is doubtlessly an important aspect of microeconomic activities, the new midpoint category is related to 'profitability'. It covers the value added concept for ensuring business success and delivery of product values.

When going beyond the theoretical definition of 'profitability' as a midpoint category, the definition of specific indicators contains further challenges. The perception of product values was evaluated as important to properly define an understanding of added value. Commonly,

[35] Note that it is only referred to published studies, as no statement on internal studies is possible in the context of this thesis. Yet, experience in assessment practice indicates that a broad range of confidential LCC exists, which may already consider revenues and benefits in addition to costs.

different value concepts are distinguished depending on the point of view and target group (compare Box 4.1).

Box 4.1: **Value-in-use vs. value-in-exchange**

Broadly, there is a differentiation between value-in-use and value-in-exchange. Value-in-exchange describes value from a neoclassical point of view and expresses the purchasing power measured through monetary values, e.g., prices. Value-in-use generally describes customer's utility during use and thus the relation between the consumer and the object consumed.

Often, products with a high value-in-use, e.g., water, have a low value-in-exchange. A similar dynamic applies for value-in-exchange, e.g., diamonds have a high value-in-exchange, but a rather low value-in-use (Lindgreen et al. 2012). This simplification does, however, not generally hold true, e.g., houses at the same time contain a high value-in-use (especially for homeless people) but also high value-in-exchange (especially for investors). Thus, those two types of value are mutually dependent on each other, as there can hardly be value without exchange and there can be no value without utility (Vargo and Lusch 2008; Azapagic and Perdan 2000).

The differentiation between both value concepts enables a logical allocation of aspects to the identified midpoint categories and indicators. Following the definitions of Aspromourgos (2013), value-in-exchange is in line with the 'value added' concept and is therefore assigned to the defined midpoint category 'profitability'. Aspects relating to the value-in-use instead address aspects of customer and business relations, as well as services and reputation, and are therefore assigned to the later introduced midpoint category 'customer satisfaction'.

4.2.2.2 Quantitative profitability characterization at the midpoint level

Following the value-in-exchange concept according to the descriptions in Box 4.1, a midpoint indicator representing the category 'profitability' includes the value added concept for displaying firms' efforts to succeed in microeconomic markets. This is normally done by including costs, benefits, and revenues. Thus, the value added indicator considers the difference between value sold and inputs purchased for products manufacturing, as described in Equation 3 (in line with the definitions of Azapagic and Perdan 2000 and May and Brennan 2006):

Equation 3: $$\boldsymbol{VA(p) = \sum_{l=1}^{L}\sum_{c=1}^{C}\{S_{c.l} - [O_{c,l} + M_{c,l}]\}}$$

where L, $C \in \mathbb{N}$ and $VA(p)$ equals the value added of product p

$S_{c,l}$ – represents total (or assumed) income of product p in life cycle stage l produced by company c

$O_{c,l}$ – represents total operating costs for producing product p in company c at life cycle stage l

$M_{c,l}$ – represents total material costs needed by company c in life cycle stage l for producing product *p*.

all values are provided in monetary units.

A product's value added[36] is consequently dependent on income through sale (*S*) minus operating (*O*) and material (*M*) costs. Labor costs are therefore included in the total sum of operational costs (and thus the value added calculation). Capital costs are excluded here, as they are accounted for within the impact category 'long-term investments' (see section 4.2.4.2). The product-related value added equals the total sum of the unit process´ value added involved in the product's life cycle within the system boundary.

Thus, the sum of all product-related *VA*(*p*) would represent the value added of the respective organization. The relation to the endpoint (damage) level can accordingly be drawn through the contribution of product-/company-specific *VA*(*p*)s compared to all (gross) value added within a defined economic system. Assumedly, as pointed out by several studies, these gross value aggregated of all sources should equal the GDP of the respective economy (Nehru, Swanson, and Dubey 1995; May and Brennan 2006; UN 2007; Hall 2015). Thus, product´s or company´s influence on the total GDP may be determinable. Therefore, 'profitability' partly

[36] A products *value added* is to be differentiated from the also often applied *contribution margin*. While the contribution margin calculation commonly includes revenues and variable costs (Torspecken 1999), the value added considers revenues and operating as well as material costs (compare Azapagic and Perdan 2000). Operating costs typically cover fixed and variable costs (Department of Economic and Social Affairs 2013). Therefore, the value added goes beyond the contribution margin by including a broader range of expenses (note that both terms are not sovereign). Inconsistencies occur in relation to labor costs, which are sometimes not covered under operating costs (e.g. compare Constable and Little 2000; May and Brennan 2006). Yet, within this thesis operating costs also incorporate labor costs.

determines the defined category 'economic prosperity' at the endpoint level. Whereas profitability's influence on the AoP 'wealth generation' may be overridingly positive, it can cause negative impacts for the AoP 'economic stability' if the focus on profits is too strong and limits in resources are neglected.

A summarized overview of the defined midpoint category can be taken from Table 13.

Table 13: Clarification and classification of terms for the proposed profitability midpoint category

Impact category	Profitability
Inventory result	Revenues and costs per life cycle stage and/or product
Characterization model	Proposed model within this thesis and the related publication of Neugebauer, Forin, and Finkbeiner 2016
Category indicator	Value added per product (group)
Characterization factor	Value added (VA(p)) per process unit
Category indicator result	Total value added per process and/or functional unit
Category endpoint	Wealth generation and economic stability by means of economic prosperity (the qualitative relations have been introduced in section 4.2.1.2)
Economic relevance	The market performance functions as a proxy for microeconomic market success.

4.2.2.3 Discussion and critical reflection of the profitability (value added) concept

Profitability sets firm´s economic performance in relation to endpoint categories, which determine the effects on a macroeconomic level through the linkage with economic prosperity by means of the (enlarged) GDP. Therewith, the value added is related to the two defined AoPs 'wealth generation' and 'economic stability', by which means the detached economic indicator has been linked to an economic mechanism.[37] Furthermore, the value added can be displayed along the life cycle of a product, which sets different production locations in perspective and displays imbalances between them. This goes beyond common LCC practice, where the final producer's perspective is typically considered and life cycle costs are summed

[37] For further background information, also consider the original article of Neugebauer, Forin, and Finkbeiner (2016), which can be found in the Annex.

up through prices of intermediate products representing the upstream supply chain. The new characterization model therefore provides a basis for comparison of the different life cycle stages comparable to midpoint indicators in environmental LCA. A direct relation to the functional unit is ensured, as all costs can directly be linked to the product.

Yet, the single components of the value added indicator may require further investigation. For instance, while one could assume the cost reduction and revenue maximization will generally increase the overall value added, labor costs embody a special-case. It may not always be beneficial to lower the labor costs, as it can cause negative drawbacks for the overall economic prosperity. The relation between labor costs and value added should in this connection be further investigated also with regard to the defined endpoint level. Different value added concepts[38], like the earlier introduced sustainable value added by Figge and Hahn (2004), can provide promising directions with regard to economic prosperity measures, such as the enlarged GDP.

Addressing the practicality of the value added indicator, the needed data are normally available through management accounting systems, as only monetary values (costs and revenues) are required to calculate the VA(p). Yet, for comprehensively calculating the value added along a product´s supply chain also secondary data sources would be required. Especially, as revenues and benefits are often sensitive from a company´s perspective. Thus, the earlier addressed LCC problem of confidential data[39] as well applies for value added calculations. Thus, while ‘profitability’ theoretically enables assessing of relevant processes along a product´s life cycle and allows for accounting of a product´s or firm´s economic situation, which determines the survival and success in the market, the lack of secondary data sources may hinder its straightforward implementation. Yet, promising starts have been introduced by e.g.

[38] Descriptions of different value added concepts, such as the sustainable or green value added, can be taken from the Glossary.

[39] Grießhammer et al. 2007; Bubeck 2002 and also Hunkeler, Rebitzer, and Lichtenvort 2008 already raised the issue of data confidentiality with regard to management accounting data or firm specific data for LCC or revenues and benefits.

Shafiee, Brennan, and Espinosa (2015) with their study on offshore wind farms. Further conclusions with this regard will be drawn in chapter 7 following on the exemplary case studies in chapter 6.

4.2.3 Refinement Tier 2 assessment – Productivity and Customer satisfaction

Even though the original focus of this chapter 4 is to present suitable and practical midpoint characterization models for the impact categories identified within Tier 1, through the EcLCA development also possible midpoint impact categories for Tier 2 could be identified. Therewith, a discrepancy[40] to the approach followed for SLCA can be recognized, where solely a brief outlook has been provided for the in section 3.4 identified midpoint categories. Following on the EcLCA approach and the ranking presented in section 4.2.1.3, Tier 2 includes the newly developed midpoint categories ‘productivity’ and ‘customer satisfaction’.

4.2.3.1 Productivity

“Productivity is commonly defined as a ratio of a volume measure of output to a volume measure of input use” (OECD 2001).[41] While there is consensus on this general understanding of the term, the measurement and definition of productivity differ broadly depending on the type of application and point of view. Productivity measures can be used to track technological improvements, efficiency, or cost savings, but also for benchmarking or determining the level of living standards (OECD 2001).

Considering classical LCC, Thomassen et al. (2009) already defined labor productivity as one economic indicator for the life cycle based assessment of dairy farms. However, no economic impact category has yet been defined addressing aspects of productivity. Productivity

[40] The discrepancy results from the initial situations of SLCA and LCC, by which means different paths have been followed with regard to the methodological developments.

[41] Some may argue that there is no clear delineation between productivity and profitability. Yet, productivity is a measure of (physical) output independent from prices, while profitability clearly depends on (input and output) prices (Ha, Strappazzon, and Fisher 2001). Productivity can affect total profitability; however, the relation is not straightforward. While e.g. productivity gains through technical changes influence profitability, training related gains in productivity may rather lead to an increase in wages than an increase in profitability (Blundell et al. 1999; Anker 2011). Furthermore, productivity gains can only result in profitability gains under the boundary condition of a certain growth level. As soon as economies stop expanding, productivity gains may lead to a reduction in total value added (Jackson 2011). Therefore, a separate consideration of both categories seems essential in the context of this thesis.

measures are normally based on economic theory and can be defined in a narrow sense when limited to output per working hours, but also in a very broad sense, when including intangible or even natural capital (Vargo and Lusch 2008).

Natural capital typically includes natural resources, such as forests, sub-soil assets, agricultural land and protected areas. It can have an important influence on the total wealth and can be transformed into other forms of capital (Hamilton et al. 2006). Yet, in the context of LCSA most aspects of natural capital are covered in LCA. Therefore, it is neglected in connection with productivity to avoid double-counting.

Intangible capital is commonly understood as the share of production that is usually neglected within the estimates of produced and natural capital. Generally, this covers the knowledge and skills of the labor force (Hamilton et al. 2006). According to broader interpretations, it can also cover information stored in humans, species, or ecosystems (Costanza et al. 1997). Furthermore, intangible capital also covers aspects of social capital and governance (Hamilton et al. 2006). Social capital and governance aspects, however, remain unconsidered within this thesis, as they were not found to be relevant from a product perspective.

Needless to say, one crucial component of intangible capital is human capital. Human capital (or employee relations) to a large extent determines the productivity within an organization. The productivity level rises and falls with employees' satisfaction, safety, skills, and knowledge (Diener and Seligman 2004; Blundell et al. 1999; Oxenburgh, Marlow, and Oxenburgh 2004). Blundell et al. (1999) point out that higher skills and knowledge within an organization's workforce positively influence the general speed, but also the flexibility and variety of production. Often education and training are listed as a way to improve employees' skills and knowledge levels. The absolute effect of education and training is, however, broadly challenged and ranges from high to no influence on productivity (Blundell et al. 1999). Therefore, aspects of training are not addressed any further and rather focus is set on education (assuming that it provides a first measure for skills and knowledge) in the subsequent considerations. Accordingly, the midpoint indicator contains two parts. The first one addresses the usual productivity measures; the second one accounts for the human capital aspects of productivity.

While the linkage between total output and business success is relatively obvious, the economic consequences resulting from using or providing different types of capital is harder to grasp. Yet. some studies draw a relation between intangible and human capital and prosperity and the generation of wealth in the long term (Ștefănescu-Mihăilă 2015; Offer 2007; Blundell et al. 1999; Hamilton et al. 2006; Diener and Seligman 2004; Jamal and Saif 2011). On this basis, ‘productivity’ is defined as a new midpoint category, translating output and labor productivity into a midpoint impact, which positively or negatively affects ‘economic prosperity’ and ‘wealth generation’. Therefore, the suggestion of The World Bank (2011) is followed, by which productivity on the corporate level is determined by intangible capital (dominated by human capital), total factor productivity (linked to technological status and change as well as natural capital), and institutional quality.

Going beyond the conceptual level, indicators are needed to determine the impact. Therefore, beside the total factor productivity, which goes in line with the output-oriented definition of productivity, the different types of capital must be considered. An earlier scheme provided by Hamilton et al. (2006) is followed, relating the different components of productivity with wealth generation (see Figure 14). Of particular interest are the components of intangible and its sub-part human capital, which are hard to determine but significantly affect the level of productivity (Diener and Seligman 2004; Blundell et al. 1999; Oxenburgh, Marlow, and Oxenburgh 2004).

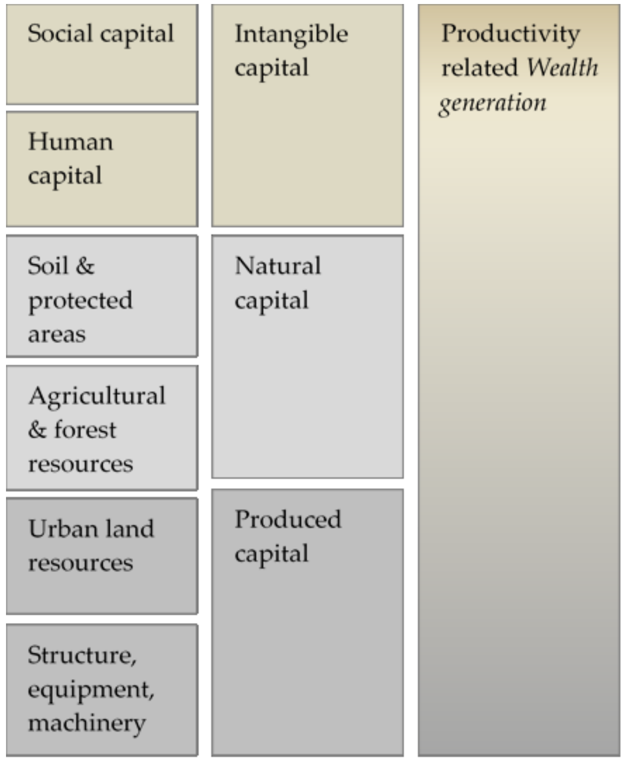


Figure 14: Productivity related components of wealth generation (adapted according to Hamilton et al. (2006)).

Usual productivity measures relate the gross value added (Thomassen et al. 2009) or volumes (IMF 2015) to the amount of labor needed to create a defined output. Adding to this, the Organization for Economic Co-operation and Development (OECD 2001) introduces *multifactor productivity measures*, which are either based on the value added or on gross output. To avoid double-counting with the proposed value-added-based midpoint indicator addressing the category 'profitability', within this thesis gross output is included for describing 'productivity' at the midpoint level (see Equation 4):

Equation 4: $$\boldsymbol{P_L(p) = \sum_{l=1}^{L} \sum_{c=1}^{C} \frac{GO_{c,l}}{L_{c,l}}}$$

where $L, C \in \mathbb{N}$; $P_L(p)$ equals the total productivity of product p;

$GO_{c,l}$ – represents the gross output in life cycle stage l for the process performed in company c (measured in total units of output)

$L_{c,l}$ – represents the labor (measured in terms of labor costs) needed by company c in life cycle stage l for producing product p.

To include the human capital aspect into the determination, *productive hours* or total person hours worked, as defined by OECD (2001) and Oxenburgh et al. (2004), can be used as a proxy for labor needed or labor services provided. Productive hours describe the total hours paid by the employer less hours not actively producing, which include injuries, illness, training, vacation, and other. Equation 4 would accordingly be transformed to:

Equation 5: $$P_L(p) = \sum_{l=1}^{L} \sum_{c=1}^{C} \frac{GO_{c,l}}{L_{c,l} - WL_{c,l}}$$

where $WL_{c,l}$ represents the work loss (hours not actively producing) within company *c* and life cycle stage *l*.

Yet, Equation 5 does not indicate any effects resulting from workers' skills, satisfaction, or knowledge. Considering e.g., studies from Jamal & Saif 2011 and Baxter & Matear 2004, the inherent complexity of human capital contributes to this dilemma. Therefore, to enable a first coverage of human capital aspects within the productivity indicator, an education measure is included, assuming that it serves as a first indication for overall knowledge and skills within the workforce. However, the equation presented below only serves as a first suggestion and further improvements are needed to cover a broader range of human capital aspects.

Wößmann (2000) suggests a simplification by focusing on a human capital related rate of return (HCRR) expressed within an exponential relation changing with an efficiency function, which weights the different years of schooling differently assuming a decreasing rate of return on education with additional schooling. It expresses the rate of return depending on years of schooling. As a first proxy the suggestions of Wößmann (2000) are followed, expressed in the following Equation:

Equation 6: $$HCRR = e^{f(LU)}$$

f(*LU*) in its simplest form is defined according to the following equation:

Equation 7: $$f(LU) = r_e \times a_s$$

where *f*(*LU*) reflects the efficiency of a unit of labor (*LU*) with s years of schooling, r_e is the rate of return on education, and a_s is the years of schooling.

First measures of rates of return on education, both social and private, are provided by Psacharopoulos 1994 and Montenegro & Patrinos 2014. However, organizations should determine their own rate of return depending on their human capital to more accurately reflect the organization's performance.

Although Wößmann (2000) considers the macro-level rather than the micro-level of economic consequences, the related function could be translated into a corporate or even product context, reflecting firm´s inherent human capital potential. Consequently, the final productivity indicator function would be defined as follows:

Equation 8: $$P_L(p) = \sum_{l=1}^{L} \sum_{c=1}^{C} \left\{ \frac{GO_{c,l}}{L_{c,l} - WL_{c,l}} \times HCRR_{c,l} \right\}$$

where $HCRR_{c,l}$ describes the rate of return be defined as follows of company *c* in life cycle stage *l*.

In its final version, it is fair to assume that the suggested midpoint indicator 'productivity' influences 'economic prosperity' at the endpoint level due to the incorporated labor productivity. It may further affect 'economic resilience' due to the incorporated human resources.[42] How the aggregation from the midpoint towards the endpoint level is performed goes beyond the scope of this thesis and will be part of further research. The presented studies of Hamilton et al. 2006; OECD 2001; and Ștefănescu-Mihăilă 2015 can therefore serve as starting points. In addition, further investigations are needed for clearly delineating 'profitability' and 'productivity'. The core question here is if and to what extent labor costs can be regarded in both midpoint categories without causing double-counting.

4.2.3.2 Customer satisfaction

Customers including consumers embody the target groups of most business activities (Payne, Storbacka, and Frow 2008). Consequently, customer relations and customer satisfaction are important for a business's success and should not be neglected within economic assessments (Vargo and Lusch 2008; Baxter and Matear 2004). Customers' value and utility are crucial for

[42] Economic resilience is normally described through three aspects: shock resistance, state of equilibrium and long-term considerations. The latter one addresses i.a. aspects of human resources and knowledge (Simmie and Martin 2010; Wood and Hertwich 2012; UNEP 2010; Briguglio et al. 2009), which in this thesis are assigned to the midpoint impact category 'productivity'. Compare also Neugebauer, Forin, and Finkbeiner (2016).

ensuring that products give prolonged satisfaction (Bovea and Vidal 2004). Customer utility is generally described through product's use and thus the relation between the consumer and the object consumed (Lindgreen et al. 2012). The core question according to Ehrenfeld (2005) is: Does a product create authentic satisfaction or does it just deliver momentary relief? It is assumed that only the former creates benefits for long-term business success. In this context, authentic satisfaction can be understood as value-in-use (introduced in Box 4.1).

In classical LCC studies, the customer is only regarded through the price he/she has to pay for receiving the desired product or service (Hunkeler, Rebitzer, and Lichtenvort 2008; Klöpffer and Ciroth 2011). Grießhammer et al. (2007) go beyond this interpretation of a customer's involvement by also addressing utility. c in this context named the customer's willingness-to-pay (WTP) for increasing products' value, which may be a reflection of the utility perception of the customer (ICAEW 2006). The WTP thus indirectly provides information on long-term business success and may according to Grießhammer et al. (2007) also serve as a proxy for customer´s acceptance. It also, according to Jonkman et al. 2003 and Hacking and Guthrie 2008, enables valuation of goods and services or even externalities by means of future costs, which are not ordinarily monetized within the market. Furthermore, the WTP enables focus on the customer, as proposed by Settanni et al. (2014).

Therefore, 'consumer satisfaction' is defined as a new midpoint category to cover aspects of utility and of value-in-use as well as customer relations within EcLCA. Consumer satisfaction may contribute to determine an organization's market success as well as indicates the customer's factual utility. Its contribution to prosperity and thus wealth is not as straightforward, as the a positive individual utility does not automatically result in a positive societal utility as pointed out by Grießhammer et al. (2007).

The abovementioned approach of Bovea and Vidal (2004) for including the WTP in the assessment is promising when going beyond the conceptual level towards indicator development, in particular as value-in-use (as introduced in Box 4.1) is by definition hard to grasp. Some interpret value-in-use as future attributable cash flows (Smals and Smits 2012). Often, value-in-use is also understood as value-based selling, considering product design, services and support, and reputation (Zadek and Tuppen 2000; Felipe et al. 2012). The customer would then react to those offers from the selling organization with emotion, cognition, and certain behaviors, which could result in a transaction of goods and services (Bovea and Vidal 2004). Grießhammer et al. (2007) in this context distinguish between the functional utility of products, the symbolic utility and the societal utility.[43] The different utilities may also express different aspects of the value-in-use. Yet, the determination of those utilities is not straightforward as especially the symbolic utility contains highly subjective elements depending on customer's life style and situation. In both ways of understanding the value-in-use, the customer's willingness-to-pay (WTP) can be a suitable measure, even though it may not be perfect.

Accordingly, a first midpoint indicator representing the category *Consumer satisfaction* is defined by including a customer's WTP. The approach of Bovea and Vidal (2004) is followed by also including the internal costs of the same product option to calculate the total customer's value.[44] It is understood as a maximizing function and has been described in the following equation:

Equation 9: $$\boldsymbol{CV = max\{WTP_i - IC_i\}}$$

where *CV* equals the customer's value, WTP_i the Willingness-to-pay for product option *i*, and IC_i the internal or production cost (*IC*) of the same product option.

Through the combination of the WTP and the IC the product's and/or firm's performance can be tracked and the definition of value is broadened. Both can be relevant for economies value-added at the macroeconomic level and may therefore affect the defined endpoint 'economic prosperity' and the AoPs 'economic stability' and 'wealth generation'. However, the detailed determination of the endpoint effects is beyond the scope of this thesis but should be part of further research.

[43] Details on the different utility concepts can be taken from the Glossary.

[44] Note that the WTP does not necessarily equal the price or revenue accounted for in the midpoint category 'profitability', as both terms are achieved based on different rationales. The WTP rather reflects the utility perception of the customer, as described by Grießhammer et al. (2007).

4.2.4 Refinement Tier 3 assessment – Long-term investments and Business diversity

Following on the outlook provided with regard to Tier 2, a brief outlook with regard to Tier 3 is introduced within this section. According to the ranking presented in section 4.2.1.3 (justification for the ranking can be found in the following subsections), Tier 3 includes 'business diversity' and 'long-term investments'. For enabling practical application of those impact categories, further research is needed to foster necessary improvement and go beyond the status quo of today.

4.2.4.1 Business diversity

Diversity has been determined as a crucial factor to ensure functioning economies (Attaran 1986; Malizia and Ke 1993). Diversity is important for two reasons: economic resilience and economic prosperity. This becomes obvious, as more complex or diverse products[45] can mostly be found within high-income countries with higher prosperity levels, whereas the least complex products can be found in low-income countries (Hausmann et al. 2013; Bowen and Wiersema 2005). Simplistically said: the more diverse the product portfolio within a certain economy, the higher the prosperity level. Thus, diversity may influence economic prosperity, as addressed by Malizia and Ke 1993; Briguglio et al. 2009; and Hausmann et al. 2013.

At the same time, diversity appears to be important to prevent and recover from external economic shocks[46] on both the economy and the firm level (Malizia and Ke 1993). For instance, an organization dependent on an industry that is likely to experience shocks is at risk of being hit by such a shock (Hill, Wial, and Wolman 2008). Within classical LCC, diversity has earlier been mentioned in the context of economic resilience (Hunkeler, Rebitzer, and Lichtenvort 2008). However, neither an impact category nor an indicator has yet been defined to address diversity on the corporate level. Nevertheless, economic studies often confirm the

[45] Note that, the two terms diversity and complexity describe the same cause according to Felipe and Hidalgo 2015; Felipe et al. 2012; and Hausmann et al. 2013.

[46] An economic shock is normally described as something, which affects the economy unexpected and unpredictable from the outside causing negative drawbacks for this economy and the related society. More information can be taken from the Glossary.

relationship between diversity and economic resilience. Thus, a link between diversity and the defined endpoint category of 'economic resilience' can be justified.

Business diversity typically addresses the microeconomic level, mainly following the research of Hill et al. 2008 and Felipe et al. 2012. It thus accounts for the diversification rate of organization's partners (Hill, Wial, and Wolman 2008) and/or the complexity of organization's products (Felipe et al. 2012). This also addresses the earlier required trade balance, which was mentioned by Heijungs, Settanni, and Guinée 2012; and UNCED 1992 in the context of economic assessments. Therefore, 'business diversity' is defined as a new midpoint category for EcLCA. Clearly, the complexity of products within an organization is linked to the knowledge and skills stored and mobilized within an organization (Hausmann et al. 2013). To avoid double-counting between this midpoint category and the earlier defined category 'productivity', within 'business diversity' knowledge is only addressed in relation to the intricate structure of organization's products. Within productivity knowledge and skills are linked to human capital related aspects, e.g., for indicating how knowledge influences the workforce and performance (see 4.2.3.1).

A firm's diversification is especially relevant for highly specialized industries and sectors, like mining or agriculture. Those industries are highly dependent on natural resources, weather conditions, and market demand. All those aspects together may be more likely to result in business or external shocks, due to changing demands, weather disasters, and unsustainable resource management (Malizia and Ke 1993; Felipe and Hidalgo 2015).

Measuring business diversity strictly at the product or corporate level appears challenging. Even though Hausmann et al. (2013) earlier suggested a product complexity index (PCI), which covers a variety of products and also considers their intricate structure. It does, however, not give an indication of if and when a firm's diversity is sufficient, as it rather displays a country's situation. A closer relation to the corporate and product level has been provided by Bowen and Wiersema (2005). They define a firm's optimal level of diversification by accounting for its strategic response resulting from competitive pressure (transaction cost theory) and resource based relatedness (resource based theory). They furthermore identify different variables influencing a firm's diversity, like resource-based dependencies, firm size, and export and import intensities. They, however, fail to address product's complexity (as suggested by Hausmann et al. (2013)). Thus, the combination of both approaches was found promising to comprehensively cover 'business diversity' at the midpoint level. However, a more thorough investigation, which goes beyond the scope of this thesis, is needed to develop a meaningful EcLCA indicator. Furthermore, the differentiation between the midpoint and macroeconomic (endpoint) level is straightforward for 'business diversity', as the defined category could generally reflect both levels. Business diversity can describe a company's as well as a region's level of diversity. However, as the resulting level of diversity heavily affects the two defined endpoints of economic prosperity and stability, here 'business diversity' is defined as a midpoint category reflecting the corporate level.

4.2.4.2 Long-term investments

Economic development can only be sustainable if constant capital stocks or at least constant capital services are ensured over a longer time period (Hamilton et al. 2006; The World Bank 2011). This is particularly important for organizations involved in natural resource business. Those resources must be carefully managed to avoid the "resource curse", which would hinder long-term development and thus prosperity (Hamilton et al. 2006; The World Bank 2011). Thus, long-term considerations influence the success and survival of an organization in the market and ensure corporate self-reliance (Bleys 2013; Ștefănescu-Mihăilă 2015; The World Bank 2011). Long-term considerations also appear relevant in connection with agricultural products, as soil fertility determines a business's success in the long term (Casson 2003). According to the Global Reporting Initiative 2013; The World Bank 2011, and others (Talberth, Cobb, and Slattery 2007; Zadek and Tuppen 2000), such long-term considerations should include general investments, reproducible capital, longevity, and technical developments. They furthermore identify investment grants, subsidies leading to capital accumulation, and genuine savings as crucial in the long term. Some (Nehru, Swanson, and Dubey 1995) even count human capital investments as crucial for growth and wealth in the long term; however, to avoid double-counting, within this thesis it is only referred to human capital in the context of productivity.

Although, Hunkeler, Rebitzer, and Lichtenvort (2008) already mentioned long-term costs and stresses that consideration have to exceed monetary considerations, within classical LCC the aspect of long-term economic development and thus long-term investment has mostly been neglected. Naturally, investment costs have been considered by targeting cost savings throughout a product's life cycle. However, aspects like the abovementioned have not yet been included, nor were impact levels defined. Furthermore, according to Casson (2003), risky economic conditions often hinder the consideration of long-term investments.

To cover issues mentioned above, 'long-term investments' as a new midpoint category is proposed, as it tends to be important for microeconomic market efficiency in the long run. This midpoint also affects 'economic resilience' at the endpoint (macroeconomic) level, as it influences economies' stability by covering the aspect of capital accumulation. This may have positive effects on import and export diversification important for resilient economies (Briguglio et al. 2009; Felipe and Hidalgo 2015; Hill, Wial, and Wolman 2008). In addition, long-term investments influence economic prosperity as genuine savings may positively contribute to a firm's success and thus to economies´ value added (Talberth, Cobb, and Slattery 2007; Zadek and Tuppen 2000).

Quantitative measures for the defined midpoint category are hard to define; however, Zadek and Tuppen (2000) proposed a qualitative indicator addressing long-term investments. They described a classification and categorization of different investment decisions, like capital investment (e.g. plants), knowledge investment (e.g. research and development), or acquisition. Defining a practical indicator on long-term investments is not trivial, as its link to the product level is challenging plus it requires retrospective and assumed prospective time series along an organization's existence (Hamilton et al. 2006). Therefore, for now only the qualitative indicator level is considered. However, the development of quantitative indicators is of utmost importance, especially as long-term considerations have far-reaching effects within and beyond economies (Zadek and Tuppen 2000).

4.2.5 Critical reflection and outlook of the EcLCA approach

With the definitions of first endpoint and midpoint categories as well as economic AoPs for EcLCA, new considerations and aspects are provided for the representation of the economic pillar within the LCSA framework. Relevant relations between the midpoint and endpoint level have been displayed through the defined impact pathway by which means economic mechanisms are indicated. Through this a more comprehensive structure for LCSA's economic pillar has been achieved, displaying relevant aspects of economic activities. Furthermore, the new structure better copes with the rationale presented in Box 2.1 and commonly targeted within the LCSA framework. Therewith, the earlier addressed challenges for LCC (compare points (i) to (iii) in section 4.2)[47] have been addressed and partly resolved or at least mitigated. Furthermore, the earlier by Wood and Hertwich (2012) named contradiction between the individual user perspective, which mainly considers the minimization of costs, and the broader socio-economic perspective, which targets the maximization of value added, has *qualitatively* been addressed through the presented impact pathway, which also indicates possible consequences at the endpoint level. For the determination of concrete measures at the endpoint level, future research may also consider broader economic assessment approaches, like ecological economics, which can provide helpful insights.

Yet, the complexity of the EcLCA approach in comparison to LCC, may at the same time add benefits and obstacles for common assessment practice. Through the inclusion of targets and impact categories a more comprehensive assessment level can be achieved, which has been required by several authors (e.g. Settanni et al. 2014; Hochschorner and Noring 2011; Wood and Hertwich 2012; Hall 2015; Gluch and Baumann 2004; Bubeck 2002; Hoogmartens et al. 2014). Thus, the new EcLCA may enhance the willingness to perform economic assessments. However, it requires additional data beyond monetary values, which may impede a straightforward implementation given the fact of lacking secondary data sources. While the classical

[47] The identified challenges refer to the identification of economic impact categories, economic target functions (AoPs) and their interlinkage through an impact pathway.

LCC cannot compete to this level of comprehensiveness, it may provide benefits in practicality, as less data is required and costs provide a simpler unit of measure.[48]

The identified Tier 1 level with its inclusion of 'profitability' may ease the transition from LCC to EcLCA by providing a bridge between both assessment types, as it is based on monetary values, but provides linkage along an economic impact pathway. Moreover, the additional categories defined go beyond that classical cost-orientated view, by also considering non-monetary measures, e.g. gross output and years of schooling for 'productivity'. Both categories 'profitability' and 'productivity' are not entirely new within business accounting practice, but have not been considered within the classical LCC framework, nor have their implications towards an economic endpoint level and economic AoPs been addressed. With the two impact categories 'business diversity' and 'long-term investments' the scope of classical LCC has further been broadened, through the inclusion of product complexity measures, export and import intensities and export diversification parameters.

The different perspectives typically regarded within LCC assessments (e.g. producer and consumer) are now reflected within the defined impact categories, as e.g. 'profitability' and 'productivity' display producers´ performance along the life cycle and 'customer satisfaction' addresses consumers´ view on certain products or services. Those midpoint and endpoint categories should preferably account for all relevant aspects along a product's life cycle. In this context, it is also worth mentioning that the list of possible and suitable midpoint and endpoint categories is not necessarily limited to the ones presented here. For instance, additional impact categories may be expedient, e.g. to better address the influence of governmental systems on the economic situation, as policy actions can have a crucial influence on the macroeconomic performance (Briguglio et al. 2009; Simmie and Martin 2010; Bleaney 1996). Furthermore, coverage of socioeconomic aspects, neither covered in SLCA nor in the new EcLCA, can be required, such as intangible capital.

With regard to the endpoint level, the growth paradigm has been questioned several times with the argument of finite resources and unsustainable consumption patterns, which may

[48] Although, LCC also faces shortcomings in practical implementation, as summarized in Table 1.

e.g. lead to irreversible environmental damage and resource depletion (Jackson 2011; Daly 1994; Meadows et al. 1972; Meadows, Meadows, and Randers 2004). Therefore, additional endpoint categories and/or AoPs can become meaningful in future considerations. However, some aspects of the growth criticism can already be covered under the endpoint category 'economic resilience'. For instance, irreversible depletion of all oil resources in a highly oil depending system may lead to a collapse of its economy. The economic resilience of the same system would be accordingly low and can thus serve as a first indication for its unsustainability.

Further emphasizing the conceptual nature of the presented EcLCA approach, all proposed categories and indicators are understood as starting points that need further investigation and adaption. Similar accounts for establishing a measurable linkage between midpoint and endpoint indicators, as within this thesis a rather qualitative relation was targeted and focus has clearly been set on the definition of first midpoint indicators representing the categories. Nevertheless, further research should include the definition of comprehensive characterization models, which have not been targeted within this thesis, but are essential for future application of the EcLCA approach. Therefore, accompanying obstacles and challenges of the different categories require consideration. To start with the already in section 4.2.2.3 identified challenges addressing 'profitability', data availability and confidentiality appear to be a crucial concern, which can hinder the categories implementation or at least usage in case studies. Yet, as soon as data are available but confidential, internal assessment can still be performed, which has already been explored by Grießhammer et al. (2007) in the context of LCC. They referred to the performance of critical reviews, which can ensure both discretion but also credibility. Furthermore, publication of average data may help to publish EcLCA results.

Going beyond the Tier 1 category 'profitability' and the general data challenge, additional challenges can be identified for the Tier 2 and 3 categories. With regard to the midpoint category 'productivity' the inclusion of the human (or even intangible) capital component may require further consideration. Even though the initial indicator proposal includes human capital aspects via the human capital rate of return, the linkage between years of schooling and value of human capital is not in any case supported by strong correlations. Mulligan and Sala-i-Martin (1997) in their study point out that under certain conditions both factors can increase without affecting the other. Therefore, different ways of determining the influence of human capital on productivity should additionally be evaluated. Several authors investigated the influence and scope of human capital aspects, e.g. Jamal and Saif (2011) considering human capital management scores, or Blundell et al. (1999) determining the contribution of human capital to national economic growth at the macroeconomic level. Further development of the midpoint category 'productivity' should consider those different approaches addressing the category development itself but also its potential linkage to the endpoint level.

Addressing the midpoint category 'customer satisfaction' the willingness-to-pay was found a suitable approximation for customer´s acceptance. Yet, WTP measures contain shortcomings, as an inherent requirement is that everybody has perfect knowledge. Thus, prices assumed through WTP would be very different, if the inconsistencies in knowledge were eliminated (Costanza et al. 1997). Rüdenauer and Grießhammer (2014) within their study point out that those inconsistencies often result from the negligence of future costs and therefore suggest to provide life cycle costs to customers e.g. at the selling point of household appliances. In addition, the WTP contains values choices, which further impedes the objectivity of the measure (Grießhammer et al. 2007). To mitigate shortcomings of the WTP concept and to better determine the consumers´ behavior, the mental accounting[49] approach can be of assistance. In addition, further consideration should orientate on utilizing the value-in-use and value-based-selling concepts in order to improve the indicator composition of the midpoint category. Further challenges occur for the latter categories proposed for Tier 3. Especially their adoption to a life cycle perspective may provide challenges, as existing indicators for both categories rather address an organization´s or even economy´s perspective.

[49] Mental accounting describes consumers´ behavior from a behavioral economics perspective and therewith helps explaining anomalies in classical economic theory. Further information can be taken from the Glossary.

4.3 Thematic classification of the methodological developments

Building on the presented Tiered approach concept of chapter 3, different methodological developments have been initiated for aligning the maturity of LCA, SLCA and LCC. Therefore, different paths have been followed for SLCA and LCC. While the focus for SLCA was set on the development of a characterization model for the midpoint category 'fair wage', for LCC firstly a more broaden framework was developed by means of EcLCA, followed by the development of a characterization model including value added as a midpoint indicator. Therewith, the three targets defined at the beginning of this chapter as well as the third overall objective of this thesis ('*Enhancements of LCSA´s methodological robustness*') have been addressed. Within the following chapter 5, the Tiered approach is now updated based on the methodological developments achieved.

In advance, within this section the general LCSA structure is shortly discussed against the background of the new EcLCA approach. Klöpffer (2008) originally defined LCSA through the three methods LCA, SLCA and LCC through the well-known formula:

Equation 10: LCSA = LCA + LCC + SLCA

Yet, as discussed in the earlier chapters of this thesis, especially the representation of the economic dimension by means of LCC has caused controversies. Several authors agree that it has been defined too narrow to comprehensively represent the economic dimension of sustainability (compare section 2.1.3 and see e.g. Wood and Hertwich 2012; Hall 2015; Gluch and Baumann 2004; Curran, Raghunathan, and Price 2004; Heijungs, Settanni, and Guinée 2012), which has also already been indicated by the Rio declaration (UNCED 1992). Several studies therefore considered further aspects going beyond the classical framework of Hunkeler, Rebitzer, and Lichtenvort (2008) (compare section 2.1.3 and 2.3.3). With the development of the new EcLCA framework those developments have been addressed and further extended for also meeting the requirements of the rationale presented in Box 2.1. Therewith the original formula of Klöpffer (2008) would accordingly transform in:

Equation 11: LCSA = LCA + <u>EcLCA</u> + SLCA

With the new structure, economic midpoint impact categories instead of cost categories are regarded representing the economic dimension. Accordingly, the midpoint categories developed will be included in the Tiered approach concept. Based on the in section 4.2.1.3 implemented ranking of the economic impact categories, the tables representing the three tiers will be updated in the next chapter. The in the previous section discussed discrepancy between LCC´s “handiness” and simplicity compared to the more complex nature of the EcLCA may partly be resolved through the inclusion of the category ‘profitability’ at Tier 1 bridging the transition between both approaches (compare section 4.2.5). The updated Tier 1 level will then be tested by applying the ‘sustainability footprint’ in the exemplary case studies in chapter 6.

5 Tiered approach 2.0

Based on the methodological developments of the previous chapter 4, this chapter presents the updated Tiered approach in the following two subsections. Therefore, it addresses the fourth research objective of this thesis (‘*Refinement of the conceptual approach considering the methodological developments*’). First, the methodological developments with regard to Tier 1 will be summarized in the next section. Second, going beyond the Tier 1 level, the main refinements relating to the economic dimension of the LCSA framework will be addressed in section 5.2.

5.1 Tier 1 revisited

The earlier stressed focus on Tier 1 enabled the development of specific characterization models, which allow for initiating a broader general application of LCSA. It includes the same topics than in the initial version of the Tiered approach, even though changes in methodological content have been implemented. The ‘sustainability footprint’ therefore still contains the carbon footprint representing LCA, fair wage representing SLCA and profitability (by means of value added) representing EcLCA (see Table 14). Although, only minor changes apply on first sight, the previously rather vague definitions of value added and fair wages have now been described in concrete characterization models. Therewith, the three indicators of the ‘sustainability footprint’ now follow comparable modelling approaches, which enhances their consistency and comparability. Furthermore, Tier 1 describes the contradiction between the environment, the producing economy and the society, as the three indicators representing the different sustainability dimensions address those different perspectives. Yet, different approaches, such as reflecting the same perspective for all three dimensions, may also provide certain benefits and will be discussed in chapter 7.

Table 14: Impact categories representing Tier 1 of the Tiered approach 2.0 concept

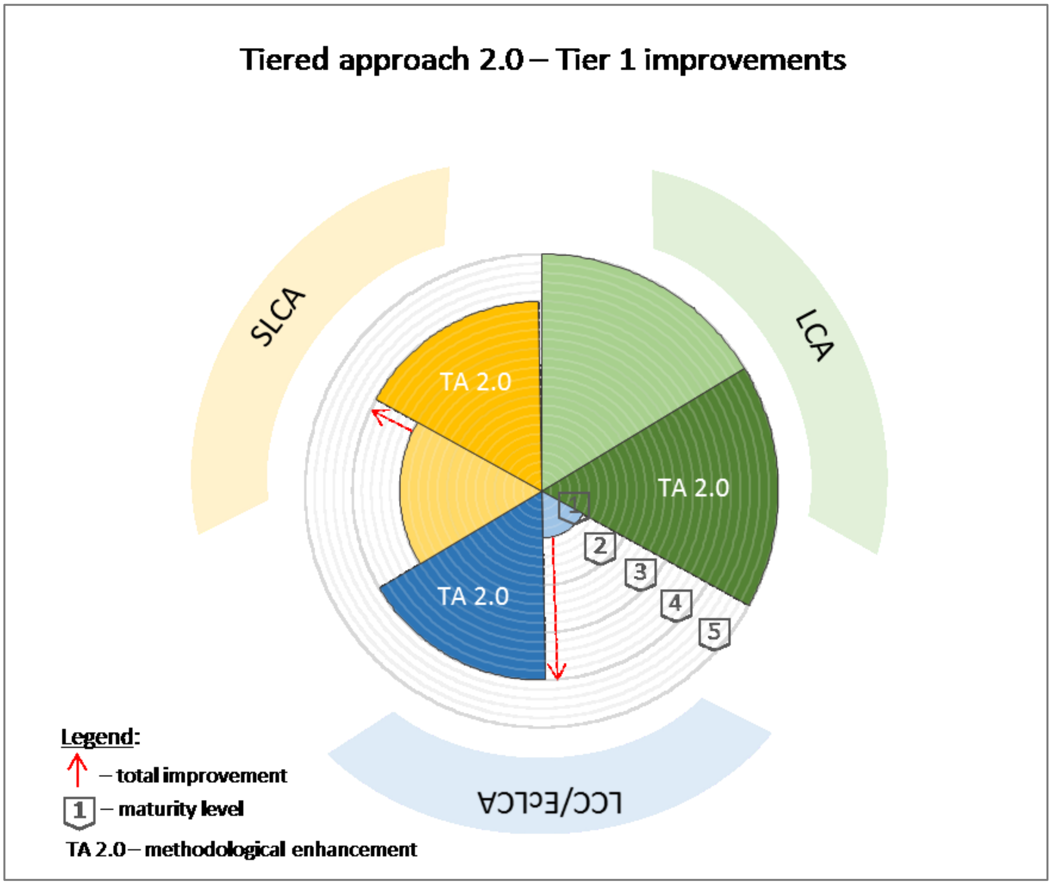
Impact categories of Tier 1 (Tiered approach 2.0)		
LCA	**SLCA**	**EcLCA**
Global climate Change	*Fair wage*	*Profitability*
**if assessing agricultural products use Eutrophication in addition*	*including minimum living wages, working time and income inequality like defined in section 4.1.1*	*including product-related value added like defined in section 4.2.2*

Table legend: *italic* impact categories indicate new developments compared to the initial Tier 1 presented in section 3.3.

The absolute range of the improvements are indicated in Figure 15. The status of the identified categories within the initial Tiered approach concept is therefore compared with the achieved status through the methodological developments (indicated through TA 2.0). The one to five scaling is based on the five steps of methodological maturity defined within section 2.1.4, Figure 8 – the steps can be listed as follows:

1) available indicators;
2) roughly defined impact categories;
3) described AoPs;
4) implemented characterization models;
5) justified impact pathways.

Improvements of the climate change category (representing Tier 1 for LCA) were not part of this thesis. Foremost, as the impact category has already reached a mature level, like indicated within sections 3.2 and 3.3. Therefore, two identical green bars are displayed within Figure 15. Focus has been set on the social and economic dimension and methodological improvements has been achieved. For the impact category fair wage, which has initially been part of the Tiered approach concept, the new characterization model enhanced the methodological maturity. Based on the methodological developments a ready-to-use characterization model is available, like required by step 4 (compare yellow bars in Figure 15). For the economic dimension even more significant improvements could be achieved, based on the development of a completely new structure by means of the EcLCA approach. Therefore, the initially defined indicator value added included in the Tiered approach concept was transferred into a characterization model, also including the definition of economic AoPs (compare blue bars in Figure 15).



*the maturity levels have been defined based on Figure 8 displayed in section 2.1.4

Figure 15: Implemented methodological improvements comparing the Tiered approach concept and the Tiered approach 2.0

5.2 General refinement of the Tiered approach concept

Even though the focus has been set on Tier 1, some developments could be achieved for Tier 2 and 3. Especially, the development of the new EcLCA framework led to a shift away from cost towards midpoint impact categories. With regard to SLCA, additional research directions have been identified within section 4.1.2 and 4.1.3, even if no concrete proposals for quantitative characterization models have been included.

For Tier 2 significant changes are considered, as the economic dimension by means of EcLCA has been revised. Based on the newly developed economic impact categories a shift from cost towards impact categories is proposed. Furthermore, additional aspects and/or research directions are proposed for the social impact categories. Therefore, Tier 2 has been adapted like shown in Table 15.

Table 15: Impact categories representing Tier 2 of the Tiered approach 2.0 concept

Impact and cost categories of Tier 2		
LCA	**SLCA**	**EcLCA**
Global climate change	*Fair wage*	*Profitability*
Stratospheric ozone depletion	*including minimum living wages, working time and income inequality like defined in section 4.1.1*	*including product-related value added like defined in section 4.2.2*
Ozone formation	Health	*Productivity*
Eutrophication	*including Humantoxicity impacts and Ionizing radiation impacts; further consideration of e.g. accidents should be part of further research like indicated in section 4.1.2.1*	*including human capital related labor-productivity like defined in section 4.2.3.1*
Acidification	Education	*Customer satisfaction*
Particulate matter	*addressing e.g. equal opportunities, literacy rate or finished degrees; further consideration towards quantitative characterization models should be part of further research like indicated in section 4.1.2.2*	*including cost corrected willingness-to-pay like defined in section 4.2.3.2*
	Working condition	
	including e.g. employment situation and labor laws; further research should focus on a clear delineation between the different categories like indicated in section 4.1.2.3	

Table legend: *italic* impact categories indicate new developments compared to Tier 2 presented in section 3.4; red impact categories are additional compared to Tier 1.

No changes for the environmental dimension have been implemented, as further developments of the LCA impact categories were not part of this thesis (compare section 2.1.1). For the social dimension, the Tier 2 considerations were limited to suggestions for the further developments of the already defined impact categories. For the economic dimension the methodological maturity has been improved by defining midpoint impact categories and economic AoPs as well as first indicators within the new EcLCA framework. Thereby, the overall maturity of the social dimension (by means of SLCA) and the economic dimension (by means of EcLCA) could be aligned (see Figure 16).

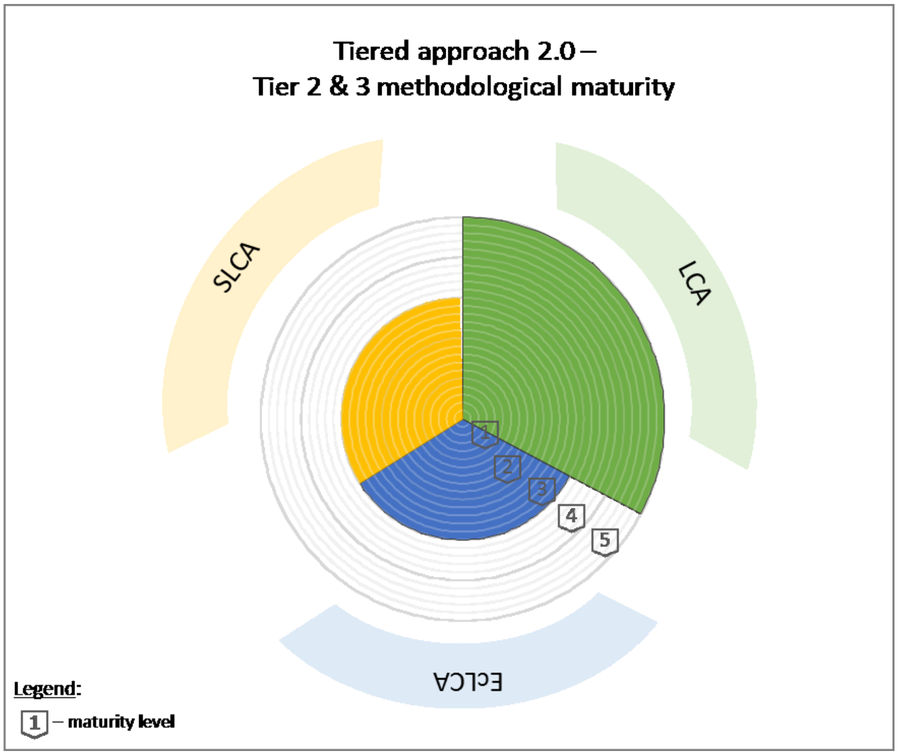


Figure 16: Methodological maturity levels of the Tiered approach 2.0 for LCA, SLCA and EcLCA

Similar to Tier 2, for Tier 3 the economic dimension is updated by means of impact categories implemented in EcLCA. Furthermore, the suggestions for the social dimension have been limited to additional research directions. Therefore, Figure 16 as well applies for Tier 3. Tier 3 of the Tiered approach 2.0 has been adapted, as shown in Table 16.

Table 16: Impact categories representing Tier 3 of the Tiered approach 2.0 concept

Impact and cost categories of Tier 3		
LCA	**SLCA**	**EcLCA**
Global climate change	*Fair wage*	*Profitability*
Stratospheric ozone depletion	*including minimum living wages, working time and income inequality like defined in section 4.1.1*	*including product-related value added like defined in section 4.2.2*
Ozone formation	Health	*Productivity*
Eutrophication	*including Humantoxicity impacts and Ionizing radiation impacts;*	*including human capital related labor-productivity like defined in section 4.2.3.1*

	further consideration of e.g. accidents should be part of further research like indicated in section 4.1.2.1	
Acidification	Education	*Customer satisfaction*
Particulate matter	*addressing e.g. equal opportunities, literacy rate or finished degrees; further consideration towards quantitative characterization models should be part of further research like indicated in section 4.1.2.2*	*including cost corrected willingness-to-pay like defined in section 4.2.3.2*
Ecotoxicological impacts	Working condition	*Business diversity*
Land use	*including e.g. employment situation and labor laws; further research should focus on a clear delineation between the different categories like indicated in section 4.1.2.3*	*including corporate diversity like defined in section 4.2.4.1*
Water use	Human rights	*Long-term investments*
Resource depletion	*including e.g. equality, dignity and diversity; further research should include welfare and well-being determinations like indicated in section 4.1.3.1*	*including capital and knowledge investment like defined in section 4.2.4.2*
	(Social) security	
	including e.g. contracts, pensions and further social provisions; further research should orientate on the requirements provided by ILO like indicated in section 4.1.3.2	
	Cultural heritage	
	including e.g. aspects of migration and man-made environment relations; further research should orientate on the requirements provided by UNESCO like indicated in section 4.1.3.3	

Table legend: *italic* impact categories indicate new developments compared to Tier 3 presented in section 3.5; red impact categories are additional compared to Tier 2.

The general refinements of the Tiered approach 2.0, as applied within this section by considering the previously implemented methodological developments, will be discussed in chapter 7. The developed characterization models representing Tier 1 have been assigned to the

Tiered approach 2.0 in the previous section and will be tested within the exemplary case studies of chapter 6. Following on chapter 6 and 7, the conclusion and outlook in chapter 8 will provide a retrospective of the achieved accomplishments, which also set the basis for further research directions.

6 Exemplary case study application

Through case study applications the applicability of the developed midpoint impact indicators is tested, in accordance to the last and fifth research objective of this thesis ('Ex*emplary case studies for testing LCSA´s stepwise implementation based on the refined conceptual approach*'). Focus is set on the Tier 1 level of the Tiered approach 2.0. Therefore, the three dimensions are considered through the three midpoint indicators – global warming potential (LCA), fair wage (SLCA), and profitability (EcLCA). Three exemplary case studies are selected demonstrating three different fields and development stages of products.

An exemplary case study on German tomatoes is included, which has partly been considered within the article submitted by Neugebauer et al. (2016). The second and the third case study emerged within a collaborative research center project and have already been part of three conference proceedings (compare Neugebauer et al. 2013; Peukert et al. 2015; Benecke et al. 2015). With the chosen case studies three different fields of study are addressed covering agricultural as well as technical concerns. While the first case study examines an existing agricultural food product of a German company, the second case study focus strives to assess a part of a new Pedelec prototype, which is still under development, and the third case study even considers a new technology within its development phase. All case studies cover the national as well as international level. Therewith, different fields of application are tested, which allow for a more valid statement on the general practicality of the newly developed Tier 1 characterization models and midpoint indicators. All exemplary case studies have therefore been slightly adapted to properly express the impact categories representing the 'sustainability footprint' (Tier 1).

6.1 Case study on tomatoes produced in Germany

To test the methodological developments on Tier 1 level for an existing product, an exemplary case study is performed using the example of German tomatoes. The case study was selected for two reasons: (1) primary data are available through contact to a German tomato producer (especially with regard to the impact categories 'fair wage' and 'profitability'), and (2) the product is of regional relevance without being too complex, which qualifies for a simplified assessment.

6.1.1 System boundaries and functional unit

All relevant processes along the supply chain of the tomato production from cradle-to-gate (Figure 17) have been considered including materials´ production for the greenhouse construction with parts from Germany, Netherlands and China; seeds´ and seedlings´ production in the Netherlands; substrate from India; pesticides and fertilizer from the Netherlands and CO_2 for the enrichment of the greenhouse air from Germany; the greenhouse operation using electricity and water produced in Germany; related management processes located in Germany; packaging with packaging materials from Germany, Italy, Turkey, Netherlands and China; and the transport processes in all related countries.

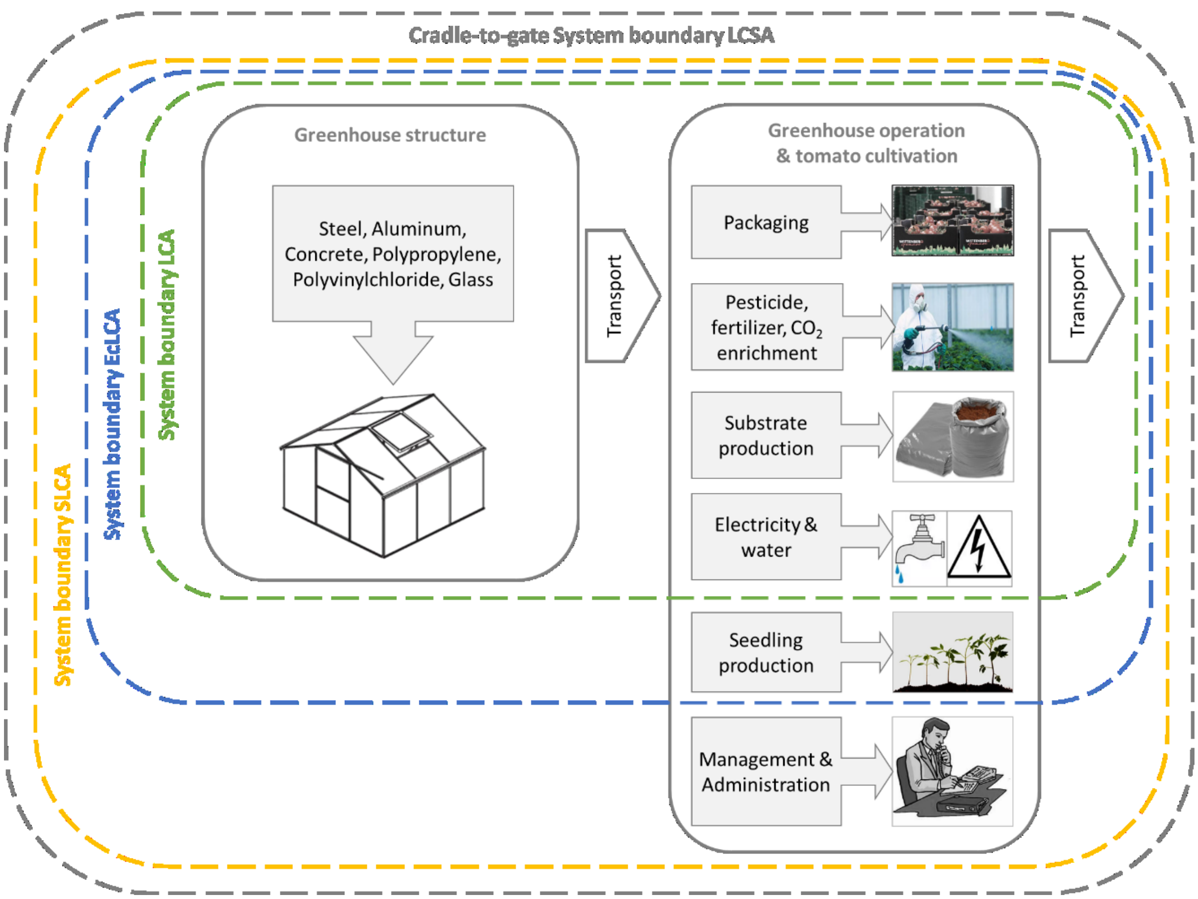


Figure 17: Cradle-to-gate LCSA system boundary for the German tomato production

While an overall system boundary for LCSA is set, the system boundaries of the three methods LCA, SLCA and EcLCA are set slightly different due to process´ relevance for the three methods.[50] Whereas for SCLA the process 'Management and Administration' is included in the system boundaries, no impacts are expected from an economic and environmental perspective. Similar accounts for seed and seedling production, which may cause social and economic impacts, but rather minor environmental impacts.

The functional unit has been set to 1 kg of tomatoes produced. For calculating the reference flow the yearly production yield of the considered production site is used to calculate the cultivation area needed to produce the functional unit (for the German production site this is 0.02 m² per kg tomatoes). All input and output flows are scaled down to that unit (compare also Martínez-Blanco et al. 2014).

6.1.2 LCA results

For the environmental dimension the global warming potential is calculated by considering five main processes – the greenhouse structure, the tomato cultivation, the fertilizer production, the greenhouse operation and the transport processes (compare Table 17). The main materials for the greenhouse are concrete, Aluminum, Steel, Polypropylene (PP), Glass and Polyvinylchloride (PVC). The respective life times of the materials have been considered for the calculation of the amount needed per functional unit (FU). Within the tomato cultivation process mainly Cocos substrate and water are required, as well as the fertilizer needed. For those process parameters, seasonal amounts have been considered for calculating the amount per FU. Within the greenhouse operation the electricity and the packaging materials have been included. With regard to packaging two main material types are included – poly-

[50] Klöpffer (2008) stresses that the system boundaries of the related LCSA methods should be consistent or ideally identical. During LCSA´s further development this view has been challenged, especially in connection with case study applications. Martínez-Blanco et al. (2014) in their study on fertilizer point out that consistent does not mean identical and that it is of greater importance that unit processes that have at least a meaningful impact on one of the three sustainability dimensions are included. This is also in accordance with the UNEP/SETAC Life Cycle Initiative (2011). This view is supported by several authors, e.g. Kruse et al. 2009; Wu, Yang, and Chen 2014; Traverso et al. 2012. Therefore, within this thesis an overall system boundary is defined including all relevant processes, yet the system boundaries of the different methods are not fully identical.

styrene and card board. An equal share of both materials has been assumed. Re-used shipping materials, such as standardized boxes from Europool or Ifco, were neglected assuming a closed-loop system by which primary burden can be neglected (compare closed-loop recycling systems according to ISO 14044 2006; and ISO 14040 2006). Transport processes are distinguished according to upstream material shipping and downstream distribution.

Table 17: Considered processes for the German tomato production including the countries of origin

Main process	Sub-process	Country of origin	Amount per FU (kg/kWh/l)
Greenhouse structure	Concrete	Germany	0.0554
	Aluminum	China	0.0009
	Steel	Germany	0.0075
	Polypropylene	Netherlands	0.0006
	Glass	Germany	0.0185
	Polyvinylchloride	Netherlands	0.0009
Tomato cultivation	Cocos substrate	India	0.0115
	Water	Germany	19.85
Fertilizer production	Nitrogen	Netherlands	0.0120
	Kalum	Netherlands	0.0058
	Phosphorus	Netherlands	0.0035
	CO2 production for air enrichment	Germany	0.0163
Greenhouse operation	Electricity	Germany	0.021
	Packaging materials (Polystyrene & card board)	Netherlands, Italy, Turkey	0.02
Transport	Materials´ shipping	Germany, Netherlands, China, India	-
	Distribution	Germany	-

Based on the given values per functional unit within Table 17 the global warming potential is calculated for all projects steps. Therefore, the GaBi database (Thinkstep 2015) and the CML method of the Institute for Environmental Sciences (Leiden University 2013) have been used.

Even though fertilizer usage can be seen as a part of the tomato cultivation process, it is separately listed here, as it contributes a significant impact. The detailed results can be taken from Figure 18.

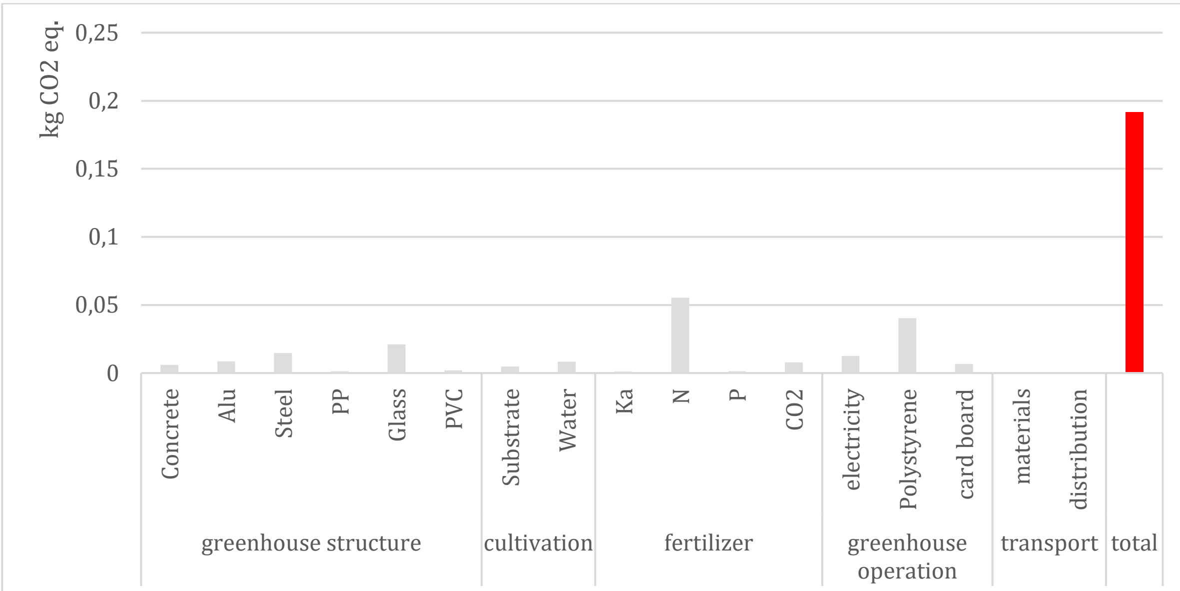


Figure 18: Global warming potential[51] for the German tomato production; the results display the processes of Table 17 considering the materials and energy used to fulfill the functional unit

Although, only the functional unit related share of materials needed for the greenhouse structure have been considered, the materials still contribute significantly to the overall impact. The biggest share however results from the fertilizer production, more specifically the nitrogen based fertilizer used within the tomato cultivation, and from the packaging material made from Polystyrene. Further materials, such as the used substrate, or sources of energy (e.g. electricity) contribute in an expected and moderate amount to the overall impact.

6.1.3 SLCA results

For the social dimension, it is focused on the groups of workers, who are expected to contribute the greatest share of working hours, such as operators or technicians, due to the exemplary nature of the case study. In a more comprehensive consideration further groups of

[51] While the definition of Tier 1 suggests to include eutrophication in addition to global warming, if agricultural products are assessed, within this exemplary case study the considerations are limited to GWP in order to ensure consistency with the other two case studies. Foremost, as the eutrophication results correlate with the GWP results – details can be taken from the Annex.

workers need to be included, such as workers performing mining operations for generating the raw materials needed. The considered groups are summarized in Table 18.

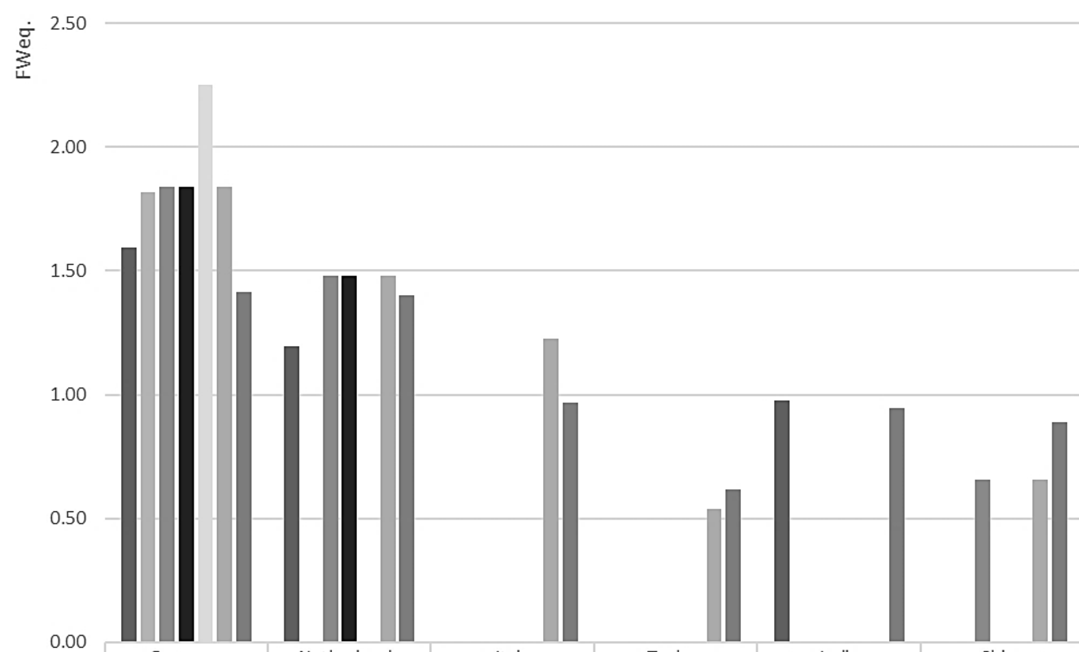
Table 18: Considered groups of workers for the German tomato production including field of work and country of production

Group of workers	Field of work	Countries of process operation
Agricultural workers	Seed and seedling production	Netherlands
	Substrate production	India
	Tomato cultivation	Germany
Workers in greenhouse management	Office management & distribution	Germany
Workers in manufacturing	Steel & glass parts greenhouse structure	Germany
	Aluminum parts greenhouse structure	China
	Plastic parts and heating system greenhouse structure	Netherlands
Workers in chemical industry	CO2 production for air enrichment within tomato cultivation	Germany
	Pesticide/fertilizer production	Netherlands
Workers in electricity/water production	Electricity needed for greenhouse operation	Germany
Workers in packaging industry	Packaging materials for tomatoes	Germany, Netherlands, Italy, Turkey, China
Workers in transportation	Transportation processes performed for all needed materials plus final transports to distribution	Germany, Netherlands, Italy, Turkey, China, India

Based on the introduced method in section 4.1.1, FWPs are calculated for all listed groups of workers and processes (compare Figure 19). Primary data on real wages and working time have been provided by the German tomato producer for the processes tomato cultivation, office management & distribution[52], which are performed in Germany. As the tomato production in Germany can be seen as a seasonal industry, monthly remuneration is considered calculated for a 12-month period, following the recommendations of Anker (2011): "Every

[52] Please note, that the primary data presented here may not represent the general situation in the German tomato production, but rather reflect the situation at the considered location of production.

industry that is not essentially seasonal should pay enough to its workers to maintain them through the slack season and through short periods of sickness." This is especially important to the workers in the tomato cultivation, as they are normally employed from March to November. Further data covering the supply chain are the taken from secondary data sources[53]. In addition, further sources (see Table 26 to Table 28) are considered for including more case specific data. With regard to data quality, only data are included which are not older than ten years. The achieved results are displayed in Figure 19.



	Germany	Netherlands	Italy	Turkey	India	China
Agricult.	1.59	1.19			0.98	
Management	1.82					
Manufact.	1.84	1.48				0.66
Chem. Ind.	1.84	1.48				
Electric.	2.25					
Packag.	1.84	1.48	1.23	0.54		0.66
Transport	1.41	1.40	0.97	0.62	0.94	0.89

[a] Values ≥ 1 are interpreted as fair, as the potentially actual wage fits or even exceeds the required MLW; values << 1 are considered as insufficient and contribute to the cases of underpayment per year, as worker's family would be unable to achieve an adequate living standard or would even live in poverty

[b] All calculated values are based family size of the respective country (by means of country-specific fertility rates).

[c] The abbreviations stand for: Agricult. – agricultural workers; Management – workers in greenhouse management; Manufact. – workers in manufacturing for the greenhouse structure; Chem. Ind. – workers in chemical

[53] Relevant data sources have been listed in a database, which has been established in connection with the article of Neugebauer et al. (2016) and can be downloaded from https://www.see.tu-berlin.de/menue/forschung/ergebnisse/fair_wage_aequivalente/.

industry; Electric. – workers in German electricity production; Packag. – workers in packaging industry; Transport – workers in transportation.

[d] The detailed calculation including data and related sources can be taken from the Annex.

Figure 19: Fair wage potentials for the German tomato production; the results display the processes of Table 18

Figure 19 shows that no significant impacts are expected for German, Dutch and Italian workers. Yet, the FWPs calculated for Chinese and Turkish workers indicates a great distance from the MLW and thus cause negative impacts for the workers and their families. Furthermore, the appearing inequality fosters the resulting negative impacts. The results for Germany and Netherlands are comparable, even though the FWPs for the Dutch workers are slightly lower. The differences for the agricultural workers may result from the different data source, as for the German production primary data were available. For the Dutch workers, secondary average data have been used. Considering the values calculated for the Indian workers, no significant impacts are expected.

6.1.4 EcLCA results

For the economic considerations of the German tomato production consider the defined value added indicator of the midpoint category 'profitability'. Therefore, the results are expressed from the perspective of the tomato producer located in Germany. Profitability impacts of upstream processes performed by different producers, such as material production or production of tomato seedlings, are not part of this thesis due to missing secondary data sources, which would allow for considering the complete supply chain. Three main categories are distinguished for the value added determination – income, material costs and operating costs. Main processes and sub-processes are allocated to the different categories orientating on the different steps of the tomato production (compare Table 19). The given monetary values are calculated per functional unit.

Table 19: Considered cost categories for calculating the value added of the German tomato production

Category	Main process	Sub-process	Euro (€) per FU
Income	Average purchase price	Price paid by food retailer	0.76
Material costs	Greenhouse structure	Aluminum	0.002

Category	Main process	Sub-process	Euro (€) per FU
		Concrete	0.0035
		Steel	0.002
		Polypropylene	0.0006
		Glass	0.018
		Polyvinylchloride	0.0004
	Packaging materials	Polystyrene	0.005
		Card board	0.05
Operating costs	Tomato cultivation	Cocos substrate	0.01
		Tomato seedlings	0.11
		Water	0.0004
		Fertilizer	0.02
		CO2 production for air enrichment	0.01
	Greenhouse operation	Electricity	0.042
		Labor	0.38
	Transport	Materials & Distribution	0.006

Based on the values presented in the Table the value added representing the impact category 'profitability' is calculated according to Equation 3 defined within section 4.2.2.2. Therefore, all relevant process costs are characterized into two value added values. Primary data on all costs categories included have been provided by the German tomato representing processes in the previous Table.[54]

Based on this, the two different value added are calculated. The red dots within Figure 20 represents the value added including infrastructure costs for the greenhouse on the left side and excluding the infrastructure costs for the greenhouse on the right side[55]. The values are calculated based on the averaged purchase price, functioning as the product-related charac-

[54] Please note, that the presented primary data may not represent the general situation in the German tomato production, but rather reflect the situation at the considered location of production.

[55] The greenhouse structure was subsidized by the European Union and is therefore not part of the expenses to be tackled by the tomato producer. However, the second value added was included to display the situation without subsidies.

terization factor, displayed in the positive green bars of Figure 20. The negative values constitute the costs spend to produce 1 kg of tomatoes (again including or excluding the infrastructure costs for the greenhouse).

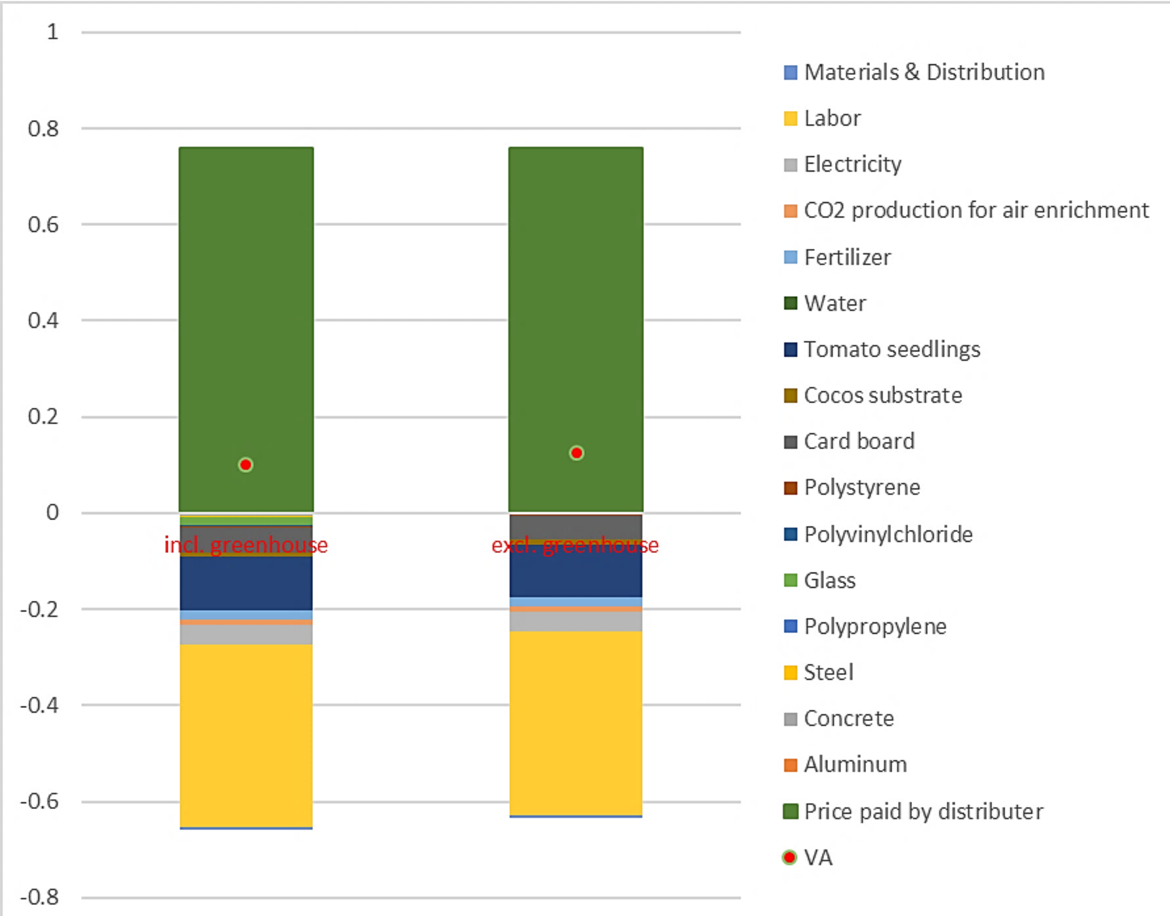


Figure 20: Value added for the German tomato production; the results display the categories and processes of Table 19 considering the monetary values per functional unit

By little surprise the labor costs significantly influence the value added, followed by the costs occurring for the tomato seedlings needed to produce one kg of tomatoes. Furthermore, the packaging material and electricity, needed to run the greenhouse, contribute a certain share to the overall impact. Nevertheless, in both cases (including or excluding the greenhouse structure) the value added constitutes a positive value, which means that the achieved value added contributes to the microeconomic market success as defined in section 4.2.2.2.

6.1.5 Interpretation and critical reflection

With the Tier 1 assessment all three dimensions of sustainability could be considered. The global warming potential provided little to no implementation challenge and could be transparently displayed for all related processes. By means of the case study, also the applicability of the newly developed fair wage method as well as of the product related valued added characterization could be proven. Yet, some challenges occurred.

The FWPs could be determined for all relevant groups of workers by using primary as well as secondary data. However, some data uncertainties apply for the case study. For instance, the FWPs calculated for the Indian workers showed no significant negative impact. Yet, the measures may contain some uncertainty, as the median[56] of average country wages was used in absence of more specific wage data. Further uncertainties may result from the average sector data, as e.g. manufacturing of the greenhouse structure and the processes that relate to chemicals and packaging are based on the same sector data. However, the results provide a good first impression of fair wage impacts for the related life cycle of the German tomato production and indicate hotspots, which are worth further investigation. A detailed case study should cover additional or preferably all relevant groups of workers along the supply chain.[57] Yet, as soon as all groups of workers are considered within a comprehensive case study further investigations of the earlier within section 4.1.1.4 discussed calculation of an overall FWP should be undertaken, e.g. by means of building a working time corrected average over all calculated FWPs. For this exemplary case study, the FWeq. are rather expressed per group of workers.

The calculation of product related value added appeared to be more challenging, as no insight in the sub-suppliers' business practice could be provided by the German tomato producer and no database has so far been created providing secondary data sources. While the value added for the core producer (the German tomato producer) could be calculated, it could not be determined for any upstream or downstream suppliers. This embodies a similar challenge

[56] The median is included instead of the average, as it is often used as the basis for determining living wages (Anker 2011).

[57] It should be noted that the characterization model for fair wage only represents workers, but does not directly address further stakeholder groups, such as consumers or local communities.

as in LCC, where costs categories are typically calculated from the perspective of the producer or consumer, but does not account for upstream or downstream suppliers. The lack of secondary data sources becomes very crucial in this context.

Despite those challenges, meaningful results could be achieved for each of the three dimensions. Naturally, the LCA results give a clear indication on existing hotspots and optimization potentials, e.g. the reduction of nitrogen based fertilizer can provide environmental benefits. With the calculation of the FWPs, life cycle hotspots for the social dimension could be identified in a similar way, e.g. the working situation in China requires further consideration. While no life cycle related hotspots in the same manner could be determined for the economic dimension, at least the value added of the primary producer was calculated, which indicates the main cost drivers and may allow for determining the influence on the macroeconomic level by means of economic prosperity considerations. In addition, first trade-offs between the three dimensions became obvious, as certain impacts significantly contribute to one dimension while they have little or no contribution to another dimension. Trade-offs could be identified between the economic and social dimension, by considering labor costs and wages. One may argue that the value added could be increased by reducing the labor costs. Yet, the social considerations by means of fair wage potentials clearly state that reductions in wages (which result from a saving of labor costs) can cause cases of underpayment, as the FWPs of the workers in the German tomato production does not significantly exceed 1. Another trade-off could be identified for the fertilizer usage, which from an economic perspective is not critical, but from an environmental perspective contributes a great share to the GWP. Thus, from an environmental perspective it was found reasonable to reduce the nitrogen based fertilizer, which has also been discussed with the German tomato producer.

6.2 Case study on Pedelec frames

A second exemplary case study is performed on frames of Pedal electric cycles (Pedelecs). The case study is partly based on the conference proceeding of Neugebauer et al. (2013), but has been adapted to the new method developments of chapter 4.

In connection with mobility bikes are generally considered as an environmentally friendly way of commuting (Bouwman and Moll 2002). A new way of cycling emerged with the development of Pedelecs combining classical bikes with a battery charged electric motor (European Union 2002). Pedelecs gain increasing relevance for several reasons (Manthey, Neupert, and Budde 2012; Lewis, Edegger, and Schriefl 2012):

- Within European and Asian markets Pedelecs constantly gain relevance
- Pedelecs are often connected to green mobility concepts in urban regions
- Several cities already established Pedelec sharing systems
- Pedelecs are applicable within different markets also including developing countries

Within the Collaborative Research Center project – CRC 1026 – targeting the achievement of sustainable manufacturing, future mobility was one important field. Therefore, Pedelecs served as a show case presenting alternative product design and improvement options. With this regard a so-called Triplec (see Figure 21) was developed combining the classical Pedelec principle with enhanced comfort (weather protection) and transport options (increased carrier capacity). Different parts of this Triplec raised questions on the best and most sustainable design, e.g. the Triplec frame was of major concern. Therefore, a comparative 'sustainability footprint' (Tier 1) has been performed comparing different frame materials and addressing different sustainability aspects.

Figure 21: Triplec as developed within CRC 1026 'Sustainable Manufacturing'[58]

6.2.1 System boundaries and functional unit

Three different frame materials are compared – Steel, Aluminum and Titanium. All relevant processes are included beginning from the raw material extraction via transport processes ending with the frame production step. Whereas the system boundaries for LCA and SLCA are identical, EcLCA additionally includes the distribution stage in order to determine purchase prices and by this means calculate the value added (compare Figure 22). Different production and finishing options are considered for the different frames (see Table 20), which are relevant from an economic and environmental perspective, but cause no difference for the social considerations. In accordance with the current market situation it is assumed that the aluminum frames are produced in Taiwan, whereas the steel and titanium frames are produced in Germany. The raw materials are supplied from different countries considering the country-specific supply situation. The iron ore is derived from Brazil (Triebskorn 2012), the bauxite comes from China (BGR 2013) and the titanium ore is supplied by Russia (Drobe and Killiches 2014)[59]. The system boundary is defined accordingly. Due to the research-oriented nature of the project and the related case study, the production locations included in the system boundary are based on certain assumptions. For instance, even if the aluminum frame has

[58] The picture is taken from an internal source of the CRC project.

[59] The assumption that the titanium is imported from Russia is additionally based on project-internal information from resource experts.

not yet been produced in Taiwan, it is likely to happen as soon as the product enters series production. Taiwan clearly dominates the global production on Aluminum bike frames, like pointed out by e.g. Gould 2014; Ratcliffe 2016; and Cycle Taiwan 2016.

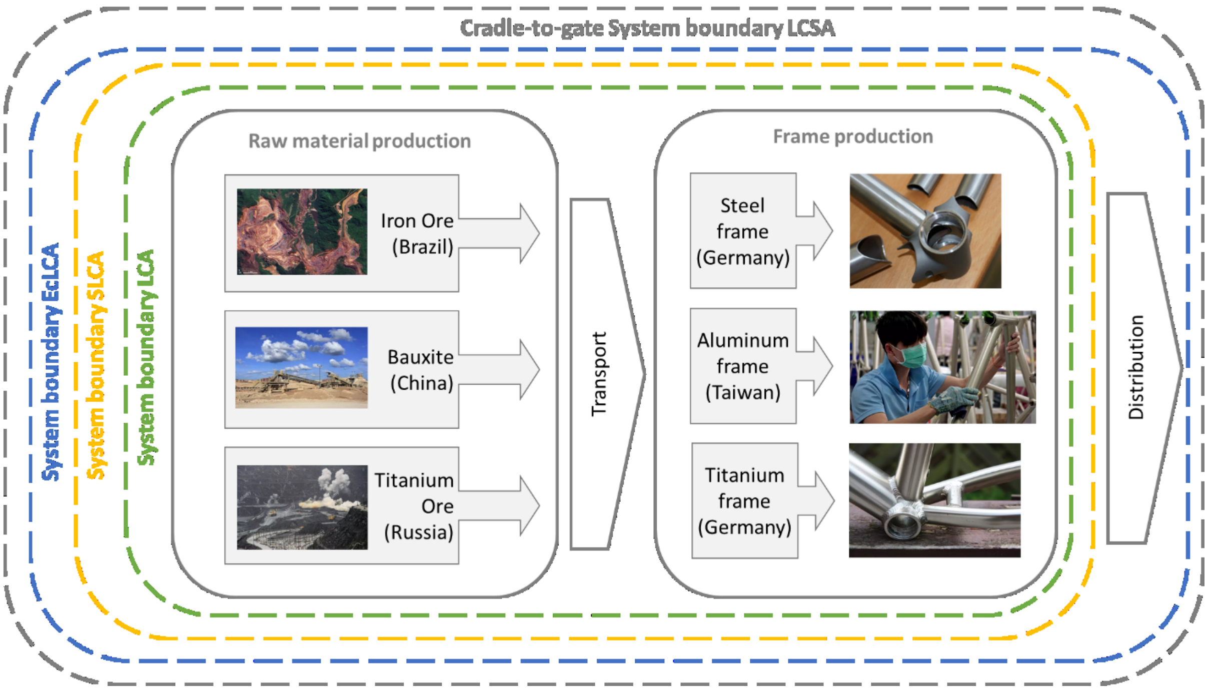


Figure 22: Cradle-to-gate LCSA system boundary for the Triplec frame production

The functional unit for the comparative assessment has been set to one piece of frame. This leads to different reference flows with regard to required material amount, connection types and finishing processes for the different frames (compare Table 20).

Table 20: Reference flow values for the different Triplec frames including weights, materials and connection/finishing options

	Carbon steel frame (DE)	Aluminium frame (TW)	Titanium frame (DE)
Weight	7.5 kg	4 kg	2 kg
Material	25CrMo4	6061-T6	Ti-6Al-2Sn-4Zr-6Mo
Type of connection	soldered or welded	welded	welded
Finishing process	galvanized or powder coated	anodized, galvanized or powder coated	anodized, galvanized or powder coated

6.2.2 LCA results

For the environmental dimension the global warming potential is calculated by considering three main process steps – the raw material production, the transportation and the frame production. The three frame options – carbon steel, aluminum and titanium – are compared by also considering different types of connection and finishing processes. Based on the reference flows defined in Table 20, the global warming potential is calculated for all frame options. Therefore, the GaBi database (Thinkstep 2015) and the CML method (Leiden University 2013) have been used.

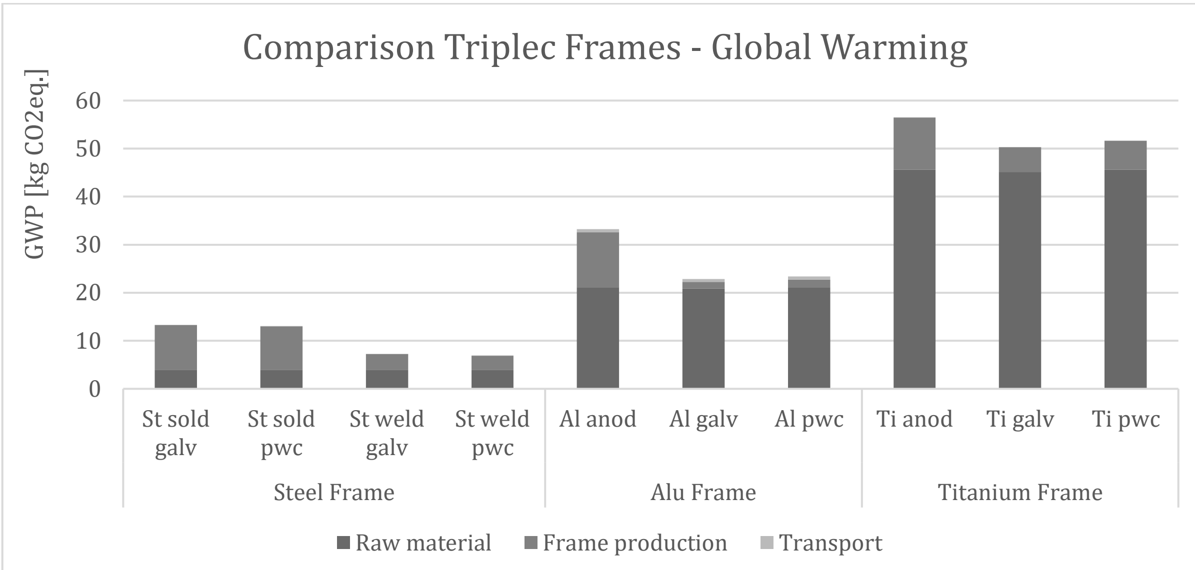


Figure 23: Global warming potential for the Triplec frame comparison; the results display the reference flow related requirements of Table 20 needed to fulfill the functional unit

As shown in Figure 23, the differences between the different frame materials are quite crucial. The titanium frame performs worst, as its raw material production with > 45 kg CO_2eq. contributes the highest share of all materials. The aluminum frame has a lower raw material burden than the titanium frame. By far the best performance has the carbon steel frame, as its raw material production undercuts that of the other materials. Differences in results for the different frame options also results from the type of connection. Welding is superior over soldering (in case of the steel frame) from a global warming perspective, due to the solder paste needed. With regard to the finishing process the anodization process performs worse than the powder coating or the galvanization, which are comparable in terms of CO_2eq.

6.2.3 SLCA results

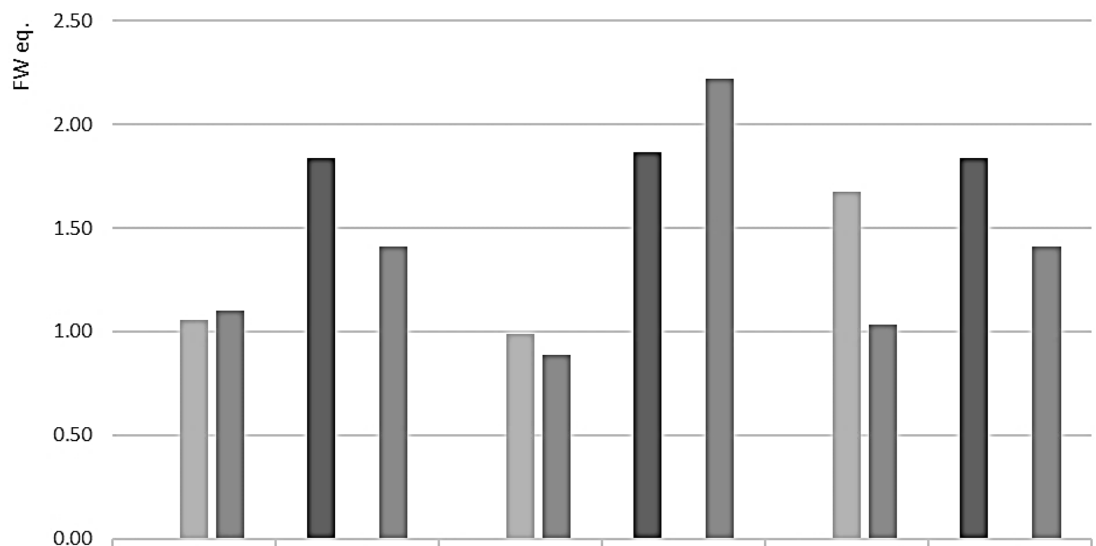
For the social dimension, it is focused on the groups of workers, who are expected to contribute the greatest share of working hours, such as manufacturer, miners and transportation workers. In a more comprehensive consideration further groups of workers need to be included, such as workers in distribution and administration. The considered groups perform the core processes needed for the Triplec frame production and are summarized in Table 21.

Table 21: Considered groups of workers for the different types of frames including field of work and production location

Frame type	Process step	Group of workers	Production location
Steel frame	Iron-ore mining	Miner	Brazil
	Frame production	Manufacturer	Germany
	Transport	Worker in transportation	Brazil & Germany
Aluminum frame	Bauxite mining	Miner	China
	Frame production	Manufacturer	Taiwan
	Transport	Worker in transportation	China & Taiwan
Titanium frame	Titanium ore mining	Miner	Russian Federation
	Frame production	Manufacturer	Germany
	Transport	Worker in transportation	Russian Federation & Germany

Based on the introduced method in section 4.1.1.2, FWPs are calculated for all listed groups of workers and processes. The data covering the supply chain are taken from secondary data sources[60]. With regard to the Brazilian transportation workers the database does not provide real average wages. Therefore, Murphy (2012) has been considered as a first approximation. With regard to data quality, only data are regarded which are not older than ten years. The achieved results are displayed in Figure 24. The detailed calculation background can be taken from Table 29 and Table 30 provided in the Annex.

[60] Relevant data sources have been listed in a database, which has been established in connection with the article of Neugebauer et al. (2016) and can be downloaded from https://www.see.tu-berlin.de/menue/forschung/ergebnisse/fair_wage_aequivalente/.



	Iron-ore Mining (Brazil)	Production (Germany)	Bauxite Mining (China)	Production (Taiwan)	Titanium Mining (Russia)	Production (Germany)
	Stainless steel & steel frame		Aluminium frame		Titanium frame	
■ Manufacturer		1.84		1.86		1.84
■ Miner	1.05		0.99		1.67	
■ Transport	1.10	1.41	0.88	2.22	1.03	1.41

[a] Values ≥ 1 are interpreted as fair, as the potentially actual wage fits or even exceeds the required MLW; values << 1 are considered as insufficient and contribute to the cases of underpayment per year, as worker's family would be unable to achieve an adequate living standard or would even live in poverty
[b] All calculated values are based family size of the respective country (by means of country-specific fertility rates).
[c] The detailed calculation including data and related sources can be taken from the Annex.

Figure 24: Fair wage potentials for the Triplec frames considering the different production locations

Figure 24 shows that no negative impacts result for all German and Taiwanese workers, as the values are >>1. The same accounts for the Russian miners. Yet, the FWPs calculated for the Chinese transport workers result in values <1. Thus, negative impacts for the workers and their families can be expected. A detailed case study should accordingly investigate those worker groups further. For the Brazilian transport and mining workers, the Chinese mining workers as well as for the Russian transport workers FWPs close to 1 were calculated. Especially, in case of the Brazilian workers, further investigations should focus on strengthening the data situation and ensuring high quality data.

6.2.4 EcLCA results

For the economic dimension, the Triplec study considers the value added of the frame producer comparing the different frame materials. Three categories are taken into account – material costs, operating costs by means of labor costs and the income achieved through sale. The required cost data have been provided by the product designers of the Triplec (CRC 1026 project partner). The labor costs and income rates are not that easy determinable, as no series production did take place, yet. Therefore, those are mainly based on assumptions reflecting a typical series production in Taiwan or respectively Germany. By this means the labor costs could be assumed through typical hourly wages[61] and process time (Freewheeler 2016; Bluecraft Bikes 2016). The concrete income gained through the sale of the Triplec or Triplec frames could not be determined. Therefore, profit margins for retailers, based on the current bike and Pedelec market situation, have been assumed for calculating the value added. A study performed by a German bank (VR 2013) concluded that the overall margin aggregates to 39.5 %. The EHI Retail Institute (EHI 2013) within its statistics refers to 36 % average benefits. Within the case study the more conservative amount is included for calculating the value added. All values can be taken from Table 22.

Table 22: Considered parameters representing the different frame types in accordance with the functional unit

Frame type[a]		Material costs [€]	Operating costs (by means of labor costs)[c]	Income through purchase [€]
Aluminum frame (Taiwan)	Al pwc	43	190.83[b] (assuming a process time of 24 hours)[d]	Assuming a 36 % profit margin[f]
	Al anod	47		
	Al galv	153		
Steel frame (Germany)	St weld pwc	52	812.94[b] (assuming a process time of 40 hours)[e]	
	St sold pwc	57		
	St weld galv	162		
	St sold galv	167		
Titanium frame (Germany)	Ti pwc	325	812.94[b] (assuming a process time of 40 hours)[e]	
	Ti anod	329		
	Ti galv	435		

[61] The wage rates are taken from the earlier introduced fair wage database and are consistent with the considered wage rates included in the next section.

[a] Abbreviations can be taken from the 'List of abbreviations'
[b] Hourly labor costs for Taiwanese and German workers are based on the database downloadable on https://www.see.tu-berlin.de/menue/forschung/ergebnisse/fair_wage_aequivalente/
[c] All process times are first approximations and should be double-checked, as soon as performing a detailed case study
[d] Assumed process time for the produced bike frames in series production according to www.free-wheelerbikeshop.com
[e] Assumed process time for the manually produced German bike frame production according to www.blue-craftbikes.de
[f] Assumed profit margin for the bike frames considered based on EHI Retail Institute (EHI 2013). Within a more comprehensive case study the profit margin should be further investigated, also with regard to differences between frames and complete Pedelecs.

Based on the values presented in the previous table the value added representing the impact category 'profitability' is calculated according to Equation 3 defined within section 4.2.2.2. Therefore, all relevant process costs are characterized into frame specific value added values. The results are presented in Figure 25.

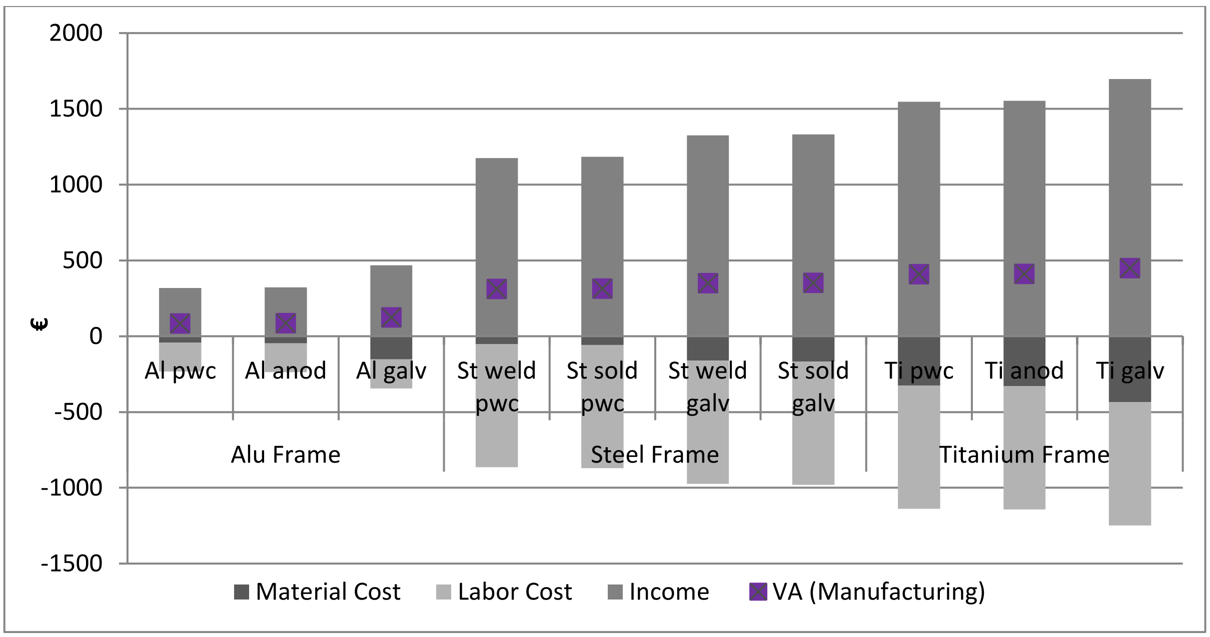


Figure 25: Value added of the different Triplec frames considering the manufacturing sites in Taiwan and Germany

Figure 25 shows that the value added of the Titanium frame is higher compared to the steel and aluminum frames. The material cost in each case only contribute a small share to the overall costs, while the labor costs, especially for the steel and titanium frames, dominate the cost side. Yet, due to the inherent assumptions on the profit margin and working hours required to produce one piece of frame, the results definitely need further investigation and until then should be interpreted with caution.

6.2.5 Interpretation and critical reflection

The 'sustainability footprint' of the different Triplec frames, revealed good results for the environmental dimension, by means of global warming potential, provided a first impression of resulting social impacts, by means of fair wage, and addressed first aspects with regard to the economic dimension, by means of value added. Comparable to the results presented within section 6.1, a decline in results comprehensiveness and accuracy can be observed for the Triplec frame case as well. While for the environmental dimension with the differentiation in raw material, transport and frame production, CO_2eq. for different stages along the life cycle can be displayed, and similar accounts for the social dimension with the determination of FWeq. for mining and production operations; a comparable consideration of the supply chain could not be achieved for the value added, as it was only displayed from the final producer perspective.

Furthermore, while the GWP provided little to no implementation challenges and could be transparently displayed for all Triplec frames, the fair wage characterization revealed some data uncertainties, in case of the Brazilian workers. Even greater data gaps have been revealed for the value added determination. Both cases once more revealed the need for comprehensive secondary data sources. The in connection with the fair wage characterization implemented database can be seen as an important starting point. However, some uncertainties remain, as e.g. the determination of realistic salaries and working hours is challenging especially with regard to the Brazilian transportation sector according to Murphy (2012). Thus, a more thorough investigation would be needed including further studies and additional sources.

Trade-offs appear between the environmental and economic dimension, as the titanium frame performs worst by means of GWP, but best by means of value added. However, before over-interpreting the results of the value added, further sources better representing the actual market situation should be included. In this context, also the general implications resulting from the value added assessment should further be investigated. For instance, while the production of the steel and titanium frames is cost intensive compared to the aluminum frame production, a great share of the added value happens in Germany, which may positively contribute to its wealth generation. The trade-off between value added created in one economy or another must therefore also be part of further investigations.

Another trade-off appears between the environmental and social dimension with regard to the aluminum frame. Whereas the frame performs medium in GWP terms, it contains potentially negative impacts for the involved Chinese mining workers. Further investigations should consequently review the Bauxite mining chain connected to the aluminum frame production.

6.3 Case study on modular machine tool frames

A third exemplary case study is included addressing the concept development of modular machine tool frames. Therefore, this case study addresses the technology development and manufacturing sector and therewith adds an additional field of assessments to be tested within the Tiered approach. The concept of modular machine tool frames has been developed within the Collaborative Research Center project – CRC 1026 – targeting the achievement of sustainable manufacturing technologies. The case study is based on two conference proceedings, which address smart manufacturing environments by means of wireless micro systems in combination with flexible machine tool frames (Benecke et al. 2015; Peukert et al. 2015). With regard to this thesis, the article sections dealing with LCSA, written by the author of this thesis, are considered. The implementation and results of the case studies performed have partly been adapted in accordance to the new method developments of chapter 4.

Within the two articles (Benecke et al. 2015; Peukert et al. 2015), a conceptual approach of reconfigurable and reusable flexible machine tool frames is presented targeting a broader technical flexibility compared to a conventional machine. As a first use case a 3-axis milling machine tool frame was chosen. The proposed modular machine tool frame (MMTF) structure is combined with wireless sensor nodes (WSN) as shown in Figure 26.

To ensure a preferably sustainable design of the MMTF and WSNs, a Tier 1 assessment has been performed, considering the core elements of the MMTF by means of hexagon blocks and a minimum set of ten electronic units required for the conceptual MMTF. The system boundaries and functional unit are defined accordingly in the following section. Due to the conceptual nature of the study, a thorough assessment of economic impacts by means of profitability was not possible at this point as not income or profit margin could be determined at this stage. Therefore, the assessment is limited to the environmental dimension by means of GWP and to the social dimension by means of FWP.

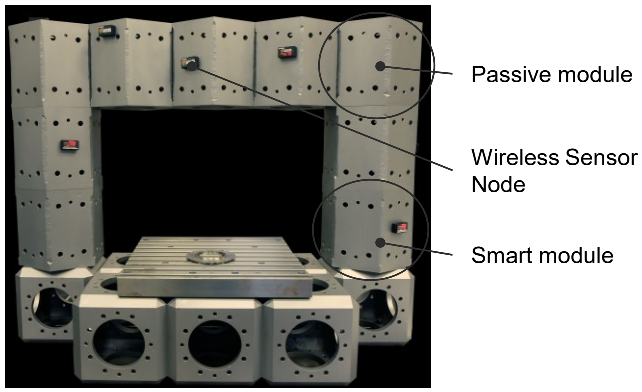


Figure 26: Flexible machine tool frame including wireless sensor nodes (according to Benecke et al. 2015)

6.3.1 System boundaries and functional unit

The case study has been performed in two steps including the hexagon as the core element of the MMTF and secondly the electronic parts (WSNs) needed for the conceptual MMTF. Therefore, the system boundaries are also defined separately for the two parts. For both parts a cradle-to-gate study is performed excluding the use-phase and the EoL-treatment.

For the hexagon production seven process steps are considered (compare Figure 27) – the raw material extraction (iron ore), the steel plate production, the water cutting of the plate, the milling of the hexagon parts, the welding and annealing of the hexagon, followed by a final milling & drilling. With regard to the raw material extraction and the steel plate production a German manufacturing site is assumed. Therefore, the iron ore is most likely distributed from Brazil (Triebskorn 2012). The energy used for producing the hexagon is taken from the German energy grid mix. The technical parameters for calculating the process times and operating material consumptions (e.g. cooling liquids) have been provided by the developers of the MMTF structure. The made assumptions serve as the basis for the sustainability footprint calculation including FWPs and GWPs.

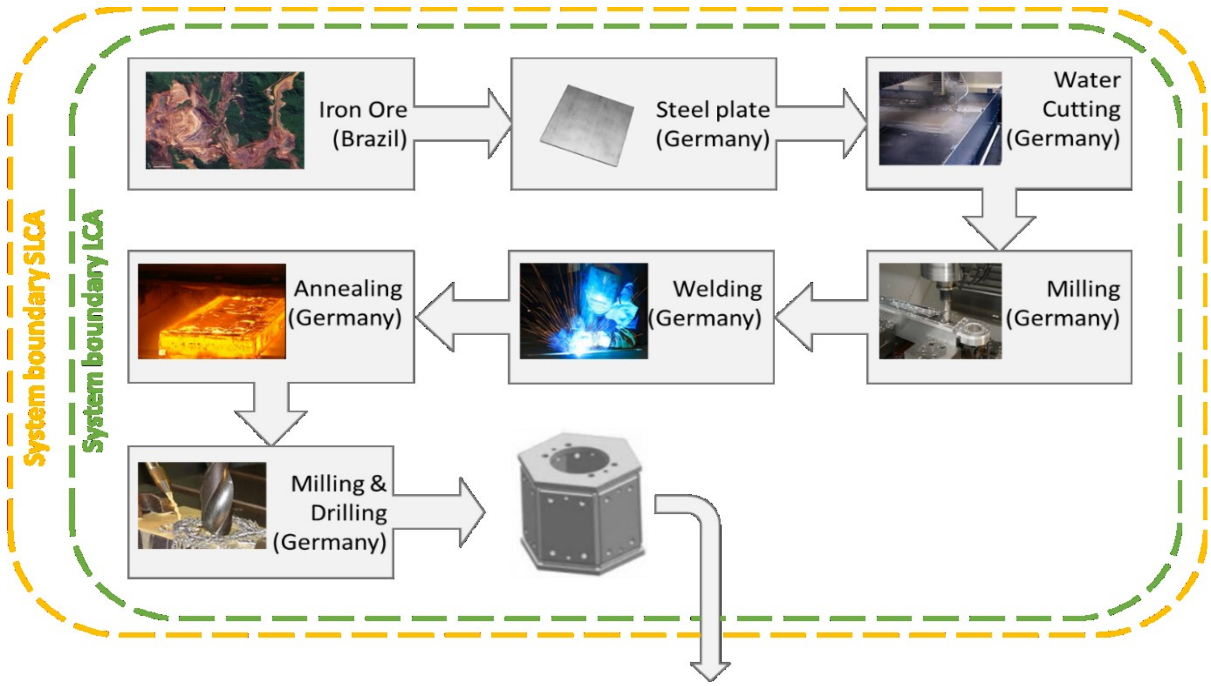


Figure 27: Cradle-to-gate system boundary for the hexagon production of the MMTF

For the WSNs the different components have been taken into account for composing one electronic unit. The currently available prototype of the WSN has a size of 20 mm x 65 mm. The WSN includes six main component groups and in total eleven components from nine different countries. The background information on the origin of the different parts have been provided by the developer of the WSNs at the Fraunhofer IZM institute. The system boundary is defined accordingly as displayed in Figure 28.

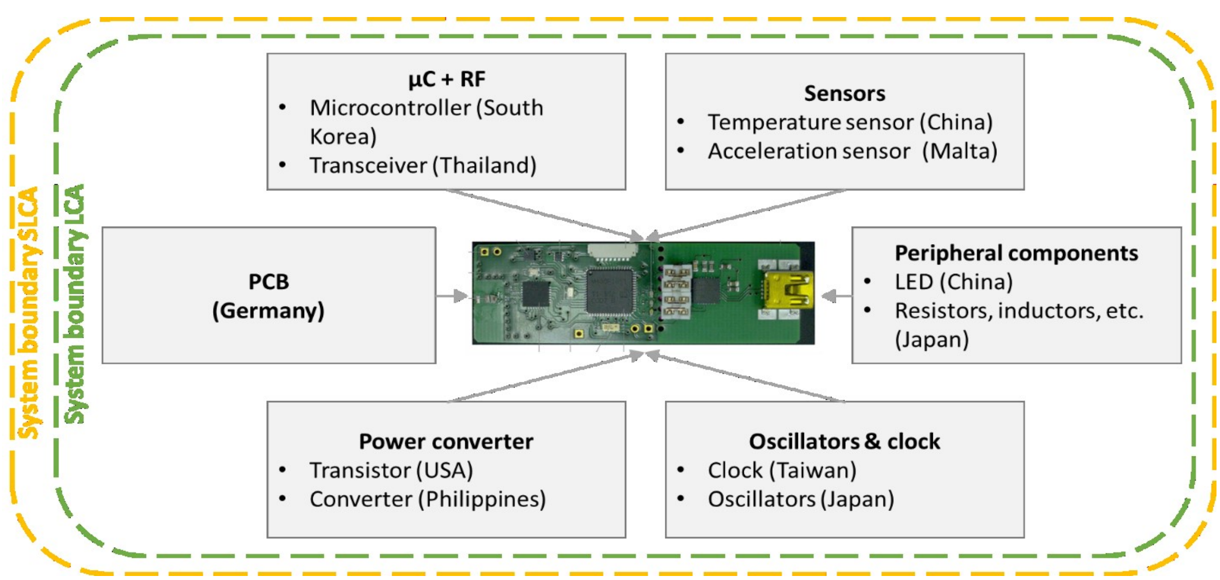


Figure 28: Cradle-to-gate system boundary for the electronic components of the WSNs

6.3.2 LCA results

Following on the defined system boundaries this section is twofold by first considering the GWP of the MMTF and subsequently of the WSNs.

6.3.2.1 Modular machine tool frames

For the environmental dimension the global warming potential is calculated by considering the process steps defined in Figure 27. The related process parameters per functional unit can be taken from Table 23. For the processes water cutting, milling and milling and drilling also some minor amounts of lubricants have been considered in the calculation. Those are nevertheless almost negligible, as the lubricant is circulated and the losses are minimal. For the calculation the GaBi database (Thinkstep 2015) and the CML method (Leiden University 2013) have been used.

Table 23: Considered processes for the hexagon production including the process parameters per functional unit

Process	Process parameter	Mass/length per functional unit
Steel plate	Original weight	23.83 kg
Water cutting	Cutting length & removed material	3,171 mm & -4.54 kg
Milling	Removed material	-1.52 kg
Welding	Welding seam & added material	2,158 mm & 0.83 kg
Annealing	Weight of workpiece	18.6 kg
Final milling & drilling	Removed material	-3.98 kg

As shown in Figure 29, great differences between the processes occur. The hexagon production is clearly dominated by the raw material production (steel plate), which is then followed by the water cutting process contributing about 16 % to the GWP. The results are obtained by assuming an already filled up closed-circle of lubricant.

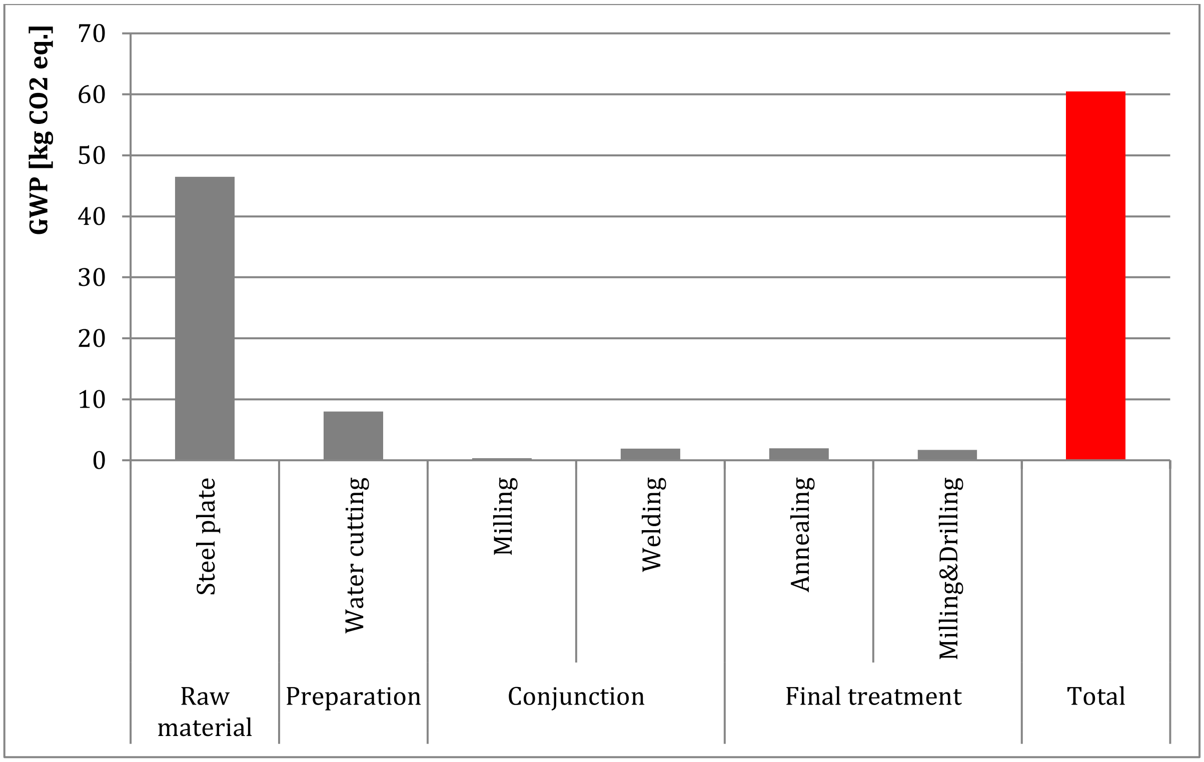


Figure 29: Global warming potential for the basic hexagon element of the MMTF; the results display the reference flow related values of Table 23 with regard to the functional unit

6.3.2.2 Wireless sensor nodes

For the environmental dimension the GWP is calculated by considering the parts addressed in Figure 28. To carry out the LCSA of the WSN, the 'GaBi6 Extension database XI: Electronics' (Thinkstep 2015) has been used. Due to the complexity and variety of microelectronic components available on the market, generic databases can only to a certain extent represent the actual situation of electronic components. The generic datasets have therefore been carefully selected after investigating the actual components to also enable a meaningful scaling with regard to the functional unit (compare Table 24). Whenever possible, data sets corresponding to the exact package and technology were selected, e.g. in case of the capacitors or the 4-layer PCB board. For some parts scaling was required based on the reference data set.

Table 24: Considered parts for the WSN production including the scaling factors per functional unit

Components included in WSN		Gabi Electronics Extension Database XI	Scaling Factor
Active components	Microcontroller	IC TQFP 44 (260mg) 10x10x1.0	0.87
	Transistor	CSP 49 (3.17x3.17mm) MPU	1
	Transceiver	IC TQFP 32 (70mg) 5x5x1.0	0.41
	LED	LED top SMD (35mg) 3.2x2.8x1.9	0.012
	Power converter	IC QFP 32 (180mg) 7x7x1.5	0.14
	Clock	IC PLCC 20 (700mg) 8.9x8.9x3.8	0.091
	Temperature sensor	SOT23 3 leads (10mg) 1.4x3x1	0.26
	Acceleration sensor	IC QFP 32 (180mg) 7x7x1.5	0.04
	Oscillator	Oscillator crystal (500mg) 11.05x4.65x2.5	0.04
Passive components	Capacitors	Piece of capacitor ceramic MLCC 0201 (0.17mg) 0.6x0.3x0.3	13
	Inductors	Coil multilayer chip 0402 (1mg)	0.51
	Resistors	Resistor thick film flat chip 0201 (0.15mg)	8
Other	PCB	Area of printed wiring board, rigid, FR4, chemSn elecAuNi, 4-layer	0.00124

The results are clearly dominated by Microcontroller and Transceiver production, as shown in Figure 30. Furthermore, the so-called active components determine 90% of the total GWP. Even though, the PCB does not count under active components it still provides a bigger share to the overall GWP. The peripheral components in contrast have close to zero contribution to the overall GWP.

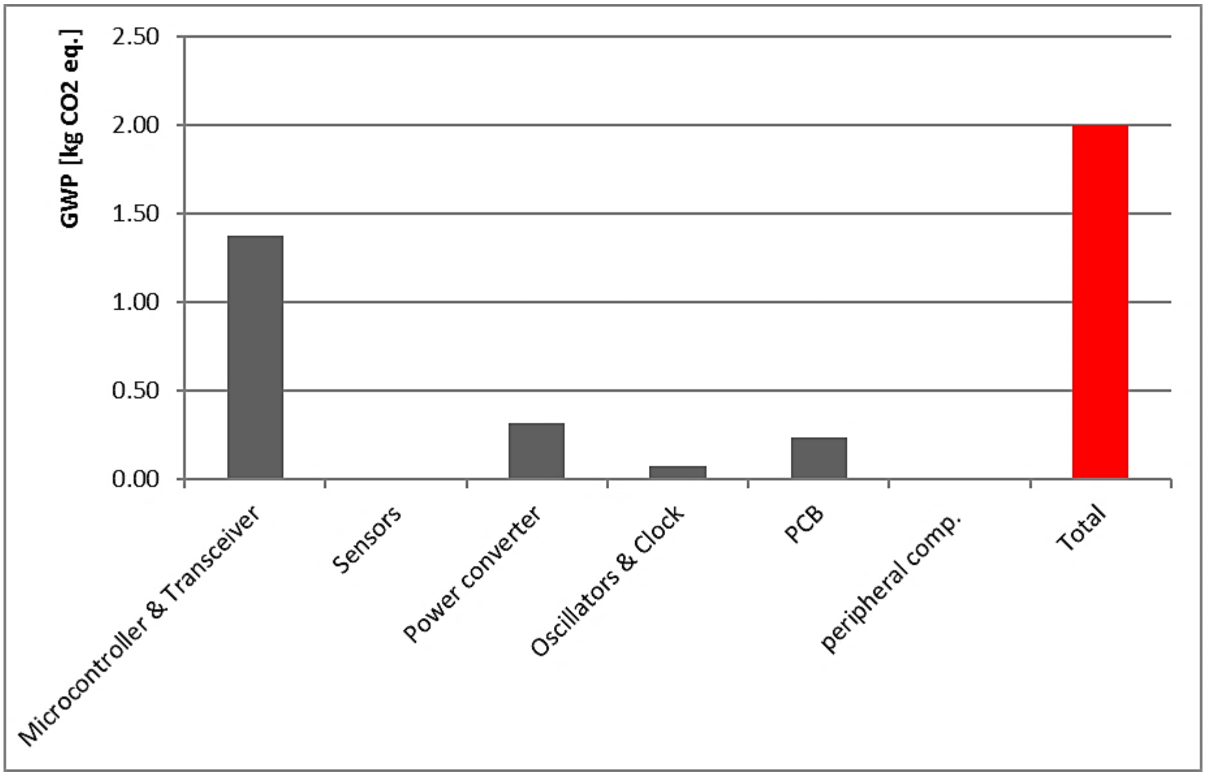


Figure 30: Carbon footprint result for wireless sensor nodes used for the modular machine tool frame

6.3.3 SLCA results

Unlike the LCA results´ presentation, the results for the FWPs are jointly displayed for both the MMTF and the WSNs. The MMTF could be summarized in two groups – the Brazilian and the German production. Even though, different processes are performed in Germany, they all require similar work operations and could therefore be expressed by one FWP. For the WSNs a different picture appears, as the single parts are produced in different countries and thus need separate consideration. Table 25 presents a summary of the processes considered for the MMTF and the WSN in accordance with the system boundaries defined in section 6.3.1.

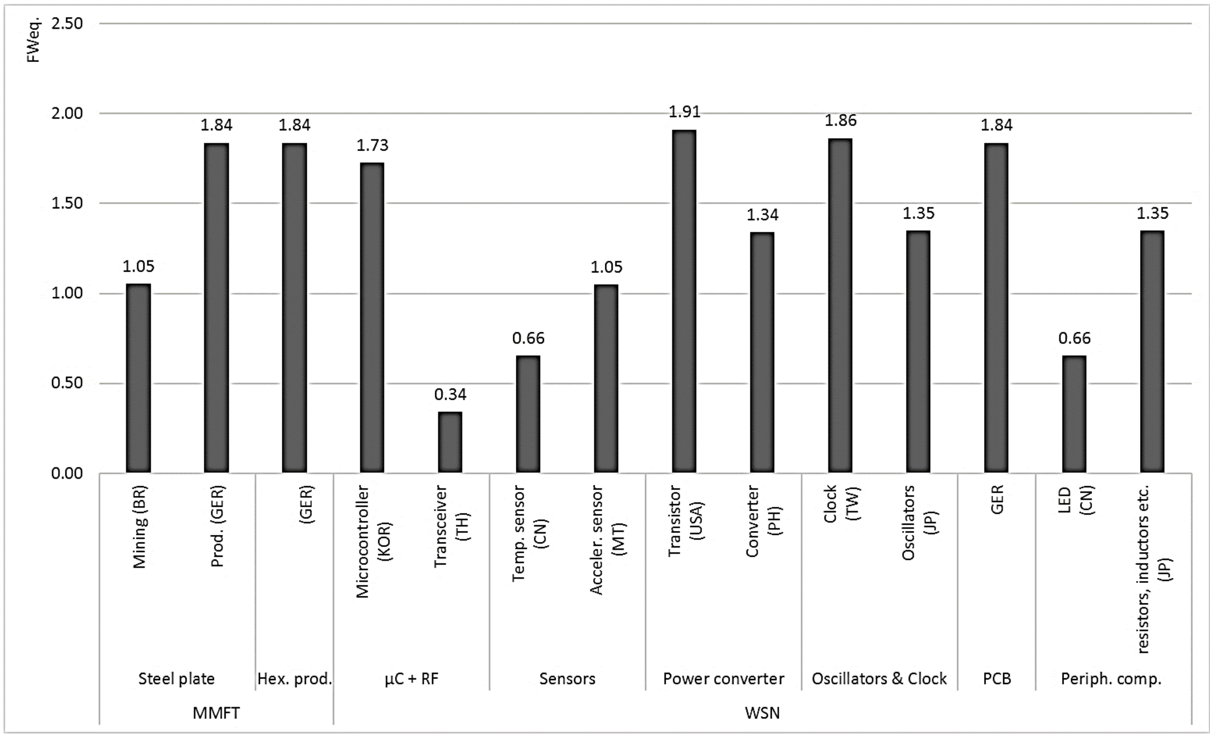
Table 25: Considered parts for the hexagon production including the group of workers and production location

Parts considered	Process step	Core group of workers	Production location
MMTF	Iron-ore mining	Miner	Brazil
	Steel plate production	Manufacturer	Germany

Parts considered	Process step	Core group of workers	Production location
	Manufacturing processes for hexagon		Germany
WSN	Microcontroller production	Manufacturer	South Korea
	Transceiver production		Thailand
	Temperature sensor & LEDs		China
	Acceleration sensor		Malta
	Transistor		USA
	Converter		Philippines
	Real time clock		Taiwan
	Oscillators & resistors, inductors etc.		Japan
	PCB		Germany

Based on the introduced method in section 4.1.1.2, FWPs are calculated for the listed groups of workers per part and production location. The needed data are taken from secondary data sources[62]. Therefore, country-specific manufacturing processes are used as a proxy for the electronics manufacturing, as more specific data are rarely available. With regard to data quality, only data are considered which are not older than ten years. The achieved results are displayed in Figure 31. In addition, Table 31 and Table 32 display more details of the calculated FWPs in the Annex.

[62] Relevant data sources have been listed in a database, which has been established in connection with the article of Neugebauer et al. (2016) and can be downloaded from https://www.see.tu-berlin.de/menue/forschung/ergebnisse/fair_wage_aequivalente/.



[a] Values ≥ 1 are interpreted as fair, as the potentially actual wage fits or even exceeds the required MLW; values << 1 are considered as insufficient and contribute to the cases of underpayment per year, as worker's family would be unable to achieve an adequate living standard or would even live in poverty

[b] All calculated values are based family size of the respective country (by means of country-specific fertility rates).

[c] The abbreviations stand for: Prod. - production; Hex. Prod. – hexagon production; Temp. - temperature; Acceler. - acceleration; Periph. Comp. – peripheral components; the country specific abbreviations are according to ISO.

[d] The detailed calculation including data and related sources can be taken from the Annex.

Figure 31: Fair wage potentials for MMTF and WSNs considering the different production locations

The results reveal high negative impacts for the manufacturing workers in Thailand and in China, as the FWPs indicate a great distance from the MLWs and thus cause negative impacts for the workers and their families. Furthermore, the appearing inequality fosters the resulting negative impacts. A detailed case study should accordingly further investigate those worker groups. For the workers in Brazil and Malta, FWPs close to one were calculated and should therefore be interpreted with caution. For all other production locations involved, no negative impacts are expected, as the FWPs are >>1. The results show that, even though the tracking of the origin for electronic components is more challenging than for the production of the MMTF, it is decisive for determining the social sustainability impacts resulting from unfair wages.

6.3.4 EcLCA results

As pointed out in the beginning of this section, the economic dimension is due to the early stage of product development and the conceptual nature of the MMTF and WSN combination for now neglected within this study. Due to the yet very unsure market response on this product solution it is simply not possible to provide a solid statement on the income or profit margin. It should however be part of further studies, as soon as additional research will have been done and the concept reached market maturity.

6.3.5 Interpretation and critical reflection

By performing a carbon footprint and fair wage assessment of the MMTF and the WSNs the environmental and social performance of the developed flexible manufacturing systems could be determined. Whereas, the overall GWP is clearly dominated by the production of the MMTF more specifically by the raw material production, the WSNs show more severe social impacts represented through FWPs. With the inclusion of both, the GWP and the FWP the products life cycle can be displayed from two different perspectives – the environmental as well as the social (workers´) perspective. In both cases the raw material production as well as the manufacturing of the MMFT are covered and it is accounted for the production of the different electronic components.

With regard to GWP, the reduction of the total amount of raw material and the improvement of process parameters in the water cutting process have been identified as the two main optimization options. Further research will accordingly focus on lightweight design principles. In addition, research will focus on the substitution of processes, e.g. by testing casting options for the hexagon production. Even though the WSNs are not dominant with regard to GWP, some improvement potentials could be identified. By further miniaturizing the sensor a GWP reduction could be achieved, which is associated with the active components. Through the minimization of energy-intensive production processes, components such as gold wire bonds and lead frames can be replaced by *FlipChip*[63] technologies. The concrete reduction potential will be part of further research.

With regard to the social dimension, the already earlier mentioned challenge of available data and high data quality applies especially for the electronic components. The data provided within the established database cover countries or sectors manufacturing sector, but do not specifically address the electronics sector. Therefore, the achieved results serve as a first indication, but need further investigation and adaption to the electronics sector.

[63] Flip Chip assemblies are smaller than traditional carrier based systems and provide advantages in transmission speed and heat conductance.

7 Discussion

This chapter is divided in four subsections. The subsection 7.1 addresses general discussion points on the initial Tiered approach concept, while the section 7.2 addresses methodological developments of this thesis, which also includes the refinements by means of the Tiered approach 2.0. The subsection 7.3 takes up the general data challenge with regard to LCSA and finally section 7.4 addresses the discussion on how to interpret LCSA results in the context of this thesis.

7.1 Critical evaluation of the Tiered approach concept

While the Tiered approach functions as a guide through LCSA, puts the confusion of indicators on order and provides simplification options for practitioners, the concept also contains some points of discussion. To begin with, as addressed within section 3.6, the general challenges of simplified approaches apply for the Tier 1 level focused on within this thesis, as the contradiction in results and lack of informative value can occur compared to broader assessments. Furthermore, considering the initial Tiered approach concept developed within chapter 3, still contains the addressed differences in maturity, when considering the impact categories included for LCA, SLCA and LCC (compare Figure 8). In addition, the provided indicator hierarchy is not set in stone and depends on the chosen criteria. A different selection of impact categories seems conceivable, by including additional criteria (e.g. addressing aspects for specific cases, as indicated for agricultural processes – eutrophication vs. global warming at the Tier 1 level) or by giving the criteria different weights (e.g. by rating method robustness over relevance, water use would be ranked prior to land use instead of the other way around). However, especially the Tier 1 level contains a high correspondence with the three criteria included and furthermore well displays different perspectives of the three dimensions. The environmental perspective therefore addresses globally relevant climate change impacts, while the social dimension accounts for the needs of workers by means of fair wages and within the economic dimension the business perspective is tackled through profitability considerations. Even though these contradictory considerations contain criteria-based justifications and display a broad perspective, producers performing a LCSA could rather be interested in indicators in closer relation to production, such as resource depletion or health & safety.

By going beyond the Tier 1 level, further discussion points appear when dealing with the Tier 2 and 3 level. For Tier 2 and 3 the number of included impact categories and indicators per tier differs for the three methods, which lead to inconsistencies and challenges in interpreting the results. Challenges in connection with LCSA´s interpretation are in more detail discussed within the following subsection 7.3. Furthermore, for all three dimensions, by means of LCA, SLCA and EcLCA, additional impact categories are possible, which cover topics not yet included, such as child development, policy actions, intangible capital, or endocrine disrupters.

7.2 Critical evaluation of the methodological developments

Apart from those shortcomings, the Tiered approach can indeed function as an indication of further research needs with regard to methodological shortcomings and inconsistencies, even though it does not tackle all the existing methodological shortcomings, which still occur for SLCA and LCC. This was addressed in chapter 4, by which methodological developments were established, following on the addressed limitations of the Tiered approach concept in section 3.7 and the identified research directions in section 3.8. Due to the differences in maturity of SLCA and LCC, the methodological developments implemented within this thesis followed different approaches. While for SLCA impact categories and AoPs have already been defined and first impact pathways have been drafted, LCC due to its narrow focus required a re-structuring (as indicated Figure 8 referring to the methodological differences and pointed out in section 3.8). Therefore, the new EcLCA approach has been proposed including economic impact categories and AoPs. For SLCA the followed approach was more straightforward by directly digging into the development of an applicable characterization model for the impact category ‘fair wage’.

While specific points of the new fair wage method have already been discussed within section 4.1.1.4, which revealed challenges e.g. regarding the relation of the FWPs to the functional unit, the determination but also consideration of the inequality factor, and the relation to the endpoint level; the performed case studies in chapter 6 specifically underlined some additional points specifically. First of all, the case studies confirmed the general applicability of the fair wage method and showed that impacts along the life cycle can be expressed. Yet, the characterization model so far does not provide a solution concept on how to cover the numerous worker groups, which are involved in the life cycle of one product. For developing a solution concept, the trade-off between a feasible and practicable but also comprehensive assessment approach must be targeted. Furthermore, the determination of an overall FWP representing the functional unit of a product or service remains challenging, but may be resolved by taking the organizational perspective into account, as suggested by Martínez-Blanco et al. (2015). Yet, the final solution may also require a consensus within the SLCA community. In addition, minor challenges with regard to data availability and quality have been indicated (e.g. the electronics industry is not yet comprehensively covered), which would require an extension of the secondary database provided in the context of this thesis. The achievement of comprehensive databases is not unsolvable, but still requires professional efforts to also ensure a certain data quality.

The new profitability method has been discussed within section 4.2.2.3, which revealed data availability and confidentiality to be crucial concerns. The case studies performed in chapter 6 confirmed this obstacle, as the value added could only be displayed from the final producer´s perspective neglecting the upstream and downstream suppliers. Thus, while the new characterization model theoretically allows for determining the value added along product´s life cycle, the data situation hinders the categories comprehensive implementation or at least usage in case studies. The benefits of easily relating the value added determination to the product level or functional unit is outweighed by this obstacle. The availability of secondary data and their inclusion in secondary databases seems pressing in this context. Further considerations with regard to data will be discussed in the following section. Nonetheless, when assuming a sufficient data situation, the impact category ‘profitability’ can indeed help to identify a balance between cost savings and value added and can show that cost savings are not beneficial in any case, e.g. securing jobs in a certain economy may benefit the overall value added at the endpoint level. The earlier by Grießhammer et al. (2007) addressed point of differentiating between different economic situations would therewith also be taken into account.

Notwithstanding the remaining challenges, the newly developed characterization models could enhance the sufficiency of Tier 1 of the initial Tiered approach (as shown in section 5.1). While, the initial midpoint category 'fair wage' (as introduced in section 3.3) did not provide a concrete definition or description on how to determine fair wages, the methodological developments enabled the achievement of a quantitative characterization model (compare section 4.1.1). Through this, also the methodological sufficiency could be enhanced following on the rationale targeted within Box 2.1.

With regard to the economic dimension neither impact categories, AoPS nor characterization models were included. Therefore, the newly defined EcLCA approach and midpoint category 'profitability' can be seen as first steps to align the economic dimension with the environmental and social one. Nevertheless, the conceptual nature of the EcLCA approach clearly requires further investigation and research in order to enable the development of concrete characterization models for Tier 2 and 3, as already indicated in section 4.2.5. The same accounts for the SLCA impact categories identified for Tier 2 and 3, where first conceptual drafts of the different midpoint impact categories exist, but no concrete characterization models. As methodological developments going beyond Tier 1 are outside the scope of this thesis; only an outlook has been provided indicating possible research directions and refinements for Tier 2 and 3 (compare chapter 4).

7.3 Data challenges in LCSA

The case studies included in this thesis indicated the need for dedicating more attention to the achievement of secondary data sources for SLCA and EcLCA.[64] With the established database for the fair wage assessment a first step has been undertaken in this direction. The fact that the database provides secondary data in form of average wage levels or working hours

[64] Data challenges may also exist for LCA; yet, for the Tier 1 level no shortcomings in secondary data could be identified, as existing databases cover a variety of products and processes and include characterization factors for climate change impacts.

does not appear problematic, as e.g. within LCA databases also average data are provided. For instance, for calculating the GWP of a certain product the upstream and downstream materials and processes are often covered by average country-specific black-box processes. The same applies for FWP, where most of the average wage values are country or sector specific, but can however be applied in a product assessment.

One of the crucial factors of the fair wage calculations are the included MLWs. The determination of those MLWs contains challenges, as indicated in section 4.1.1.2. In this context, further research is needed for improving the data availability and quality. A meaningful start has already been made by the Wagenindicator Foundation (Guzi and Kahanec 2014), which aims at a broad country-specific data collection. Those survey-based values provide benefits compared to the PPP-based measures – provided by the Sweatfree Contracting Ordinance (City and County of San Francisco 2014) – and are therefore preferred within this thesis.

In addition, a more detailed differentiation between rural and urban regions and their related MLWs would be beneficial for the validity of assessment results, as e.g. countries like China face great differences between rural and urban population. Additional uncertainties related to incomplete data could be addressed by including different sources. However, some data gaps still exist for certain countries and especially product chains, e.g. the electronics industry. This however applies also for EcLCA and even LCA, as data on electronics are typically of generic nature (compare section 6.3). Further uncertainties result from the needed conversion to one currency unit ensuring comparability. Therefore, the Euro has been chosen and used as an average conversion rates over a one-year period, which dampens extreme fluctuations. One could even think about including a longer time frame (e.g. 5 to 10 years) to account for long-term fluctuations.

A different picture appears with regard to the impact category ‘profitability’ and the EcLCA approach. No database providing secondary data has so far been established, which has proven to be an obstacle for comprehensively performing the economic assessment in the context of the ‘sustainability footprint’. While primary data can typically be gathered for the direct producer, the reflection of producers along the products´ life cycle provided some challenges. Therewith, the new EcLCA approach seems to face similar data-related shortcomings as the classical LCC[65], which commonly fails in displaying costs for different life cycle processes and rather displays one producer´s perspective. The achievement of databases providing secondary data would therefore be essential. Those may also help in circumventing the confidentiality issue, as databases could provide average datasets, which are not sensitive in terms of a business´ performance.

With regard to the Tier 2 and 3 level, the availability of data becomes even more challenging for two reasons - especially, for SLCA and EcLCA secondary data sources are if at all only limitedly available, and impact categories (also for LCA) may not fully be covered through provided inventories of databases. The further orientation on the Tiered approach ranking can in this context be helpful in providing focus for both further methodological developments, but also fostering the achievement of comprehensive databases considering inventories of selected impact categories.

7.4 Interpretation of LCSA results

The interpretation of LCSA results clearly goes beyond the complexity of single-dimension studies (Cinelli et al. 2013). Several authors identify LCSA´s interpretation as challenging and suggest to separately display results for each dimension (Valdivia et al. 2012; Zamagni, Pesonen, and Swarr 2013; Arcese, Merli, and Lucchetti 2013; Hunkeler and Rebitzer 2005). Therewith, trade-offs that may appear between the three dimensions can be displayed and discussed. This holds true for the Tiered approach concept and especially the Tier 1 level focused on. Yet, prior to the methodological developments implemented in chapter 4, comparing environmental impact category results with cost category results and social risk factors appeared to be an inadequate basis of comparison. With the achievement of characterization models for SLCA (‘fair wage’) and EcLCA (‘profitability’), this imbalance could be mitigated. The impact categories chosen furthermore represent crucial topics of production processes, by including global warming potential representing an important environmental concern, fair

[65] Grießhammer et al. 2007; Bubeck 2002 and also Hunkeler, Rebitzer, and Lichtenvort 2008 already raised the issue of data confidentiality with regard to management accounting data or firm specific data for LCC or revenues and benefits.

wage representing the workers´ situation, and profitability addressing the organizations performance, which is in line with the ISO 14044 requirement that assessments shall reflect a comprehensive set of environmental, (social and economic) issues in relation to the product system studied.

While the interpretation of the LCSA indicator results could be enhanced by means of the developed characterization models at Tier 1, for Tier 2 and 3 only small alignments in methodological robustness could be achieved, as indicated in Figure 16. An equal evaluation of the indicator results for the three methods does however not seem possible so far, due to the missing basis of comparison by means of characterization models. This relates to both the number of indicators included per dimension but also the maturity of the indicators involved.

Further interpretation challenges with regard to results´ consistency and accuracy have already been discussed in connection with the Tiered approach concept (compare section 3.6), addressing the lack of informative value and the limitations accompanying simplified assessment approaches (such as the 'sustainability footprint'). Considerations of correlations between different indicators may mitigate these inconsistencies.

Further challenges are likely to emerge with regard to the endpoint level and potential interlinkages between the sustainability dimensions, e.g. climate change impacts affect simultaneously the endpoints of health and ecosystem stability. However, within this thesis these considerations are deferred, as focus has been set on Tier 1 and on the midpoint rather than the endpoint level.

8 Conclusion and Outlook

Review of the status of LCSA (chapter 2), revealed several challenges especially with regard to the differences in maturity of LCA, SLCA and LCC and the practicability and methodological robustness of SLCA and LCC. After summarizing the core challenges for the two methods, which relate to methodological inconsistencies and obstacles for implementation as well as data availability (compare Table 1), relevant topics for LCSA have been identified and guidance through midpoint impact categories and indicators of LCSA has been provided with the Tiered approach concept developed (chapter 3).

By means of the Tiered approach a consistent way of dealing with LCSA has been presented. Inconsistent approaches, which randomly include indicators into the LCA framework in order to also express social and economic performance, are therewith avoided. The provided structure of the Tiered approach also allows for the identification of shortcomings, such as the different maturity levels of LCA, SLCA and LCC representing the three dimensions. The Tiered approach concept led to the identification of clear research directions by structuring LCSA indicators and impact categories in a hierarchical way. Not only did the achieved hierarchy provide preferable impact categories based on the criteria-based ranking, it also revealed a broad range of impact and cost categories already considered within the three methods – LCA, SLCA and LCC. Three tiers have been defined to rank the numerous impact and cost categories representing the three methods. The criteria-based ranking resulted in a hierarchy by considering three criteria – practicality, relevance and method robustness.

The first tier was identified as promising for methodological developments. Those methodological developments have been displayed in chapter 4. The indicators identified for the Tier 1 level – namely global warming potential, fair wage potential and value added – have already (even if inconsistently) been part of case studies, which served as the basis for further developments. Focus for the developments was set on the social indicator fair wage and the economic indicator value added. Global warming potential is already sufficiently described through an impact category and therefore did not require further improvements. Methodological developments going beyond the Tier 1 level were outside the scope of this thesis; yet, an outlook and refinements also indicating possible research directions for Tier 2 and 3 have as well been presented within chapter 4.

For achieving a consistent implementation of fair wage impacts, a *quantitative* characterization model has been developed in section 4.1.1 representing the respective midpoint impact category. It is seen as a starting point towards a comprehensive determination of fair wage impacts along products´ life cycles and therewith provides a broadened status quo of SLCA. The inclusion of fair wages at the midpoint level allows to account for worker´s economic situation embodying a necessary requirement for an adequate living standard, in accordance to Maslow´s pyramid of needs. Further research is needed to improve the data quality (especially in connection to the MLWs). In addition, further investigations are needed with regard to the included inequality factor and the FWPs relation to the functional unit as well as the quantitative relation to the endpoint level.

Through re-structuring economic assessment practice within the LCSA framework by means of EcLCA (compare section 4.2.1) and the achievement of a characterization model at the Tier 1 level by means of the midpoint category ‘profitability’ (compare section 4.2.2), economic impact definitions and AoPs could be achieved. With the impact category ‘profitability’ and the defined impact indicator value added a transition from LCC towards the new EcLCA approach was achieved by setting costs into perspective with revenues and relating them to an economic impact pathway and AoPs. The related uncertainties with regard to data availability, but also the model´s maturity and its relation to the endpoint level, have been discussed in section 4.2.2.3.

With the developed characterization models (‘fair wage’ and ‘profitability’) the ‘sustainability footprint’ at Tier 1 could be complemented and aligned allowing for consistent and simplified assessments including all three sustainability dimensions. Therewith, also an orientation on the typically targeted and adopted structure of LCSA, as presented within Box 2.1, became possible. With this alignment (even though so far limited to the first tier of the Tiered approach concept) an equal comparison between the three dimensions has been enabled. Furthermore, by means of the now enhanced ‘sustainability footprint’ (Tier 1), LCSA´s implementation may be facilitated, through the defined characterization models.

With the presented approach of this thesis, by first structuring LCSA´s impact and cost categories followed by the development of an indicator hierarchy and the subsequent development of characterization models for the Tier 1 level, it has been shown that:

- Alignment of the different maturity levels of LCA, SLCA and EcLCA is possible
- Quantitative characterization models can be achieved for SLCA
- Impact categories, characterization models and AoPs can be defined for the economic dimension of LCSA

The performed case studies in chapter 6 served as first test cases for the methodological developments of chapter 4. They confirmed the general applicability of the developed characterization models, but also revealed challenges for their practicality, mainly related to missing secondary data sources, which have been discussed in chapter 7. By this means, further research needs could be identified, which relate to the developed Tiered approach concept, the defined impact categories and developed characterization models representing Tier 1, the developed EcLCA approach, as well as to LCSA in general, as naturally this thesis could not solve or tackle all challenges of the LCSA framework.

Further research with regard to the developed characterization models should mainly address the achievement of secondary data sources to enhance their practicality but also the linkage to the defined endpoint categories to better address the social and economic mechanisms followed. For both impact categories – fair wage and profitability – so far only qualitative relations to the endpoint level have been indicated. Thus, investigations may initially focus on interlinkages, which can be based on earlier studies or mechanism. For instance, the relation of income (inequality) and human health damages has been analyzed by several studies (e.g. Feschet et al. 2013; Bocoum, Macombe, and Revéret 2015) and therefore an adoption to SLCA appears more likely. The same accounts for the interlinkage between a product´s value added and economic prosperity, which can be measured by the classical or enlarged GDP, as the relation has already been described by e.g. Azapagic and Perdan 2000; UN 2007.

The mentioned challenge of adequate secondary data sources is not specific for the two midpoint categories defined for Tier 1, but rather apply in general to LCSA and especially to SLCA and EcLCA. Yet, the specific development of databases appears to be easier if associated with method developments, as shown for the fair wage case. Therefore, by successively developing further characterization models, accompanied databases could be developed. Available secondary data sources appear also relevant for the implementation of the newly developed EcLCA approach. While the classical LCC may due to its narrow perspective have some benefits in applicability (even though a comprehensive coverage of life cycle costs is also challenging), EcLCA takes into account a broader economic perspective by linking micro- and macroeconomic considerations. Yet, it requires secondary databases in order to display products´ life cycle.

For determining further research directions with regard to both the development of further characterization models but also the possible linkage to the endpoint level, the within this thesis presented Tiered approach concept as well as the displayed impact pathways (compare section 4.1.1.3 and 4.2.1.2) can be of assistance. Yet, working groups within the LCSA community might also be helpful to identify relevant topics. Some topics can require a subdivision in order to enable meaningful characterization models, e.g. health or human rights, which definitely requires decisions of such working groups towards a certain consensus. The thesis presented here (hopefully) serves as an impulse for fostering those developments. This also accounts for more complex and still pending topics such as the discussion on intra- and intergenerational equity. This topic cannot solely be addressed by one of the three LCSA methods, but is rather of general relevance. The new EcLCA with its inclusion of the economic AoP ‘economic stability’ as well as the endpoint category ‘economic resilience’ may provide a first step for considering important economic aspects of intra- and intergenerational equity, like diversity and distribution. More research is needed in this context for also covering social and environmental aspects of intra- and inter-generational equity, like access to education, food and clean water. For complementing the broader picture, the ecological economics approach (Spash 2012) or Sen’s capability approach (Sen 2013) can provide helpful insights for further developments, as both consider equity as an important concern. They further help with developing tools towards strong sustainability concepts, considering economy as a subset of the environment, which embodies another discussion point of the LCSA framework worth further investigation.

9 References

Adolphus, Katie, Clare L Lawton, and Louise Dye. 2013. “The Effects of Breakfast on Behavior and Academic Performance in Children and Adolescents.” *Frontiers in Human Neuroscience* 7. Frontiers Media SA: 425. doi:10.3389/fnhum.2013.00425.

AERA. 2016. “American Educational Research Association > Home.” http://www.aera.net/.

Agyapong-Kodua, K., B.M. Wahid, and R.H. Weston. 2011. “Towards the Derivation of an Integrated Process Cost-Modelling Technique for Complex Manufacturing Systems.” *International Journal of Production Research* 49 (24): 7361–77. doi:10.1080/00207543.2010.535861.

Akerlof, George A, and Janet L Yellen. 1990. “The Fair Wage-Effort Hypothesis and Unemployment.” *The Quarterly Journal of Economics* 105 (2): 255–83.

Amienyo, David, and Adisa Azapagic. 2016. “Life Cycle Environmental Impacts and Costs of Beer Production and Consumption in the UK.” *The International Journal of Life Cycle Assessment*. doi:10.1007/s11367-016-1028-6.

Amnesty International. 1998. “Human Rights Principles For Companies.”

Anand, Sudhir, and Amartya Sen. 2000. “Human Development and Economic Sustainability.” *World Development* 28 (12): 2029–49. doi:10.1016/S0305-750X(00)00071-1.

Anker, Richard. 2006. “Living Wages around the World: A New Methodology and Internationally Comparable Estimates.” *International Labour Review* 145 (4).

———. 2011. *Estimating a Living Wage : A Methodological Review*. Geneva: International Labour Office.

Arcese, Gabriella, Roberto Merli, and Maria Claudia Lucchetti. 2013. “Life Cycle Approach : A Critical Review in the Tourism Sector.” *The 3rd World Sustainability Forum*, 1–10.

Aspromourgos, Tony. 2013. *On the Origins of Classical Economics: Distribution and Value from William Petty to Adam Smith*. https://books.google.com/books?hl=de&lr=&id=h18VUvrW0y4C&pgis=1.

Atkinson, Anthony B. 1970. “On the Measurement of Inquality.” *Journal of Economic Theory* 2: 244–63.

Attaran, Mohsen. 1986. “Industrial Diversity and Economic Performance in U.S. Areas.” *The Annals of Regional Science* 20 (2): 44–54. doi:10.1007/bf01287240.

Azapagic, A, and S Perdan. 2000. “Indicators of Sustainable Development for Industry :” *Process Safety and Environmental Protection* 78 (4): 243–61. https://www.escholar.manchester.ac.uk/api/datastream?publicationPid=uk-ac-man-scw:103501&datastreamId=POST-PEER-REVIEW-PUBLISHERS.PDF.

Babones, Salvatore J. 2008. “Income Inequality and Population Health: Correlation and Causality.” *Social Science and Medicine* 66 (7): 1614–26. doi:10.1016/j.socscimed.2007.12.012.

Bare, Jane C., Patrick Hofstetter, David W. Pennington, and Helias A. Udo de Haes. 2000. “Midpoints versus Endpoints : The Sacrifices and Benefits.” *International Journal of Life Cycle Assessment* 5 (6): 319–26.

Basel Convention. 2011. “Basel Convention Home Page.” http://www.basel.int/.

Baumann, Henrikke, and Anne-Marie Tillmann. 2004. *The Hitch Hiker´s Guide to LCA*. Lund: Studentenlitteratur AB.

Baxter, Roger, and Sheelagh Matear. 2004. “Measuring Intangible Value in Business-to-Business Buyer-Seller Relationships: An Intellectual Capital Perspective.” *Industrial Marketing Management* 33 (6): 491–500. doi:10.1016/j.indmarman.2004.01.008.

Bellù, Lorenzo Giovanni, and Paolo Liberati. 2006. “Describing Income Inequality - Theil Index and Entropy Class Indexes.” *EASYPol*.

Bems, Rudolfs, and Robert C Johnson. 2015. “Demand for Value Added and Value-Added Exchange Rates.” *IMF Working Paper*. Vol. WP/15/199. doi:10.3386/w21070.

Benecke, Stephan, Sabrina Neugebauer, Bernd Peukert, Nils F Nissen, and Eckart Uhlmann. 2015. “Sustainability Assessment for Wireless Micro Systems in Smart Manufacturing Environments.” In *Proceedings of EcoDesign 2015 International Symposium*.

Bennett, Fran. 2014. “The ‘Living Wage’, Low Pay and in Work Poverty: Rethinking the Relationships.” *Critical Social Policy* 34: 46–65. doi:10.1177/0261018313481564.

Benoit, Catherine, and Bernard Mazijn, eds. 2009. *Guidelines for Social Life Cycle Assessment of Products*. UNEP/SETAC Life Cycle Initiative.

Benoît, Catherine, Marzia Traverso, Sonia Valdivia, Gina Vickery-Niederman, Juliane Franze, Lina Azuero, Andreas Ciroth, Bernard Mazijn, and Deana Aulisio. 2013. “The Methodological Sheets for Sub-Categories in Social Life Cycle Assessment (S-LCA).”

Berger, Markus, and Matthias Finkbeiner. 2011. “Correlation Analysis of Life Cycle Impact Assessment Indicators Measuring Resource Use.” *International Journal of Life Cycle Assessment* 16 (1): 74–81. doi:10.1007/s11367-010-0237-7.

Berger, Markus, Ruud van der Ent, Stephanie Eisner, Vanessa Bach, and Matthias Finkbeiner. 2014. “Water Accounting and Vulnerability Evaluation (WAVE) - Considering Atmospheric Evaporation Recycling and the Risk of Freshwater Depletion in Water Footprinting.” *Environmental Science & Technology*, March. doi:10.1021/es404994t.

BGR. 2013. “Aluminium / Bauxit - Rohstoffwirtschaftliche Steckbriefe.” Hannover.

Bienge, Katrin, Justus Von Geibler, Michael Lettenmeier, Oliver Adria, and Michael Kuhndt. 2009. “Sustainability Hot Spot Analysis : A Streamlined Life Cycle Assessment towards Sustainable Food Chains.” In *9th European IFSA Symposium*, 4–7. Vienna.

Birnbaum, Linda S., and Paul Jung. 2011. “From Endocrine Disruptors to Nanomaterials: Advancing Our Understanding of Environmental Health to Protect Public Health.” *Health Affairs* 30 (5): 814–22. doi:10.1377/hlthaff.2010.1225.

Bleaney, Michael F. 1996. “Macroeconomic Stability, Investment and Growth in Developing

Countries." *Journal of Development Economics* 48 (2): 461–77. doi:http://dx.doi.org/10.1016/0304-3878(95)00049-6.

Bleys, Brent. 2013. "The Regional Index of Sustainable Economic Welfare for Flanders, Belgium." *Sustainability* 5 (2): 496–523. doi:10.3390/su5020496.

Blok, Kornelis, Mark Huijbregts, Lex Roes, Berthe Van Haaster, Edgar Hertwich, Richard Wood, Michael Z Hauschild, Paula Antunes, Stefanie Hellweg, and Andreas Ciroth. 2013. "A Novel Methodology for the Sustainability Impact Assessment of New Technologies." Utrecht.

Bloom, David E., and David Canning. 2007. "Commentary: The Preston Curve 30 Years on: Still Sparking Fires." *International Journal of Epidemiology* 36 (3): 498–99. doi:10.1093/ije/dym079.

Bluecraft Bikes. 2016. "Wie Entsteht Ein Rahmen von Bluecraft Bikes?" http://bluecraftbikes.de/253-2/.

Blundell, R, L Dearden, C Meghir, and B Sianesi. 1999. "Human Capital Investment: The Returns from Education and Training to the Individual, the Firm and the Economy." *Financial Studies* 20 (1): 1–23. doi:10.1111/j.1475-5890.1999.tb00001.x.

Bocoum, Ibrahima, Catherine Macombe, and Jean-Pierre Revéret. 2015. "Anticipating Impacts on Health Based on Changes in Income Inequality Caused by Life Cycles." *The International Journal of Life Cycle Assessment* 20 (3): 405–17. doi:10.1007/s11367-014-0835-x.

Boons, Frank, Carlos Montalvo, Jaco Quist, and Marcus Wagner. 2013. "Sustainable Innovation, Business Models and Economic Performance: An Overview." *Journal of Cleaner Production* 45 (April). Elsevier Ltd: 1–8. doi:10.1016/j.jclepro.2012.08.013.

Boulay, Anne-marie, Jane Bare, Lorenzo Benini, Markus Berger, Alessandro Manzardo, Manuele Margni, Masaharu Motoshita, and Michael Lathuillière. 2016. "The WULCA Consensus for Water Scarcity Footprints : Assessing Impacts of Water Consumption Based on the Available Water Remaining (AWARE) (Submitted)." *Environmental Science and Technology (Submitted)*, 1–23.

Bouwman, Mirjan E., and Henri C. Moll. 2002. "Environmental Analyses of Land Transportation Systems in the Netherlands." *Transportation Research Part D: Transport and Environment* 7 (5): 331–45. doi:10.1016/S1361-9209(02)00002-0.

Bovea, M.D, and R Vidal. 2004. "Increasing Product Value by Integrating Environmental Impact, Costs and Customer Valuation." *Resources, Conservation and Recycling* 41 (2): 133–45. doi:10.1016/j.resconrec.2003.09.004.

Bowen, Harry P., and Margarethe F. Wiersema. 2005. "Foreign-Based Competition and Corporate Diversification Strategy." *Strategic Management Journal* 26 (12): 1153–71. doi:10.1002/smj.499.

Braveman, Paula A., Catherine Cubbin, Susan Egerter, Sekai Chideya, Kristen S. Marchi, Marilyn Metzler, Samuel Posner, et al. 2005. "Socioeconomic Status in Health Research." *JAMA* 294 (22). American Medical Association: 2879–88. doi:10.1001/jama.294.22.2879.

Briguglio, Lino, Gordon Cordina, Nadia Farrugia, and Stephanie Vella. 2009. "Economic Vulnerability and Resilience: Concepts and Measurements." *Oxford Development Studies*. Vol. 37. doi:10.1080/13600810903089893.

Bubeck, Desmond. 2002. *Life Cycle Costing Im Automobilbau*. 1sted. Hamburg: Verlag Dr. Kovac.

Cabrita, Jorge. 2013. "Developments in Collectively Agreed Working Time." *European Observatory of Working Life*. http://www.eurofound.europa.eu/observatories/eurwork/comparative-information/developments-in-collectively-agreed-working-time-2013#fig9.

Carvalho, Laurence, and Brian Moss. 1995. "The Current Status of a Sample of English Sites of Special Scientific Interest Subject to Eutrophication." *Aquatic Conservation: Marine and Freshwater Ecosystems* 5: 191–204.

Casson, Anne. 2003. "Oil Palm, Soy Beans & Critical Habitat Loss." Zurich.

Chang, Y.-J., G. Sproesser, S. Neugebauer, K. Wolf, R. Scheumann, A. Pittner, M. Rethmeier, and M. Finkbeiner. 2015. "Environmental and Social Life Cycle Assessment of Welding Technologies." In *Procedia CIRP*, 26:293–98. doi:10.1016/j.procir.2014.07.084.

Chang, Ya-Ju, Laura Schneider, and Matthias Finkbeiner. 2015. "Assessing Child Development: A Critical Review and the Sustainable Child Development Index (SCDI)." *Sustainability* 7 (5): 4973–96. doi:10.3390/su7054973.

Cheema, Amar, and Dilip Soman. 2006. "Malleable Mental Accounting: The Effect of Flexibility on the Justification of Attractive Spending and Consumption Decisions." *Journal of Consumer Psychology* 16 (1): 33–44. doi:10.1207/s15327663jcp1601_6.

Cinelli, Marco, Stuart R. Coles, Andreas Jørgensen, Alessandra Zamagni, Chalaka Fernando, and Kerry Kirwan. 2013. "Workshop on Life Cycle Sustainability Assessment: The State of the Art and Research needs—November 26, 2012, Copenhagen, Denmark." *The International Journal of Life Cycle Assessment* 18 (7): 1421–24. doi:10.1007/s11367-013-0573-5.

City and County of San Francisco. 2014. "Sweatfree Contracting Ordinance." http://www.sfgsa.org/index.aspx?page=434.

Cobham, Alex, and Andy Sumner. 2013. "Putting the Gini Back in the Bottle? 'the Palma' As a Policy-Relevant Measure of Inequality." London. http://www.kcl.ac.uk/aboutkings/worldwide/initiatives/global/intdev/people/Sumner/Cobham-Sumner-15March2013.pdf.

Constable, David, and Arthur D. Little. 2000. *Total Cost Assessment Methodology*. Edited by Center for Waster Reduction Technologies. American Institute of Chemical Engineers.

Costanza, Robert, Ralph d'Arge, Rudolf De Groot, Stephen Farber, Monica Grasso, Bruce Hannon, Karin Limburg, et al. 1997. "The Value of the World's Ecosystem Services and Natural Capital." *Nature* 387 (6630). Nature Publishing Group: 253–60. doi:10.1038/387253a0.

Costanza, Robert, Jon Erickson, Karen Fligger, Alan Adams, Christian Adams, Ben Altschuler, Stephanie Balter, et al. 2004. “Estimates of the Genuine Progress Indicator (GPI) for Vermont, Chittenden County and Burlington, from 1950 to 2000.” *Ecological Economics* 51 (1–2): 139–55. doi:10.1016/j.ecolecon.2004.04.009.

Čuček, Lidija, Jiří Jaromír Klemeš, and Zdravko Kravanja. 2012. “A Review of Footprint Analysis Tools for Monitoring Impacts on Sustainability.” *Journal of Cleaner Production* 34 (October): 9–20. doi:10.1016/j.jclepro.2012.02.036.

Curran, Michael, Laura de Baan, An M. De Schryver, Rosalie Van Zelm, Stefanie Hellweg, Thomas Koellner, Guido Sonnemann, and Mark A. J. Huijbregts. 2011. “Toward Meaningful End Points of Biodiversity in Life Cycle Assessment.” *Environmental Science & Technology* 45 (1): 70–79. doi:10.1021/es101444k.

Curran, R., S. Raghunathan, and M. Price. 2004. “Review of Aerospace Engineering Cost Modelling: The Genetic Causal Approach.” *Progress in Aerospace Sciences* 40 (8): 487–534. doi:10.1016/j.paerosci.2004.10.001.

Cycle Taiwan. 2016. “Over 80 % of All Medium to High End Bicycles and Bike Components Are Made in Taiwan or in Taiwanese Owned Factories.” http://cycletaiwan.com/buy-direct.html.

Dalgaard, Randi, Jannick Schmidt, and Anna Flysjö. 2014. “Generic Model for Calculating Carbon Footprint of Milk Using Four Different LCA Modelling Approaches.” *Journal of Cleaner Production*, January. Elsevier Ltd, 1–8. doi:10.1016/j.jclepro.2014.01.025.

Daly, Herman E. 1994. *For the Common Good: Redirecting the Economy Toward Community, the Environment, and a Sustainable Future*. Beacon Press. http://books.google.com/books?id=TZAIU1yqyRkC&pgis=1.

De Maio, Fernando G. 2007. “Income Inequality Measures.” *Journal of Epidemiology and Community Health* 61: 849–52. doi:10.1136/jech.2006.052969.

Department of Economic and Social Affairs. 2013. “System of Environmental-Economic Accounting for Energy - Draft Version for Global Consultation.” https://unstats.un.org/unsd/envaccounting/seeae/chapterList.asp.

Deutscher Bundestag. 2013. “Schlussbericht Der Enquete-Kommission - Wachstum, Wohlstand, Lebensqualität (Final Report of the Enquete Commission - Growth, Wealth and Life Quality).” Bonn.

Diener, Ed, and Martin E P Seligman. 2004. “Beyond Money - Toward an Economy of Well-Being.” *Psychological Science in the Public Interest* 5 (1): 1–31.

Dong, Jun, Yong Chi, Daoan Zou, Chao Fu, Qunxing Huang, and Mingjiang Ni. 2014. “Energy–environment–economy Assessment of Waste Management Systems from a Life Cycle Perspective: Model Development and Case Study.” *Applied Energy* 114 (February). Elsevier Ltd: 400–408. doi:10.1016/j.apenergy.2013.09.037.

Dreyer, Louise Camilla, Michael Z. Hauschild, and Jens Schierbeck. 2010. “Characterisation of Social Impacts in LCA: Part 1: Development of Indicators for Labour Rights.” *International Journal of Life Cycle Assessment* 15 (3): 247–59. doi:10.1007/s11367-009-0148-7.

Dreyer, Louise Camilla, Michael Z Hauschild, and Jens Schierbeck. 2006. "A Framework for Social Life Cycle Impact Assessment." *International Journal of Life Cycle Assessment* 11 (2): 88–97.

Drobe, Malte, and Franziska Killiches. 2014. *Vorkommen Und Produktion Mineralischer Rohstoffe – Ein Ländervergleich*.

EC. 2005. *The Directive on "Ambient Air Quality and Cleaner Air for Europe."* Europe: Commission of the European Communities.

EEA. 2005. "EEA Core Set of Indicators." Luxembourg.

EHI. 2013. "Strukturdaten Und Kennzahlen Zum Deutschen Fahrradeinzelhandel." http://www.handelsdaten.de/sport-und-freizeitartikelhandel/strukturdaten-und-kennzahlen-zum-deutschen-fahrradeinzelhandel.

Ehrenfeld, John R. 2005. "The Roots of Sustainability." *Sloan Management Review* 46 (2): 23–25.

Ekener-Petersen, Elisabeth, and G??ran Finnveden. 2013. "Potential Hotspots Identified by Social LCA - Part 1: A Case Study of a Laptop Computer." *International Journal of Life Cycle Assessment* 18 (1): 127–43. doi:10.1007/s11367-012-0442-7.

Elkington, John. 1998. *Cannibals with Forks: The Triple Bottom Line of 21st Century Business*. Gabriola Island: New Society Publishers. http://www.amazon.de/Cannibals-Forks-Century-Business-Capstone/dp/1841120847.

EPA. 2012. "Environmental Databases." http://www.epa.gov/opp00001/science/efed_databasesdescription.htm#ecotoxicity.

Erlandsson, Martin, and Mathias Borg. 2003. "Generic LCA-Methodology Applicable for Buildings, Constructions and Operation Services—today Practice and Development Needs." *Building and Environment* 38 (7): 919–38. doi:10.1016/S0360-1323(03)00031-3.

Eurofound. 2013. "Impact of the Crisis on Working Conditions in Europe." Dublin.

European Chemicals Agency. 2016. "REACH - ECHA." http://echa.europa.eu/regulations/reach.

European commission. 2007. "Life Cycle Costing (LCC) as a Contribution to Sustainable Construction : A Common Methodology."

European Commission. 2009. *Making Sustainable Consumption and Production a Reality: A Guide for Business and Policy Makers to Life Cycle Thinking and Assessment*. Book. doi:10.2779/91521.

———. 2014. "Economic Stability and Growth." http://ec.europa.eu/economy_finance/euro/why/stability_growth/index_en.htm.

———. 2015. "European Platform on Life Cycle Assessment (LCA)." http://ec.europa.eu/environment/ipp/lca.htm.

European Union. 2002. "DIRECTIVE 2002/24/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL." Misc. Official Journal of the European Communities. http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2002:124:0001:0044:EN:PDF.

FAO. 2014. *World Reference Base for Soil Resources 2014 - International Soil Classification System for Naming Soils and Creating Legends for Soil Maps*. Edited by Food and agriculture organization of the united Nations. Rome.

Felipe, Jesus, and Cesar Hidalgo. 2015. "Economic Diversification Implications for Kazakhstan." In *Development and Modern Industrial Policy in Practice: Issues and Country Experiences*, edited by Jesus Felipe, 160–96. Cheltenham, Northampton: Asian Development Bank. https://books.google.com/books?hl=de&lr=&id=oN8WCQAAQBAJ&pgis=1.

Felipe, Jesus, Utsav Kumar, Arnelyn Abdon, and Marife Bacate. 2012. "Product Complexity and Economic Development." *Structural Change and Economic Dynamics* 23 (1). Elsevier B.V.: 36–68. doi:10.1016/j.strueco.2011.08.003.

Feschet, Pauline, Catherine MacOmbe, Michel Garrabé, Denis Loeillet, Adolfo Rolo Saez, and François Benhmad. 2013. "Social Impact Assessment in LCA Using the Preston Pathway: The Case of Banana Industry in Cameroon." *International Journal of Life Cycle Assessment* 18 (2): 490–503. doi:10.1007/s11367-012-0490-z.

Figge, Frank, and Tobias Hahn. 2004. "Sustainable Value Added—measuring Corporate Contributions to Sustainability beyond Eco-Efficiency." *Ecological Economics* 48 (2): 173–87. doi:10.1016/j.ecolecon.2003.08.005.

Finkbeiner, Matthias. 2009. "Carbon Footprinting—opportunities and Threats." *The International Journal of Life Cycle Assessment* 14 (2): 91–94. doi:10.1007/s11367-009-0064-x.

Finkbeiner, Matthias, Robert Ackermann, Vanessa Bach, Markus Berger, Gerhard Brankatschk, Ya-ju Chang, Marina Grinberg, et al. 2014. "Challenges in Life Cycle Assessment: An Overview of Current Gaps and Research Needs." In *LCA Compendium - The Complete World of Life Cycle Assessment*, edited by Walter Klöpffer, 207–58. LCA Compendium – The Complete World of Life Cycle Assessment. Dordrecht: Springer Netherlands. doi:10.1007/978-94-017-8697-3.

Finkbeiner, Matthias, Atsushi Inaba, Reginald B H Tan, Kim Christiansen, and Hans-jürgen Klüppel. 2006. "The New International Standards for Life Cycle Assessment : ISO 14040 and ISO 14044." *International Journal of Life Cycle Assessment* 11 (2): 80–85.

Finkbeiner, Matthias, Erwin M. Schau, Annekatrin Lehmann, and Marzia Traverso. 2010. "Towards Life Cycle Sustainability Assessment." *Sustainability* 2 (10): 3309–22. doi:10.3390/su2103309.

Freewheeler. 2016. "The Freewheeler Bike Shop." http://www.freewheelerbikeshop.com/#!policies/c257.

Frischknecht, R., a. Braunschweig, P. Hofstetter, and P. Suter. 2000. "Human Health Damages due to Ionising Radiation in Life Cycle Impact Assessment." *Environmental Impact Assessment Review* 20 (2): 159–89. doi:10.1016/S0195-9255(99)00042-6.

Fuchs, Victor R. 2004. "Reflections on the Socio-Economic Correlates of Health." *Journal of*

Health Economics 23 (4): 653–61. doi:10.1016/j.jhealeco.2004.04.004.

FWN. 2016. “Fair Wage Network.” http://www.fair-wage.com/.

Galli, Alessandro, Thomas Wiedmann, Ertug Ercin, Doris Knoblauch, Brad Ewing, and Stefan Giljum. 2012. “Integrating Ecological, Carbon and Water Footprint into a ‘Footprint Family’ of Indicators: Definition and Role in Tracking Human Pressure on the Planet.” *Ecological Indicators* 16 (May). Elsevier Ltd: 100–112. doi:10.1016/j.ecolind.2011.06.017.

Geyer, Siegfried, Orjan Hemström, Richard Peter, and Denny Vågerö. 2006. “Education, Income, and Occupational Class Cannot Be Used Interchangeably in Social Epidemiology. Empirical Evidence against a Common Practice.” *Journal of Epidemiology and Community Health* 60 (9): 804–10. doi:10.1136/jech.2005.041319.

Ghosheh, Naj. 2013. *Working Conditions Laws Report 2012: A Global Review*.

Giddings, Bob, Bill Hopwood, and Geoff O’Brien. 2002. “Environment, Economy and Society: Fitting Them Together into Sustainable Development.” *Sustainable Development* 10 (4): 187–96. doi:10.1002/sd.199.

Global Reporting Initiative. 2013. “G4 - Sustainability Reporting Guideline.” Amsterdam. www.globalreporting.org.

Gluch, Pernilla, and Henrikke Baumann. 2004. “The Life Cycle Costing (LCC) Approach: A Conceptual Discussion of Its Usefulness for Environmental Decision-Making.” *Building and Environment* 39 (5): 571–80. doi:10.1016/j.buildenv.2003.10.008.

Goedkoop, Mark, Reinout Heijungs, Mark Huijbregts, An De Schryver, Jaap Struijs, and Rosalie Van Zelm. 2009. “ReCiPe 2008 - A Life Cycle Impact Assessment Method Which Comprises Harmonised Category Indicators at the Midpoint and the Endpoint Level.” Den Haag.

Goldin, Rebecca. 2015. “Causation vs Correlation.” stats.org. http://www.stats.org/causation-vs-correlation/.

Gould, Jens. 2014. “Taiwan: The Bicycle Kingdom.” *The Financialist*, August 21. https://www.thefinancialist.com/taiwan-the-bicycle-kingdom/.

Graff, Arno, Susan Klose, Andrea Minkos, Ute Dauert, and Stefan Feigenspan. 2014. “Luftqualität 2013 - Vorläufige Auswertung.” Dessau-Roßlau.

Grießhammer, Rainer, Catherine Benoît, Louise Camilla Dreyer, Anna Flysjö, Bernard Mazijn, Andrée-lise Méthot, and Bo Weidema. 2006. “Feasibility Study : Integration of Social Aspects into LCA,” no. May 2005: 1–14.

Grießhammer, Rainer, Matthias Buchert, Carl-Otto Gensch, Christian Hochfeld, Andreas Manhart, and Ina Rüdenauer. 2007. “PROSA – Product Sustainability Assessment.” Vol. 49. Freiburg.

Guinée, Jeroen B, ed. 2002. *Handbook on Life Cycle Assessment - Operational Guide to the ISO Standards*. Dodrecht: Kluwer Academic Publishers. http://www.springer.com/environment/book/978-1-4020-0228-1?otherVersion=978-1-4020-0557-2.

Guzi, Martin, and Martin Kahanec. 2014. "WageIndicator Living Wages Methodological Note." Amsterdam.

Ha, Arthur, Loris Strappazzon, and William Fisher. 2001. "What Is the Difference between Productivity and Profit ?" Working Paper Series. Victoria.

Hacking, Theo, and Peter Guthrie. 2008. "A Framework for Clarifying the Meaning of Triple Bottom-Line, Integrated, and Sustainability Assessment." *Environmental Impact Assessment Review* 28 (2–3): 73–89. doi:10.1016/j.eiar.2007.03.002.

Haes, Helias a. Udo De, Olivier Jolliet, Greg Norris, and Konrad Saur. 2002. "UNEP/SETAC Life Cycle Initiative: Background, Aims and Scope." *The International Journal of Life Cycle Assessment* 7 (4): 192–95. doi:10.1007/BF02978872.

Hall, Murray R. 2015. "A Transdisciplinary Review of the Role of Economics in Life Cycle Sustainability Assessment." *The International Journal of Life Cycle Assessment*, 1625–39. doi:10.1007/s11367-015-0970-z.

Hamilton, Kirk, Giovanni Ruta, Katharine Bolt, Anil Markandya, Suzette Pedroso-Galinato, Patricia Silva, M. Saeed Ordoubadi, Glenn-Marie Lange, and Liaila Tajibaeva. 2006. *Where Is the Wealth of Nations?* Washington DC: World Bank. doi:10.1596/978-0-8213-6354-6.

Hansen, Erik G., and Stefan Schaltegger. 2016. "The Sustainability Balanced Scorecard: A Systematic Review of Architectures." *Journal of Business Ethics* 133 (2). Springer Netherlands: 193–221. doi:10.1007/s10551-014-2340-3.

Hauschild, M.Z., L.C. Dreyer, and a. Jørgensen. 2008. "Assessing Social Impacts in a Life Cycle perspective—Lessons Learned." *CIRP Annals - Manufacturing Technology* 57 (1): 21–24. doi:10.1016/j.cirp.2008.03.002.

Hausmann, Ricardo, Cesar A. Hidalgo, Sebastian Bustos, Michele Coscia, Alexander Simoes, and Muhammed A. Yildirim. 2013. *The Atlas of Economic Complexity*. Cambridge: MIT Press.

Heijungs, Reinout, Gjalt Huppes, and Jeroen B. Guinée. 2010. "Life Cycle Assessment and Sustainability Analysis of Products, Materials and Technologies. Toward a Scientific Framework for Sustainability Life Cycle Analysis." *Polymer Degradation and Stability* 95 (3): 422–28. doi:10.1016/j.polymdegradstab.2009.11.010.

Heijungs, Reinout, Ettore Settanni, and Jeroen Guinée. 2012. "Toward a Computational Structure for Life Cycle Sustainability Analysis: Unifying LCA and LCC." *The International Journal of Life Cycle Assessment* 18 (9): 1722–33. doi:10.1007/s11367-012-0461-4.

Heink, Ulrich, and Ingo Kowarik. 2010. "What Are Indicators? On the Definition of Indicators in Ecology and Environmental Planning." *Ecological Indicators* 10 (3): 584–93. doi:10.1016/j.ecolind.2009.09.009.

Heller, Martin C, and Gregory a Keoleian. 2003. "Assessing the Sustainability of the US Food System: A Life Cycle Perspective." *Agricultural Systems* 76 (3): 1007–41. doi:10.1016/S0308-521X(02)00027-6.

Henderson, Andrew, Alexi Ernstoff, Susie Chung, and Olivier Jolliet. 2012. "Assessing Direct Impact of Products on Consumers in LCA." In . Tacoma: Conference of the American

Center of Life Cycle Assessment LCA XII – Life Cycle Thinking … Life Cycle Living.

Hill, Edward, Howard Wial, and Harold Wolman. 2008. "Exploring Regional Economic Resilience." *Working Paper 2008-04*. Berkley. http://www.econstor.eu/handle/10419/59420.

Hochschorner, Elisabeth, and Maria Noring. 2011. "Practitioners' Use of Life Cycle Costing with Environmental Costs—a Swedish Study." *The International Journal of Life Cycle Assessment* 16 (9): 897–902. doi:10.1007/s11367-011-0325-3.

Hodgson, John G., Jerry Tallowin, Roger L. H. Dennis, Ken Thompson, Peter Poschlod, Mewa S. Dhanoa, Mike Charles, et al. 2014. "Changing Leaf Nitrogen and Canopy Height Quantify Processes Leading to Plant and Butterfly Diversity Loss in Agricultural Landscapes." Edited by Edith Adam. *Functional Ecology* 28 (5): 1284–91. doi:10.1111/1365-2435.12253.

Hoekstra, Arjen Y, Ashok K Chapagain, Maite M Aldaya, and Mesfin M Mekonnen. 2009. "Water Footprint Manual - State of the Art 2009." Enschede.

Hofstetter, Patrick, and Ruedi Müller-Wenk. 2005. "Monetization of Health Damages from Road Noise with Implications for Monetizing Health Impacts in Life Cycle Assessment." *Journal of Cleaner Production* 13 (13–14): 1235–45. doi:10.1016/j.jclepro.2005.05.011.

Hoogmartens, Rob, Steven Van Passel, Karel Van Acker, and Maarten Dubois. 2014. "Bridging the Gap between LCA, LCC and CBA as Sustainability Assessment Tools." *Environmental Impact Assessment Review* 48. Elsevier Inc.: 27–33. doi:10.1016/j.eiar.2014.05.001.

Human Rights Watch. 2016. "Human Rights Watch." https://www.hrw.org/.

Hunkeler, David. 2006. "Societal LCA Methodology and Case Study." *International Journal of Life Cycle Assessment* 11 (6): 371–82.

Hunkeler, David, and Gerald Rebitzer. 2005. "The Future of Life Cycle Assessment." *International Journal of Life Cycle Assessment* 10 (5): 305–8.

Hunkeler, David, Gerald Rebitzer, and Kerstin Lichtenvort. 2008. *Environmental Life Cycle Costing*. CRC Press. doi:10.1201/9781420054736.

Hutchins, Margot J., and John W. Sutherland. 2008. "An Exploration of Measures of Social Sustainability and Their Application to Supply Chain Decisions." *Journal of Cleaner Production* 16 (15): 1688–98. doi:10.1016/j.jclepro.2008.06.001.

ICAEW. 2006. *Measurement in Financial Reporting Information for Better Markets Initiative*. ICAEW.

Ilg, Patrick, Christoph Hoehne, and Edeltraud Guenther. 2015. "High-Performance Materials in Infrastructure: A Review of Applied Life Cycle Costing and Its Drivers – the Case of Fiber-Reinforced Composites." *Journal of Cleaner Production* 112. Elsevier Ltd: 926–45. doi:10.1016/j.jclepro.2015.07.051.

ILO. 1970. "Convention C131 - Minimum Wage Fixing Convention." *Convention from the International Labour Organization*. http://www.ilo.org/dyn/normlex/en/f?p=NORMLEXPUB:12100:0::NO::P12100_ILO_CODE:C131.

———. 2008. “ILO Declaration on Social Justice for a Fair Globalization.” In *International Labour Conference at Its Ninety-Seventh Session*. Geneva: International Labour Organization.

———. 2010a. “International Standard Classification of Education (ISCED-76).” http://laborsta.ilo.org/applv8/data/isced76e.html.

———. 2010b. “International Standard Classification of Education (ISCED-97).” http://laborsta.ilo.org/applv8/data/isced97e.html.

———. 2010c. “LABORSTA Internet.” *Statistics by Topic*. http://laborsta.ilo.org/.

———. 2011a. “Conditions of Work and Employment Programme.” *TRAVAIL Legal Databases*. http://www.ilo.org/dyn/travail/travmain.byCountry2.

———. 2011b. “Conditions of Work and Employment Programme: Working Time in the Twenty-First Century.” Geneva, Switzerland.

———. 2016a. “Declaration on Fundamental Principles and Rights at Work.” http://www.ilo.org/declaration/lang--en/index.htm.

———. 2016b. “Social Security Database.” http://www.ilo.org/dyn/sesame/IFPSES.SSDBMENU.

ILO, OECD, IMF, and Worldbank. 2012. “Boosting Jobs and Living Standards in G20 Countries.” Geneva, Washington DC, Paris.

IMF. 2015. “How the IMF Promotes Global Economic Stability.” *IMF Factsheet*. Washington.

Ingwersen, Wesley, Heriberto Cabezas, Anne Weisbrod, Tarsha Eason, Bayou Demeke, Xin (Cissy) Ma, Troy Hawkins, Seung-Jin Lee, Jane Bare, and Manuel Ceja. 2014. “Integrated Metrics for Improving the Life Cycle Approach to Assessing Product System Sustainability.” *Sustainability* 6 (3): 1386–1413. doi:10.3390/su6031386.

International Labour Organization. 1952. “Convention C102 - Social Security (Minimum Standards) Convention.” http://www.ilo.org/dyn/normlex/en/f?p=NORMLEXPUB:12100:0::NO:12100:P12100_INSTRUMENT_ID:312247:NO.

IPCC. 2007. “Climate Change 2007 : An Assessment of the Intergovernmental Panel on Climate Change.” *Synthesis Report*. Vol. 446. Synthesis Report. IPCC. doi:10.1256/004316502320517344.

———. 2013. *IPCC: Climate Change 2013 - The Physical Science Basis*. Edited by Thomas F. Stocker, Dahe Qin, Gian-Kasper Plattner, Melinda M.B. Tignor, Simon K. Allen, Judith Boschung, Alexander Nauels, Yu Xia, Vincent Bex, and Pauline M. Midgley. Fifth Asse. New York: Cambridge University Press, Cambridge.

Isaksen, Jan, Nils Gunnar Songstad, and Arild Spissoy. 2002. *Socio-Economic Effects of HIV/AIDS in African Countries*. Bergen: Chr Michelsen Institute.

ISO. 2008. *Buildings and Constructed Assets - Service-Life Planning - Life-Cycle Costing*.

ISO 14040. 2006. *Environmental Management - Life Cycle Assessment - Principles and*

Framework. *… assessment—Principles and Framework (ISO 14040: …*. Deutsches Institut für Normung e.V.

ISO 14044. 2006. *Environmental Management - Life Cycle Assessment - Requirements and Guidelines*. Deutsches Institut für Normung e.V.

ISO 14047. 2002. *ISO 14047 - Illustrative Examples on How to Apply ISO 14042 - Life Cycle Assessment - Life Cycle Impact Assessment*.

Jackson, Tim. 2011. “Prosperity without Growth.” *World Tourism Forum Lucerne*, 12. doi:http://dx.doi.org/10.1111/j.1530-9290.2009.00213.x.

Jamal, Waseef, and Iqbal Saif. 2011. “Impact of Human Capital Management on Organizational Performance.” *European Journal of Economics, Finance and Adminstrative Sciences*, no. 34.

Jeswani, Harish Kumar, Adisa Azapagic, Philipp Schepelmann, and Michael Ritthoff. 2010. “Options for Broadening and Deepening the LCA Approaches.” *Journal of Cleaner Production* 18 (2). Elsevier Ltd: 120–27. doi:10.1016/j.jclepro.2009.09.023.

Jolliet, Olivier, Rolf Frischknecht, Jane Bare, Anne-Marie Boulay, Cecile Bulle, Peter Fantke, Shabbir Gheewala, et al. 2014. “Global Guidance on Environmental Life Cycle Impact Assessment Indicators: Findings of the Scoping Phase.” *The International Journal of Life Cycle Assessment* 19 (4): 962–67. doi:10.1007/s11367-014-0703-8.

Jolliet, Olivier, Manuele Margni, Raphael Charles, Sbastien Humbert, Jerome Payet, Gerald Rebitzer, and Ralph Rosenbaum. 2003. “IMPACT 2002 + : A New Life Cycle Impact Assessment Methodology.” *International Journal of Life Cycle Assessment* 8 (6): 324–30.

Jolliet, Olivier, Ruedi Müller-Wenk, Jane Bare, Alan Brent, Mark Goedkoop, Reinout Heijungs, Norihiro Itsubo, Claudia Pefia, David Pennington, Jose Potting, Gerald Rebitzer, Mary Stewart, Helias Udo de Haes, et al. 2004. “The LCIA Midpoint-Damage Framework of the UNEP/SETAC Life Cycle Initiative.” *International Journal of Life Cycle Assessment* 9 (6): 394–404.

Jonkman, S.N., P.H.A.J.M. van Gelder, and J.K. Vrijling. 2003. “An Overview of Quantitative Risk Measures for Loss of Life and Economic Damage.” *Journal of Hazardous Materials* 99 (1): 1–30. doi:10.1016/S0304-3894(02)00283-2.

Jørgensen, Andreas. 2010. “Developing the Social Life Cycle Assessment - Addressing Issues of Validity and Usability.” DTU.

Jørgensen, Andreas, Agathe Le Bocq, Liudmila Nazarkina, and Michael Hauschild. 2008. “Methodologies for Social Life Cycle Assessment.” *International Journal of Life Cycle Assessment* 13 (2): 96–103.

Jørgensen, Andreas, Matthias Finkbeiner, Michael S. Jørgensen, and Michael Z. Hauschild. 2010. “Defining the Baseline in Social Life Cycle Assessment.” *The International Journal of Life Cycle Assessment* 15 (4): 376–84. doi:10.1007/s11367-010-0176-3.

Jørgensen, Andreas, Ivan T. Herrmann, and Anders Bjørn. 2013. “Analysis of the Link between a Definition of Sustainability and the Life Cycle Methodologies.” *The International Journal* *of Life Cycle Assessment*, July. doi:10.1007/s11367-013-0617-x.

Jørgensen, Andreas, Lufanna C. H. Lai, and Michael Z. Hauschild. 2010. "Assessing the Validity of Impact Pathways for Child Labour and Well-Being in Social Life Cycle Assessment." *The International Journal of Life Cycle Assessment* 15 (1): 5–16. doi:10.1007/s11367-009-0131-3.

JPI Cultural Heritage. 2016. "JPI on Cultural Heritage and Global Change - A New Challenge for Europe." http://www.jpi-culturalheritage.eu/.

JRC. 2010a. *ILCD Handbook: Framework and Requirements for LCIA Models and Indicators*. Edited by Michael Hauschild, Mark Goedkoop, Jeroen Guinée, Reinout Heijungs, Mark Huijbregts, Olivier Jolliet, Manuele Margni, and An De Schryver. First Edit. Ispra: European Commission.

———. 2010b. *ILCD Handbook: General Guide on LCA - Detailed Guidance*. Edited by Michael Hauschild, Stig Olsen, and Anders Schmidt. First Edit. Ispra: European Commission.

———. 2010c. "ILCD Handbook - General Guide for Life Cycle Assessment - Detailed Guidance." Luxembourg. doi:10.2788/38479.

———. 2011. *ILCD Handbook: Recommendations for Life Cycle Impact Assessment in the European Context*. Edited by Michael Hauschild, Mark Goedkoop, Jeroen Guinée, Reinout Heijungs, Mark Huijbregts, Olivier Jolliet, Manuele Margni, and An De Schryver. First edit. Ispra: European Commission. doi:10.278/33030.

Karlewski, Hannah. 2015. "Social Life Cycle Assessment in Der Automobilindustrie." Technische Universität Berlin. doi:10.1007/978-981-287-296-8.

Kenrick, Douglas T, Vladas Griskevicius, Steven L Neuberg, and Mark Schaller. 2010. "Renovating the Pyramid of Needs: Contemporary Extensions Built Upon Ancient Foundations." *Perspectives on Psychological Science : A Journal of the Association for Psychological Science* 5 (3): 292–314. doi:10.1177/1745691610369469.

Khan, M. Nasir, and Firoz Mohammad. 2014. "Eutrophication: Challenges and Solutions." In *Eutrophication: Causes, Consequences and Control*, edited by Abid A. Ansari and Sarvajeet Singh Gill, 1–15. Dordrecht: Springer Netherlands. doi:10.1007/978-94-007-7814-6.

Klöpffer, Walter. 2008. "Life Cycle Sustainability Assessment of Products." *International Journal of Life Cycle Assessment* 13 (2): 89–95.

Klöpffer, Walter, and Andreas Ciroth. 2011. "Is LCC Relevant in a Sustainability Assessment?" *International Journal of Life Cycle Assessment* 16 (2): 99–101. doi:10.1007/s11367-011-0249-y.

Klöpffer, Walter, and Birgit Grahl. 2014. *Life Cycle Assessment (LCA) - A Guide to Best Practice*. Weinheim, Germany: Wiley-VCH Verlag GmbH & Co. KGaA. http://books.google.com/books?id=5kqxzNYoXKgC&pgis=1.

Kruse, Sarah a., Anna Flysjö, Nadja Kasperczyk, and Astrid J. Scholz. 2009. "Socioeconomic Indicators as a Complement to Life Cycle Assessment—an Application to Salmon Production Systems." *The International Journal of Life Cycle Assessment* 14 (1): 8–18.

doi:10.1007/s11367-008-0040-x.

Kyrkilis, George, Arhontoula Chaloulakou, and Pavlos a Kassomenos. 2007. “Development of an Aggregate Air Quality Index for an Urban Mediterranean Agglomeration: Relation to Potential Health Effects.” *Environment International* 33 (5): 670–76. doi:10.1016/j.envint.2007.01.010.

Labuschagne, Carin, and Alan C Brent. 2006. “Social Indicators for Sustainable Project and Technology Life Cycle Management in the Process Industry.” *International Journal of Life Cycle Assessment* 11 (1): 3–15. doi:http://dx.doi.org/10.1065/lca2006.01.233.

Lam, Hon Loong, Petar Varbanov, and Jiří Klemeš. 2010. “Minimising Carbon Footprint of Regional Biomass Supply Chains.” *Resources, Conservation and Recycling* 54 (5): 303–9. doi:10.1016/j.resconrec.2009.03.009.

Leiden University. 2013. “CMLCharacterisation Factors.” http://cml.leiden.edu/software/data-cmlia.html.

Lewis, T, C Edegger, and Schriefl E. 2012. “Pedelecs and Renewable Energy.” Misc. Edited by energieautark consulting gmbh.

Lindgreen, Adam, Martin K. Hingley, David B. Grant, and Robert E. Morgan. 2012. “Value in Business and Industrial Marketing: Past, Present, and Future.” *Industrial Marketing Management* 41 (1). Elsevier Inc.: 207–14. doi:10.1016/j.indmarman.2011.11.025.

Louise Camilla Dreyer, Michael Z. Hauschild, and Jens Schierbeck. 2010. “Characterisation of Social Impacts in LCA. Part 2: Implementation in Six Company Case Studies.” *The International Journal of Life Cycle Assessment* 15: 385–402.

Majeau-Bettez, Guillaume, Stefan Pauliuk, Richard Wood, Evert A. Bouman, and Anders Hammer Str??mman. 2016. “Balance Issues in Input-Output Analysis: A Comment on Physical Inhomogeneity, Aggregation Bias, and Coproduction.” *Ecological Economics* 126. Elsevier B.V.: 188–97. doi:10.1016/j.ecolecon.2016.02.017.

Malizia, Emil E, and Shanzi Ke. 1993. “The Influence of Economic Diversity on Unemployment and Stability.” *Journal of Regional Science* 33 (2): 221. doi:10.1111/j.1467-9787.1993.tb00222.x.

Manthey, Nora, Hannes Neupert, and Angela Budde. 2012. “GoPedelec.” Wien.

Martínez-Blanco, Julia, Matthias Finkbeiner, and Atsushi Inaba. 2015. “Guidance on Organizational Life Cycle Assessment.”

Martínez-Blanco, Julia, Annekathrin Lehmann, YaJu Chang, and Matthias Finkbeiner. 2015. “Social Organizational LCA (SOLCA) - a New Approach for Implementing Social LCA.” *International Journal of Life Cycle Assessment*, no. 20: 1586–99. doi:10.1007/s11367-015-0960-1.

Martínez-Blanco, Julia, Annekatrin Lehmann, Pere Muñoz, Assumpció Antón, Marzia Traverso, Joan Rieradevall, and Matthias Finkbeiner. 2014. “Application Challenges for the Social Life Cycle Assessment of Fertilizers within Life Cycle Sustainability Assessment.” *Journal of Cleaner Production* 69 (April). Elsevier Ltd: 34–48. doi:10.1016/j.jclepro.2014.01.044.

Maslow, A. H. 1943. "A Theory of Human Motivation." *Psychological Review* 50: 370–96.

———. 1954. *Motivation and Personality*. New York: Harper.

May, J.R., and D.J. Brennan. 2006. "Sustainability Assessment of Australian Electricity Generation." *Process Safety and Environmental Protection* 84 (2): 131–42. doi:10.1205/psep.04265.

Meadows, Donella H, Dennis L Meadows, Jørgen Randers, and William W Behrens. 1972. *The Limits to Growth*. Edited by John Dryzek and David Schlosberg. *Chelsea*. Vol. 205. Universe Books. doi:10.1111/j.1752-1688.1972.tb05230.x.

Meadows, Donella, Dennis Meadows, and Jorgen Randers. 2004. *Limits to Growth: The 30-Year Update (Google eBook)*. http://books.google.com/books?hl=de&lr=&id=QRyQiINGW6oC&pgis=1.

Milà i Canals, Llorenç, Christian Bauer, Jochen Depestele, Alain Dubreuil, and Ruth Freiermuth Knuchel. 2007. "Framework for LCIA of Land Use Land Use in LCA - Key Elements in a Framework for Land Use Impact Assessment Within LCA Land Use in LCA." *International Journal of Life Cycle Assessment* 12 (1): 5–15.

Möhner, Matthias, Manfred Lindtner, Heinz Otten, and Hans Gille. 2006. "American Journal of Industrial Medicine Volume 49 Issue 4 2006 [Doi 10.1002%2Fajim.20289] Matthias Möhner; Manfred Lindtner; Heinz Otten; Hans-G. Gille -- Leukemia and Exposure to Ionizing Radiation A.pdf." *American Journal of Industrial Medicine* 49: 238–48. doi:10.1002/ajim.20289.

Montenegro, Claudio, and Harry Anthony Patrinos. 2014. "Comparable Estimates of Returns to Schooling Around the World." WPS7020. Education Global Practice Group.

Moriizumi, Yue, Naohiro Matsui, and Hiroki Hondo. 2010. "Simplified Life Cycle Sustainability Assessment of Mangrove Management: A Case of Plantation on Wastelands in Thailand." *Journal of Cleaner Production* 18 (16–17). Elsevier Ltd: 1629–38. doi:10.1016/j.jclepro.2010.07.017.

Mücke, Hans-Guido. 2008. "Air Quality Management in the WHO European Region--Results of a Quality Assurance and Control Programme on Air Quality Monitoring (1994-2004)." *Environment International* 34 (5): 648–53. doi:10.1016/j.envint.2007.12.008.

Mulligan, C.B., and X. Sala-i-Martin. 1997. "A Labor Income-Based Measure of the Value of Human Capital: An Application to the States of the United States." *Japan and the World Economy* 9 (2): 159–91. doi:10.1016/S0922-1425(96)00236-8.

Murphy, Peter. 2012. "The Long, Brutal Haul from Farm to Port in Brazil." *Reuters*, November 1. http://www.reuters.com/article/us-brazil-transport-grains-idUSBRE8A014020121101.

Musaazi, Moses Kizza, Abigail R. Mechtenberg, Juliet Nakibuule, Rachel Sensenig, Emmanuel Miyingo, John Vianney Makanda, Ali Hakimian, and Matthew J. Eckelman. 2015. "Quantification of Social Equity in Life Cycle Assessment for Increased Sustainable Production of Sanitary Products in Uganda." *Journal of Cleaner Production* 96. Elsevier Ltd: 569–79. doi:10.1016/j.jclepro.2013.10.026.

Nehru, Vikram, Eric Swanson, and Ashutosh Dubey. 1995. "A New Database on Human Capital Stock in Developing and Industrial Countries: Sources, Methodology, and Results." *Journal of Development Economics* 46 (2): 379–401. doi:10.1016/0304-3878(94)00054-G.

Neugebauer, Sabrina, Ya-ju Chang, Markus Maliszewski, Kai Lindow, and Rainer Stark. 2013. "Life Cycle Sustainability Assessment & Sustainable Product Development: A Case Study on Pedal Electric Cycles (Pedelec)." In *Proceedings of11th Global Conference on Sustainable Manufacturing*, 549–54. Berlin.

Neugebauer, Sabrina, Yasmine Emara, Christine Hellerström, and Matthias Finkbeiner. 2016. "Calculation of Fair Wage Potentials throughout Products´ Life Cycle – Introduction of a New Midpoint Impact Category for Social Life Cycle Assessment." *Journal of Cleaner Production* (in press). doi:10.1016/j.jclepro.2016.11.172.

Neugebauer, Sabrina, Silvia Forin, and Matthias Finkbeiner. 2016. "From Life Cycle Costing to Economic Life Cycle Assessment—Introducing an Economic Impact Pathway." *Sustainability* 8 (5): 428. doi:10.3390/su8050428.

Neugebauer, Sabrina, Julia Martinez-Blanco, René Scheumann, and Matthias Finkbeiner. 2015. "Enhancing the Practical Implementation of Life Cycle Sustainability Assessment - Proposal of a Tiered Approach." *Journal of Cleaner Production* 102: 165–176. doi:10.1016/j.jclepro.2015.04.053.

Neugebauer, Sabrina, Marzia Traverso, René Scheumann, Ya-Ju Chang, Kirana Wolf, and Matthias Finkbeiner. 2014. "Impact Pathways to Address Social Well-Being and Social Justice in SLCA—Fair Wage and Level of Education." *Sustainability* 6 (8): 4839–57. doi:10.3390/su6084839.

Niemeijer, David, and Rudolf S. de Groot. 2008. "A Conceptual Framework for Selecting Environmental Indicator Sets." *Ecological Indicators* 8 (1): 14–25. doi:10.1016/j.ecolind.2006.11.012.

Norris, Gregory A. 2006. "Social Impacts in Product Life Cycles Towards Life Cycle Attribute Assessment." *International Journal of Life Cycle Assessment* 1 (1): 97–104.

Nussbaum, Martha C. 2003. "Capabilities as Fundamental Entitlements: Sen and Social Justice." *Feminist Economics*.

NZ Government. 2016. "Ministry for Culture and Heritage." http://www.mch.govt.nz/.

O'Brien, Martin, Alison Doig, and Roland Clift. 1996. "Social and Environmental Life Cycle Assessment (SELCA) - Approach and Methodological Development." *International Journal of Life Cycle Assessment* 1 (4): 231–37.

OECD. 2001. "Measuring Productivity." *OECD Manual*. Paris. doi:10.1787/9789264194519-en.

———. 2008a. "Key Environmental Indicators." doi:10.2110/pec.72.02.0001.

———. 2008b. *OECD Guidelines for Multinational Enterprises*. Annual Report on the OECD Guidelines for Multinational Enterprises. OECD Publishing. doi:10.1787/mne-2002-en.

———. 2012. *Education Today*. Education Today. OECD Publishing. doi:10.1787/edu_today-2013-en.

———. 2013a. “OECD Statistics.” http://stats.oecd.org/index.aspx.

———. 2013b. *Education at a Glance 2013: OECD Indicators*. Education at a Glance. OECD Publishing. doi:10.1787/eag-2013-en.

———. 2016. “Health.” http://www.oecd.org/health/.

Offer, Avner. 2007. “A Vision of Prosperity.” In *SDC Commission Workshop*, 1–11.

Öko-Institut. 1987. “Product Portfolio Analysis - Needs, Products and Consequences (Produktlinienanalyse - Bedürfnisse, Produkte Und Ihre Folgen).” *Kölner Volksblatt Verlag*.

Oxenburgh, Maurice, Penelope S.P. Marlow, and Andrew Oxenburgh. 2004. *Increasing Productivity and Profit through Health and Safety: The Financial Returns from a Safe Working Environment (Google eBook)*. http://books.google.com/books?hl=de&lr=&id=NS4G3qYcvywC&pgis=1.

Oxfam International. 2009. “Oxfam Poverty Footprint - Understanding Business Contribution to Development.” Oxford.

Parent, Julie, Carmela Cucuzzella, and Jean Pierre Revéret. 2010. “Impact Assessment in SLCA: Sorting the sLCIA Methods according to Their Outcomes.” *International Journal of Life Cycle Assessment* 15 (2): 164–71. doi:10.1007/s11367-009-0146-9.

Parris, Thomas M., and Robert W. Kates. 2003. “Characterizing and Measuring Sustainable Development.” *Annual Review of Environment and Resources* 28 (1): 559–86. doi:10.1146/annurev.energy.28.050302.105551.

Payne, AdrianF., Kaj Storbacka, and Pennie Frow. 2008. “Managing the Co-Creation of Value.” *Journal of the Academy of Marketing Science* 36 (1). Springer US: 83–96. doi:10.1007/s11747-007-0070-0.

PayScale. 2015. “PayScale - Salary Comparison, Salary Survey, Search Wages.” *India Industry - Shipping, Transportation, Warehousing*. http://www.payscale.com/.

Pennington, D W, J Potting, G Finnveden, E Lindeijer, O Jolliet, T Rydberg, and G Rebitzer. 2004. “Life Cycle Assessment Part 2: Current Impact Assessment Practice.” *Environment International* 30 (5): 721–39. doi:10.1016/j.envint.2003.12.009.

Pesonen, Hanna-Leena, and Susanna Horn. 2012. “Evaluating the Sustainability SWOT as a Streamlined Tool for Life Cycle Sustainability Assessment.” *The International Journal of Life Cycle Assessment* 18 (9): 1780–92. doi:10.1007/s11367-012-0456-1.

Peukert, Bernd, Stephan Benecke, Janire Clavell, Sabrina Neugebauer, Nils F. Nissen, Eckart Uhlmann, Klaus-Dieter Lang, and Matthias Finkbeiner. 2015. “Addressing Sustainability and Flexibility in Manufacturing Via Smart Modular Machine Tool Frames to Support Sustainable Value Creation.” In *Proceedings of the 22nd CIRP Conference on Life Cycle Engineering*, 29:514–19. Sydney: Elsevier B.V. doi:10.1016/j.procir.2015.02.181.

Picket, Kate, and Richard Wilkinson. 2010. *The Spirit Level: Why Greater Equality Makes Societies Stronger*. New York: Bloomsbury Press.

Pradhan, Menno, and Martin Ravallion. 2011. “Measuring Poverty Using Qualitative

Perceptions of Welfare.” *Policy Research Working Paper*.

Psacharopoulos, George. 1994. “Returns to Investment in Education: A Further Update.” *Education Economics* 12 (2): 111–34. doi:10.1080/0964529042000239140.

Ratcliffe, Alison. 2016. “‘Secret’ Giant Is World’s Biggest Bicycle Manufacturer and Still Growing.” *Supply Management*. http://www.cips.org/supply-management/news/2016/january/secret-giant-is-worlds-biggest-bicycle-manufacturer-and-still-growing/.

Reap, John, Felipe Roman, Scott Duncan, and Bert Bras. 2008. “A Survey of Unresolved Problems in Life Cycle Assessment.” *The International Journal of Life Cycle Assessment* 13 (5): 374–88. doi:10.1007/s11367-008-0009-9.

Rebitzer, G, T Ekvall, R Frischknecht, D Hunkeler, G Norris, T Rydberg, W-P Schmidt, S Suh, B P Weidema, and D W Pennington. 2004. “Life Cycle Assessment Part 1: Framework, Goal and Scope Definition, Inventory Analysis, and Applications.” *Environment International* 30 (5): 701–20. doi:10.1016/j.envint.2003.11.005.

Rebitzer, Gerald, and David Hunkeler. 2003. “Life Cycle Costing in LCM: Ambitions, Opportunities, and Limitations.” *The International Journal of Life Cycle Assessment* 8 (5): 253–56. doi:10.1007/BF02978913.

Ristimäki, Miro, Antti Säynäjoki, Jukka Heinonen, and Seppo Junnila. 2013. “Combining Life Cycle Costing and Life Cycle Assessment for an Analysis of a New Residential District Energy System Design.” *Energy* 63. Elsevier Ltd: 168–79. doi:10.1016/j.energy.2013.10.030.

Rönnberg, Cecilia, and Erik Bonsdorff. 2004. “Baltic Sea Eutrophication : Area-Specific Ecological Consequences.” *Hydrobiologia* 514: 227–41.

Rosenbaum, Ralph K., Till M. Bachmann, Lois Swirsky Gold, Mark a. J. Huijbregts, Olivier Jolliet, Ronnie Juraske, Annette Koehler, et al. 2008. “USEtox—the UNEP-SETAC Toxicity Model: Recommended Characterisation Factors for Human Toxicity and Freshwater Ecotoxicity in Life Cycle Impact Assessment.” *The International Journal of Life Cycle Assessment* 13 (7): 532–46. doi:10.1007/s11367-008-0038-4.

Rüdenauer, Ina, and Rainer Grießhammer. 2014. “Verhaltensökonomisch Optimale Und Praxisgerechte Informationen Im Handel Zu Betriebskosten von Haushaltsgeräten.” *Umweltpsychologie* 18 (34): 42–60.

Schneider, Laura, Markus Berger, Eckhard Schüler-Hainsch, Sven Knöfel, Klaus Ruhland, Jörg Mosig, Vanessa Bach, and Matthias Finkbeiner. 2013. “The Economic Resource Scarcity Potential (ESP) for Evaluating Resource Use Based on Life Cycle Assessment.” *The International Journal of Life Cycle Assessment* 19 (3): 601–10. doi:10.1007/s11367-013-0666-1.

Schulten, Thorsten. 2014. “WSI Minimum Wage Database.” Vol. 49. Düsseldorf. http://www.boeckler.de/wsi-tarifarchiv_44064.htm.

Schwermer, Sylvia. 2007. “Ökonomische Bewertung von Umweltschäden.” Dessau.

Selman, Mindy, and Suzie Greenhalgh. 2009. "Eutrophication: Policies, Actions, and Strategies to Address Nutrient Pollution." *WRI Policy Note*, September. wri.org.

Sen, Amartya. 2013. "The Ends and Means of Sustainability." *Journal of Human Development and Capabilities* 14 (1): 6–20. doi:10.1080/19452829.2012.747492.

Seppälä, Jyri, Maximilian Posch, Matti Johansson, and Jean-Paul Hettelingh. 2006. "Country-Dependent Characterisation Factors for Acidification and Terrestrial Eutrophication Based on Accumulated Exceedance as an Impact Category Indicator." *The International Journal of Life Cycle Assessment* 11 (6): 403–16. doi:10.1065/lca2005.06.215.

SETAC. 1993. "Guidelines for Life-Cycle Assessment: A 'Code of Practice.'" In *SETAC Technical Workshops*. Sesimbra: SETAC Press. https://www.setac.org/?page=PTWorkshops.

Settanni, Ettore, Linda B. Newnes, Nils E. Thenent, Glenn Parry, and Yee Mey Goh. 2014. "A through-Life Costing Methodology for Use in Product–service-Systems." *International Journal of Production Economics* 153. Elsevier: 161–77. doi:10.1016/j.ijpe.2014.02.016.

Seuring, Stefan. 2013. "A Review of Modeling Approaches for Sustainable Supply Chain Management." *Decision Support Systems* 54 (4). Elsevier B.V.: 1513–20. doi:10.1016/j.dss.2012.05.053.

Seuring, Stefan, and Martin Müller. 2008. "From a Literature Review to a Conceptual Framework for Sustainable Supply Chain Management." *Journal of Cleaner Production* 16 (15): 1699–1710. doi:10.1016/j.jclepro.2008.04.020.

Shafiee, Mahmood, Feargal Brennan, and Inés Armada Espinosa. 2015. "Development of a Whole Life Cost Model for Offshore Wind Farms." *Safety and Reliability of Complex Engineered Systems*, no. 2014. The International Journal of Life Cycle Assessment: 1019–27. doi:10.1201/b19094-135.

SHDB. 2013. "Social Hotspot Database." http://socialhotspot.org/home-about-shdb/.

Simmie, James, and Ron Martin. 2010. "The Economic Resilience of Regions: Towards an Evolutionary Approach." *Cambridge Journal of Regions, Economy and Society* 3 (1): 27–43. doi:10.1093/cjres/rsp029.

Singh, Rajesh Kumar, H.R. Murty, S.K. Gupta, and a.K. Dikshit. 2012. "An Overview of Sustainability Assessment Methodologies." *Ecological Indicators* 15 (1). Elsevier Ltd: 281–99. doi:10.1016/j.ecolind.2011.01.007.

Smals, Raphaël G M, and Armand a J Smits. 2012. "Value for Value-The Dynamics of Supplier Value in Collaborative New Product Development." *Industrial Marketing Management* 41 (1). Elsevier Inc.: 156–65. doi:10.1016/j.indmarman.2011.11.022.

Sneddon, Chris, Richard B. Howarth, and Richard B. Norgaard. 2006. "Sustainable Development in a Post-Brundtland World." *Ecological Economics* 57 (2): 253–68. doi:10.1016/j.ecolecon.2005.04.013.

Souza, Danielle M., Ricardo F M Teixeira, and Ole P. Ostermann. 2015. "Assessing Biodiversity Loss due to Land Use with Life Cycle Assessment: Are We There Yet?" *Global Change Biology* 21 (1): 32–47. doi:10.1111/gcb.12709.

Spash, Clive L. 2012. “New Foundations for Ecological Economics.” *Ecological Economics* 77. Elsevier B.V.: 36–47. doi:10.1016/j.ecolecon.2012.02.004.

Ștefănescu-Mihăilă, Ramona. 2015. “Social Investment, Economic Growth and Labor Market Performance: Case Study—Romania.” *Sustainability* 7 (3): 2961–79. doi:10.3390/su7032961.

Swarr, Thomas E., David Hunkeler, Walter Klöpffer, Hanna-Leena Pesonen, Andreas Ciroth, Alan C. Brent, and Robert Pagan. 2011. “Environmental Life-Cycle Costing: A Code of Practice.” *The International Journal of Life Cycle Assessment* 16 (5): 389–91. doi:10.1007/s11367-011-0287-5.

SweatFree. 2013. “Non-Poverty Wages for Countries Around the World.” Accessed May 3. http://www.sweatfree.org/nonpovertywages.

Talberth, John, Clifford Cobb, and Noah Slattery. 2007. “The Genuine Progress Indicator.” Oakland.

Thaler, Richard H. 1999. “Mental Accounting Matters.” *Journal of Behavioral Decision Making* 12: 183–206. doi:10.1002/(SICI)1099-0771(199909)12:3<183::AID-BDM318>3.0.CO;2-F.

The World Bank. 2011. “The Changing Wealth of Nations.” Washington DC. doi:10.1596/978-0-8213-8488-6.

———. 2013. “Education: Overview.” http://web.worldbank.org/WBSITE/EXTERNAL/TOPICS/EXTEDUCATION/0,,contentMDK:20575742~menuPK:282393~pagePK:210058~piPK:210062~theSitePK:282386,00.html.

———. 2014a. “Poverty for All - Ending Extreme Poverty.” Washington DC.

———. 2014b. “Price Level Ratio of PPP Conversion Factor.” http://data.worldbank.org/indicator/PA.NUS.PPPC.RF.

———. 2015. “World Development Indicators: Distribution of Income or Consumption.” http://wdi.worldbank.org/table/2.9#.

———. 2016a. “Better Working Conditions, Better Performance: Findings From Cambodia.” http://www.worldbank.org/en/events/2014/11/14/better-working-conditions-better-performance-findings-from-cambodia.

———. 2016b. “Health.” http://www.worldbank.org/en/topic/health.

———. 2016c. “Industry, Value Added (% of GDP).” http://data.worldbank.org/indicator/NV.IND.TOTL.ZS.

———. 2016d. “Social Protection & Labor.” http://data.worldbank.org/topic/labor-and-social-protection.

Thinkstep. 2015. “No Title.” *GaBi Software*. https://www.thinkstep.com/software/gabi-lca/.

Thomassen, M.A., M.A. Dolman, K.J. van Calker, and I.J.M. de Boer. 2009. “Relating Life Cycle Assessment Indicators to Gross Value Added for Dutch Dairy Farms.” *Ecological Economics* 68 (8–9). Elsevier B.V.: 2278–84. doi:10.1016/j.ecolecon.2009.02.011.

Torspecken, Hans-Dieter. 1999. *Die Deckungsbeitragsrechnung*. Edited by Lutz Irgel. 4thed. Wiesbaden: Betriebswirtschaftlicher Verlag Dr. Th. Gabler GmbH.

Traverso, Marzia, Francesco Asdrubali, Annalisa Francia, and Matthias Finkbeiner. 2012. “Towards Life Cycle Sustainability Assessment: An Implementation to Photovoltaic Modules.” *The International Journal of Life Cycle Assessment* 17 (8): 1068–79. doi:10.1007/s11367-012-0433-8.

Triebskorn, Elena. 2012. “Der Deutsche Außenhandel Im Jahr 2011.” *Wirtschaft Und Statistik*. www.destatis.de.

TurkStat. 2010. “Labour Costs and Earning Statistics.” *Turkish Statistical Institute*. http://www.turkstat.gov.tr/PreTablo.do?alt_id=1008.

Turnbull, Joanna, Diana Lee, Dilys Parkinson, Patrick Phillips, Ben Francis, Suzanne Webb, Victoria Bull, and Michael Ashby, eds. 2010. *Oxford Advanced Learner’s Dictionary*. 8 th. Oxford: Oxford University Press.

Tynkkynen, Nina, Paula Schönach, Mia Pihlajamäki, and Dmitry Nechiporuk. 2014. “The Governance of the Mitigation of the Baltic Sea Eutrophication: Exploring the Challenges of the Formal Governing System.” *Ambio* 43 (1): 105–14. doi:10.1007/s13280-013-0481-8.

UBA. 2012. “German Resource Efficiency Programme (ProgRess) - Programme for the Sustainable Use and Conservation of Natural Resources.” Berlin.

———. 2016. “Health.” https://www.umweltbundesamt.de/en/topics/health.

UN. 2007. “Indicators of Sustainable Development: Guidelines and Methodologies.” New York.

———. 2016a. “Sustainable Development Goals.” http://www.un.org/sustainabledevelopment/sustainable-development-goals/.

———. 2016b. “The Ten Principles - UN Global Compact.” https://www.unglobalcompact.org/what-is-gc/mission/principles.

———. 2016c. “The Universal Declaration of Human Rights.” http://www.un.org/en/universal-declaration-human-rights/.

UNCED. 1992. “A Summary of the Proceedings of the United Nations Conference on Environment and Development.” In *Earth Summit Bulleting*. Rio de Janeiro.

UNDP. 2014. “Human Development Statistical Tables.” *Human Development Reports*. http://hdr.undp.org/en/data.

UNECE. 2012. “Gothenburg Protocol - Air Pollution - Environmental Policy - UNECE.” http://www.unece.org/environmental-policy/conventions/envlrtapwelcome/guidance-documents-and-other-methodological-materials/gothenburg-protocol.html.

———. 2016a. “Civil Liability.” http://www.unece.org/env/civil-liability/welcome.html.

———. 2016b. “Education for Sustainable Development.” http://www.unece.org/env/esd.html.

———. 2016c. “UNECE Homepage.” http://www.unece.org/info/ece-homepage.html.

UNEP. 2007. “The Montreal Protocol on Substances That Deplete the Ozone Layer.” *Handbook*. http://ozone.unep.org/new_site/en/Treaties/treaties_decisions-hb.php?sec_id=5.

———. 2010. “Connecting the Dots.” Nairobi.

———. 2012. “Greening the Economy - Through Life Cycle Thinking.”

———. 2013. *YEAR BOOK 2013: Emerging Issues in Our Global Environment*. Edited by UNEP Division of Early Warning and Assessment. Nairobi: United Nations Environment Programme.

———. 2014. “Climate Change - about Adaption, Mitigation, Finance, REDD+ and Outreach.” http://www.unep.org/climatechange/NewHome/tabid/794594/Default.aspx.

———. 2016. “Climate Change Finance - Rural Energy Enterprise Development (REED).” http://www.unep.org/climatechange/finance/SeedCapital/REED/tabid/29554/Default.aspx.

UNEP/SETAC Life Cycle Initiative. 2011. *Towards a Life Cycle Sustainability Assessment- Making Informed Choices on Products*. Paris: United Nations Environment Programme.

UNEP, and SETAC. 2011. “Global Guidance Principles for Life Cycle Assessment Databases.” Paris.

UNESCO. 2011. “International Standard Classification of Education (ISCED) 2011 - Draft.”

———. 2016a. “Asia-Pacific Awards for Cultural Heritage Conservation.” http://www.unescobkk.org/culture/heritage/awards/.

———. 2016b. “Intangible Heritage - Culture Sector.” http://www.unesco.org/culture/ich/.

United Nations. 1987. *Report of the World Commission on Environment and Development - Our Common Future*. Edited by World Commission on Environment and Development. Oxford, New York, Toronto: Oxford University Press.

———. 1998. “Kyoto Protocol to the United Nations Framework - Convention on Climate Change.” Kyoto.

———. 2012. “A Guide to UN Water.”

United States. 2016. “The United States Social Security Administration.” https://www.ssa.gov/.

University of Amsterdam. 2014. “WageIndicator.org.” http://www.wageindicator.org/main.

Valdivia, Sonia, Cassia M. L. Ugaya, Jutta Hildenbrand, Marzia Traverso, Bernard Mazijn, and Guido Sonnemann. 2012. “A UNEP/SETAC Approach towards a Life Cycle Sustainability Assessment—our Contribution to Rio+20.” *The International Journal of Life Cycle Assessment* 18 (9): 1673–85. doi:10.1007/s11367-012-0529-1.

van der Voet, Ester, Sander De Bruyn, and Arnold Tukker. 2009. “Environmental Impact of the Use of Natural Resources and Products.” Leiden.

Vanclay, Frank. 2002. “Conceptualising Social Impacts.” *Environmental Impact Assessment Review* 22 (3): 183–211. doi:10.1016/S0195-9255(01)00105-6.

Vargo, Stephen L., and Robert F. Lusch. 2008. “Service-Dominant Logic: Continuing the Evolution.” *Journal of the Academy of Marketing Science* 36 (1): 1–10. doi:10.1007/s11747-007-0069-6.

Velthof, G L, J P Lesschen, J Webb, S Pietrzak, Z Miatkowski, M Pinto, J Kros, and O Oenema. 2014. “The Impact of the Nitrates Directive on Nitrogen Emissions from Agriculture in the EU-27 during 2000-2008.” *The Science of the Total Environment* 468–469 (3). Elsevier B.V.: 1225–33. doi:10.1016/j.scitotenv.2013.04.058.

Ver.di. 2016. “Das Macht Richtig Arbeit.” *(That Makes a Lot of Work)*. https://www.verdi.de/themen/arbeit.

VR. 2013. “Branchen Spezial - Fahrradeinzelhandel.”

Watson, Robert T, Thomas Rosswall, Achim Steiner, Klaus Töpfer, Salvatore Arico, and Peter Bridgewater. 2005. “Ecosystems and Human Well-Being: Biodiversity Sysnthesis.” Edited by Robert T Watson, Thomas Rosswall, Achim Steiner, Klaus Töpfer, Salvatore Arico, and Peter Bridgewater. *Ecosystems*. Vol. 5. Millenium Assessments. Washington: World Resources Institute. doi:10.1196/annals.1439.003.

Weidema, Bo. 2006. “The Integration of Economic and Social Aspects in Life Cycle Impact Assessment.” *International Journal of Life Cycle Assessment* 1 (1): 89–96.

WHO. 2016. “World Health Organization Data.” World Health Organization. http://www.who.int/gho/en/.

Wiedmann, Thomas, and Jan Minx. 2008. “A Definition of Carbon Footprint.” In *Ecological Economics Research Trends*, edited by Carolyn C. Pertsova. New York: Nova Science Publishers.

Wikimedia Foundation. 2015. “List of Statutory Minimum Employment Leave by Country.” *Wikipedia - The Free Encyclopedia*. https://en.wikipedia.org/wiki/List_of_statutory_minimum_employment_leave_by_country.

WMO. 2013. “The Global Climate 2001-2010 - a Decade of Climate Extremes.” Geneva.

Wood, Richard, and Edgar G. Hertwich. 2012. “Economic Modelling and Indicators in Life Cycle Sustainability Assessment.” *The International Journal of Life Cycle Assessment* 18 (9): 1710–21. doi:10.1007/s11367-012-0463-2.

Woon, Kok Sin, and Irene M.C. Lo. 2016. “An Integrated Life Cycle Costing and Human Health Impact Analysis of Municipal Solid Waste Management Options in Hong Kong Using Modified Eco-Efficiency Indicator.” *Resources, Conservation and Recycling* 107. Elsevier B.V.: 104–14. doi:10.1016/j.resconrec.2015.11.020.

Worldsalaries. 2008. “Average Salary Income Comparison- Italy.” *Italy Average Salaries & Expenditures*. http://www.worldsalaries.org/italy.shtml.

Wößmann, Ludger. 2000. “Specifying Human Capital: A Review , Some Extensions , and Development Effects.” 1007. Kiel.

Wu, Ruqun, Dan Yang, and Jiquan Chen. 2014. “Social Life Cycle Assessment Revisited.”

Sustainability 6 (7): 4200–4226. doi:10.3390/su6074200.

Zadek, Simon, and Chris Tuppen. 2000. “Adding Values - The Economics of Sustainable Business.” London.

Zaire, Reinhard, Michael Notter, Werner Riedel, and Eckhard Thiel. 1997. “Unexpected Rates of Chromosomal Instabilities and Alterations of Hormone Levels in Namibian Uranium Miners.” *Radiation Research* 147 (5): 579–84.

Zamagni, Alessandra, Hanna-Leena Pesonen, and Thomas Swarr. 2013. “From LCA to Life Cycle Sustainability Assessment: Concept, Practice and Future Directions.” *The International Journal of Life Cycle Assessment* 18 (9): 1637–41. doi:10.1007/s11367-013-0648-3.

Zieschank, Roland, and Hans Diefenbacher. 2012. “The National Welfare Index as a Contribution to the Debate on a More Sustainable Economy.” Berlin.

Glossary

Area of protection (AoP):	Within life cycle based assessments typically aggregated ***endpoints***, which contain certain values of society. Commonly, these AoPs describe something that needs to be protected within a certain area (Haes et al. 2002; Jørgensen et al. 2008). For ***LCA*** three AoPs are typically defined: ecosystem quality (also listed as natural environment), resources (also named natural resources) and human health (Goedkoop et al. 2009; JRC 2010b). Human health may rather be included in ***SLCA***, as described by Hacking and Guthrie, (2008) and UNEP, (2012). For SLCA a commonly used AoP is human well-being (Jørgensen et al. 2008; Weidema 2006). Human well-being is often also referred to as social well-being (Benoit and Mazijn 2009) or human dignity (Dreyer, Hauschild, and Schierbeck 2006).
Discount rate	Discount rates can be relevant for the determination of future costs within LCC, as indicated by e.g. Dong et al., (2014). Choosing the “correct” discount rate is however controversial, as it highly depends on the point of view. High discount rates favor the present and are often chosen in business oriented contexts; low discount rates favor future aspects and thus are often preferred in the context of inter-generational equity (Hoogmartens et al. 2014).
Economic shock	An economic shock is normally described as something, which affects the economy unexpected from the outside causing negative drawbacks for this economy and the related society (Offer 2007; Bleaney 1996). Aspects playing a key role in avoiding such shocks are economic resilience, namely macroeconomic stability, microeconomic market efficiency, good governance and social development (Briguglio et al. 2009).
Impact category:	Within an impact category relevant environmental/social/economic inventory results are assigned to certain impacts. Through characterization factors quantitative impact indicators can be determined representing the different categories (JRC 2010a). The different types of impact categories are also defined in Box 2.5.
Endpoint category:	Endpoint categories typically define damage levels (e.g. damage to human health, damage to ecosystems or economic resilience), which positively or negatively influence the defined AoP(s) (JRC 2010a).
Midpoint category	Midpoint categories typically describe an intermediate state at a defined ***impact pathway*** between the inventory result (in ***LCA*** normally specific emissions – see

	inventory indicator) and the damage level (normally defined as ***endpoint categories***) (Jolliet et al. 2004). Examples for midpoint categories are: fair wage, global climate change, profitability.
Impact pathway: ***(cause-effect-chain)***	Impact pathways connect single aspects (like e.g. emissions) with impact or damage levels (Jolliet et al. 2004). In LCA those are normally defined as cause-effect chains describing environmental mechanisms (Bare et al. 2000). For SLCA and LCC, comparable mechanisms can be considered. For LCA and thus accordingly LCSA inventory, midpoint and endpoint categories can be differentiated describing different stages along a cause-effect-chain. Cause-effect relationships between indicators on the different levels (midpoint and endpoint) and AoPs in this sense describe the (predictable or expected) damage or benefit resulting from different actions (Jørgensen et al. 2010).
Indicator:	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 (Turnbull et al. 2010; Parris and Kates 2003). The 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). 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. Further information can also be taken from Box 2.4.
Endpoint indicator:	Endpoint impact indicators then can be seen as measurement endpoints to determine the level of damage (JRC 2010a).
Inventory indicator:	Inventory indicators can be characterized as simple variables (Bare et al. 2000). They express single issues, e.g. pure emission factors instead of emission equivalents, salaries/wages without relating them to fair wages or material costs without considering the resulting value added.
Midpoint indicator:	Midpoint indicators can be seen as parameters in the environmental/social/economic mechanism network (Bare et al. 2000). Examples for midpoint indicators are: global warming potential, fair wage potential, product-specific value added.
Life cycle sustainability assessment (LCSA)	Assessment method covering all three dimensions of sustainability (Klöpffer 2008), by including ***life cycle assessment*** (environment), ***social life cycle assessment*** (society) and ***life cycle costing*** (economy). Resulted from the PROSA method (Öko-

	Institut 1987; Grießhammer et al. 2007) and the SELCA approach (O'Brien, Doig, and Clift 1996). LCSA is in more detail described in section 2.1 of this thesis.
Life cycle assessment (LCA)	LCA is a standardized assessment method for assessing the potential environmental impacts (latest version: ISO 14044 2006). Currently, LCA is widely used to investigate the potential environmental impacts of products and processes (Klöpffer and Grahl 2014). LCA is in more detail described in section 2.1.1 of this thesis.
Life cycle costing (LCC)	LCC was originally developed to rank different investment options, but did for a long time not consider operating costs occurring during the product´s life time (Gluch and Baumann 2004). Currently, it is an assessment methods reflecting costs associated with a product´s life cycle. Hunkeler et al. (2008) differentiate between three types of LCC – conventional LCC, environmental LCC and societal LCC. LCC is in more detail described in section 2.1.3 of this thesis.
Social life cycle assessment (SLCA)	SLCA is an assessment method that strives to assess the potential social impacts of products in relation to the different stakeholder groups affected by the products´ manufacturing (Benoit and Mazijn 2009). SLCA is in more detail described in section 2.1.2 of this thesis.
Mental accounting	Mental accounting is a set of subjective and cognitive form of individuals´ bookkeeping used to organize, evaluate, and keep track of financial activities and to control consumption. It also contains a certain ambiguity and flexibility, as consumers contain different mental accounts. It furthermore significantly influences the consumers´ choices and therefore contains a certain relevance in connection with economic assessments. (Thaler 1999; Cheema and Soman 2006)
Sustainable development	Sustainable development according to the Brundtland Commission (United Nations 1987) is defined as a development *"that meets the needs of the present without compromising the ability of future generations to meet their own needs*". It inherently contains two key aspects, first the concept of 'needs', in particular the essential needs of the world's poor, and second the fact of a limited world, which depends on the environment's ability to meet present and future needs.
Utility analysis (PROSA)	The in PROSA (Grießhammer et al. 2007) defined utility (or benefit) analysis complements the included sustainability assessment by adding the consumer´s perspective. The analysis contains different elements, e.g. consumer´s living situation, type of purchase, or type of product. A distinction is made in needs and wants,

	describing the objective and subjective aspects normally influencing the consumer. In this context, also different utility concepts are distinguished, such as functional utility or symbolic utility, which are described below.
Functional utility	Functional utility according to PROSA (Grießhammer et al. 2007) describes the technical and practical purpose of a product, process or service. This purpose is normally described by elements, such as robustness, life time, quality, safety etc.
Symbolic utility	Symbolic utility according to PROSA (Grießhammer et al. 2007) describes a subjective and often not quantifiable satisfaction, which results from the usage of the product or service. This relates to aspects, like status, competence, identity, or compensation. Those aspects are normally taken up by marketing instruments, which try to artificially increase the product value.
Societal utility	Societal utility according to PROSA (Grießhammer et al. 2007) describes the macroeconomic perspective and is therefore to be differentiated from the ***functional and symbolic utility***, which describe individual microeconomic utility aspects. From the different utility concepts trade-offs can result, as individual utility or value gains may result in negative societal consequences due to societal or environmental costs.
Value added	Value added in economic considerations is typically determined through revenues, costs and benefits (Thomassen et al. 2009; Figge and Hahn 2004; Azapagic and Perdan 2000). The value added can be calculated per unit, process, company or even country. The value added is in more detail described in section 4.2.2 of this thesis. In addition to the classical economic value added, different concepts have been defined, such as the ***green net value added and the sustainable value added***.
Green value added	The green net value added is based on the principle that the value of a product must be greater than the environmental and human health damages it produces (Ingwersen et al. 2014). Therefore, it is defined as the net value added minus externality costs. Therefore, the value added is corrected by environmental and social consequences.
Sustainable value added	The sustainable value added is inspired by the strong sustainability concept and measures whether a company creates extra value while ensuring that every environmental and social impact are constant (Figge and Hahn 2004). It therefore extends the classical value added consideration by social and environmental aspects.

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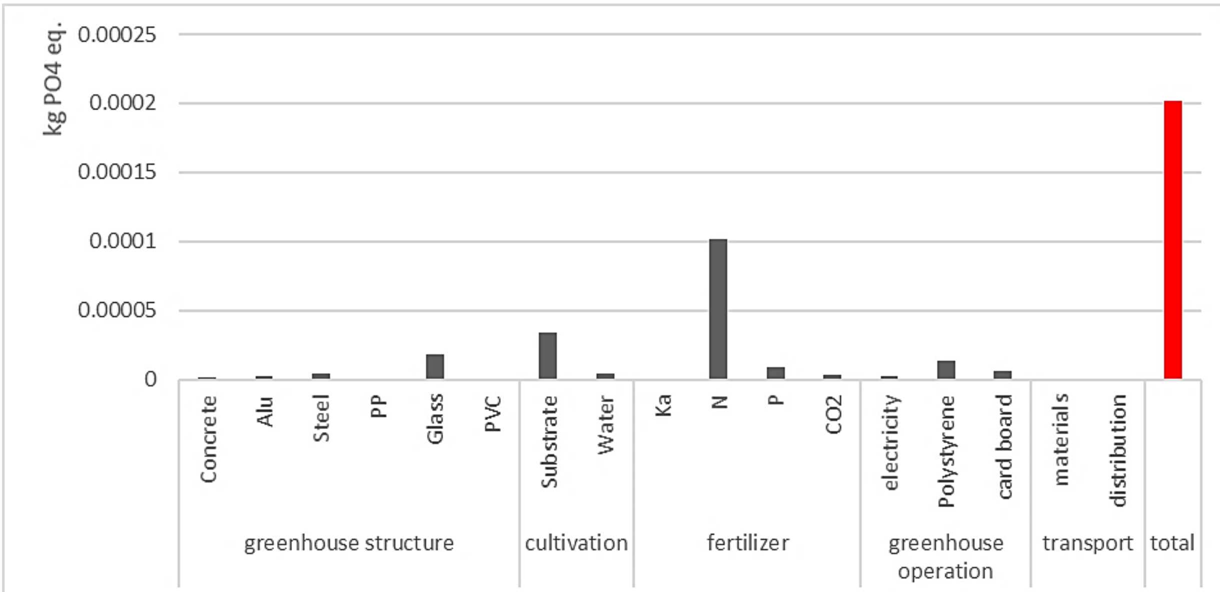
Annex

Detailed case study calculations

Calculation – case study on tomatoes produced in Germany



*Note that the results for the most parts correlate with the calculated GWP results presented in Figure 18. Differences only occur for the substrate and the phosphorus fertilizer.

Figure 32: Eutrophication potential for the German tomato production; the results display the processes of Table 17 considering the materials and energy used to fulfill the functional unit

Table 26: Considered average wage levels related to processes and countries representing the groups of workers along the life cycle of the German tomato production

Category	Actual wage level									
Process	Tomato Production						Green House Structure	Packaging	Green House Operation	Transport
Sub-process	Tomato cultivation	Tomato Seeds	Substrate Production	Pesticides/ Fertilizer	CO2 enrichment	Management/ Administration	Manufacturing	Material production	Energy	all processes
Economy/Unit	€/month	€/month	€/month	€/month	€/month	€/month	€/month	€/month	€/month	€/month
China							293.55[a]	293.55[a]		397.95[a]
Germany	2,500.00[b]				3,381.73[a]	2,850.00[b]	3,381.73[a]	3,381.73[a]	4114,93[a]	2,726.53[a]
India			227.17[c]							219.42[d]
Italy								1,724.00[e]		1,400.00[e]
Netherlands		2,197.00[a]		2,689.00[a]			2,689.00[a]	2,689.00[a]		2,575.00[a]
Turkey								471.12[f]		524.52[f]

[a] The collected wage data have been taken from ILO, (2010).
[b] The relevant data have been provided by a German tomato producer. The values reflect the wage level of the workers working in the core tomato production and in the related management and administration at a production location in eastern Germany.
[c] The wage data have been taken from the WageIndicator Foundation (University of Amsterdam 2014).
[d] The wage data have been taken from PayScale, (2015).
[e] The wage data have been taken from Worldsalaries, (2008).
[f] The wage data have been taken from TurkStat, (2010).

Table 27: Considered contracted working time, time actually worked and vacation days per process and country

Category	Working time														
Process	Tomato production			Green House Structure			Packaging			Energy			Transport		
Sub-category[a]	contr. h/week	real h /week	v-days /week	contr. h/week	real h /week	v-days /week	contr. h/week	real h /week	v-days /week	contr. h/week	real h /week	v-days /week	contr. h/week	real h /week	v-days /week
Econ-omy/Unit	h/week	h/week	d/week	h/week	h/week	d/week	h/week	h/week	d/week	h/week	h/week	d/week	h/week	h/week	d/week
China				44.00[b]	47,90[c]	0.40[d]	44.00[b]	47.90[c]	0.40[d]				44.00[b]	48.10[c]	0.40[d]
Germany	40.00[e]	41.66[f]	0.48[e]	40.00[b]	38.40[c]	0.73[d]	40.00[b]	38.40[c]	0.73[d]	40.00[b]	38.20[c]	0.73[d]	40.00[b]	40.30[c]	0.73[d]
India	48.00[b]	47.00[f]	0.23[d]										48.00[b]	45.00[c]	0.23[d]
Italy							40.00[b]	35.90[c]	0.62[d]				40.00[b]	36.90[c]	0.62[d]
Nether-lands	40.00[b]	39.00[f]	0.58[d]	40.00[c]	38.50[c]	0.58[d]	40.00[b]	38.50[c]	0.58[d]				40.00[b]	39.00[c]	0.58[d]
Turkey							42.50[b]	47.07[g]	0.23[d]				42.50[b]	45.62[g]	0.23[d]

[a] Abbreviations stand for: contr. h/week – contracted weekly working hours; real h/week – (real) average hours actually worked per week; v-days/week – vacation days per week based on yearly averages including also public holidays.

[b] The average contracted working hours have been calculated based on the average of different sources. Relevant sources are Anker, (2006) and ILO, (2011).

[c] The real hours actually worked per week have been taken from ILO, (2010).

[d] The average vacation days have been calculated based on statutory vacation days per year, including public holidays. Relevant sources are ILO, (2011) and (Ghosheh 2013; Cabrita 2013; Wikimedia Foundation 2015).

[e] The given contracted working hours and vacation days have been provided by the German tomato producer.

[f] The real hours actually worked per week have been calculated based on an average from different sources. Relevant sources are (Anker 2006; Cabrita 2013; ILO 2010c; ILO 2011a; OECD 2013a).

[g] The real hours actually worked per week have been taken from TurkStat, (2010).

Table 28: Considered income related Gini Index values and considered minimum living wages per country, and calculated fair wage potentials per process and country

Category	**Gini Index[a]**	**MLW[b] €/month**	***Fair wage potentials[c]***									
Sub-process	all	all	Tomato cultivation	Tomato Seeds	Substrate Production	Pesticides/ Fertilizer	Management/ Administration	Green House Structure	Packaging	CO2 enrichment	Energy	Transport
China	0.42	311.14						0.66	0.66			0.89
Germany	0.28	1,506.51	1.59				1.82	1.84	1.84	1.84	2.25	1.41
India	0.34	200.36			0.98							0.94
Italy	0.36	1,195.37							1.23			0.97
Netherlands	0.31	860.00		1.19		1.48		1.48	1.48			1.40
Turkey	0.40	633.40							0.54			0.62

[a] For all countries the income related Gini indices were taken from UNDP, (2014).

[b] The Minimum Living Wages (MLWs) have been determined based on Wagenindicator Foundation (University of Amsterdam 2014) and/or Sweatfree Ordinance (City and County of San Francisco 2014).

[c] All calculated *fair wage equivalents* have been calculated under consideration of (real) average wages, MLWs, contracted and (real) average working time (incl. vacation days and sick-leave). Inequality factors by means of the Gini Index values have been included for all secondary data used, as they represent the average country or sector situation. The primary data used have not been corrected through the IEF, as they lie above the average sector and country wage paid.

Calculation – case study on Pedelec frames

Table 29: Considered data for the FWP calculation of the Triplec frames including MLWs and Gini Index values per country, as well as working time and average sector wages.

Category	MLW[a]	Gini Index[b]	Working time				vacation days[d]	Considered average sector wage[f]		
Additional information			Contracted[c]	real working time mining[d]	real working time manufacturing[d]	real working time transport[d]	days/week	Mining	Manufacturing	Transport
Country/unit	€/month	%	Øh/week				Ød/week	€/month		
China	311.14	0.421	44	45.2		48.1	0.40	417.48		397.95
Germany	1506.51	0.283	40		38.4	40.3	0.73		3381.73	2726.53
Russian Federation	347.98	0.401	40	34.5		35	-	598.7		374.32
Brazil	423.33	0.547	44	44.9		45.9	0.49	720.87		768[g]
Taiwan	607.53	0.338	43		42.62	41.33	0.13		1271.17	1468.6

[a] The Minimum Living Wages (MLWs) have been determined based on Wagenindicator Foundation (University of Amsterdam 2014) and/or Sweatfree Ordinance (City and County of San Francisco 2014).
[b] For all countries the income related Gini indices were taken from UNDP, (2014).
[c] The average contracted working hours have been calculated based on the average of different sources. Relevant sources are Anker, (2006) and ILO, (2011).
[d] The real hours actually worked per week have been taken from ILO, (2010).
[e] The average vacation days have been calculated based on statutory vacation days per year, including public holidays. Relevant sources are ILO, (2011) and (Ghosheh 2013; Cabrita 2013; Wikimedia Foundation 2015).
[f] The collected wage data have been taken from ILO, (2010).
[g] The wage for transportation workers in Brazil has been taken from Murphy 2012.

Table 30: Calculated fair wage potentials of the Triplec frames per process and country

Triplec frame	Stainless steel & steel frame			Aluminum frame			Titanium frame		
Process (Country)	**Iron-ore Mining**	**Production**	**Transport**	**Bauxite Mining**	**Production**	**Transport**	**Titanium Mining**	**Production**	**Transport**
China				0.99		0.88			
Germany		1.84	1.41					1.84	1.41
Russian Federation							1.67		1.03
Brazil	1.05		1.10						
Taiwan					1.86	2.22			

*All calculated *fair wage potentials* have been calculated under consideration of (real) average wages, MLWs, contracted and (real) average working time (incl. vacation days and sick-leave) and Gini Index values, which function as inequality measures.

Calculation – case study on flexible machine tool frames

Table 31: Considered data for the FWP calculation of the flexible machine tool frames including MLWs and Gini Index values per country, as well as working time and average sector wages.

Category	MLW[a]	Gini Index[b]	Working time			vacation days[d]	Considered average sector wage[f]	
Additional information			Contracted[c]	real working time mining[d]	real working time manufacturing[d]	days/week	Mining	Manufacturing
Country/unit	EUR/month	%	Øh/week			Ød/week	€/month	
Brazil	423.33	0.547	44	44.9		0.49	720.87	
China	311.14	0.421	44		47.9	0.40		293.55
Germany	1506.51	0.283	40		38.4	0.73		3381.73
Japan	1266.80	0.379	40		42.4	0.17		2191.7
Malta	928.67	0.279	44		39.4	0.73		1109.33
Philippines	180.97	0.430	48		47.4	0.31		316.72
South Korea	1039.8	0.302	40		43.7	0.29		2289.72
Taiwan	607.53	0.338	43		42.62	0.13		1271.17
Thailand	382.9	0.394	48		61.43	0.35		212.74
USA	1144.81	0.408	40		40.8	0.12		2740.85

[a] The Minimum Living Wages (MLWs) have been determined based on Wagenindicator Foundation (University of Amsterdam 2014) and/or Sweatfree Ordinance (City and County of San Francisco 2014).
[b] For all countries the income related Gini indices were taken from UNDP, (2014).
[c] The average contracted working hours have been calculated based on the average of different sources. Relevant sources are Anker, (2006) and ILO, (2011).
[d] The real hours actually worked per week have been taken from ILO, (2010).
[e] The average vacation days have been calculated based on statutory vacation days per year, including public holidays. Relevant sources are ILO, (2011) and (Ghosheh 2013; Cabrita 2013; Wikimedia Foundation 2015).
[f] The collected wage data have been taken from ILO, (2010).

Table 32: Calculated fair wage potentials of the flexible machine tool frames per part and country

LEGO frame	MMTF			WSNs							
Process (Country)	**Iron-ore Mining**	**Steel plate production**	**Hexagon prod.**	**µC + RF**	**Sensors**	**Power converter**	**Clock**	**Oscillators**	**PCB**	**LED**	**Resistors, inductor, etc.**
Brazil	1.05										
China					0.66					0.66	
Germany		1.84	1.84						1.84		
Japan								1.35			1.35
Malta					1.05						
Philippines						1.34					
South Korea				1.73							
Taiwan							1.86				
Thailand				0.34							
USA						1.91					

*All calculated *fair wage potentials* have been calculated under consideration of (real) average wages, MLWs, contracted and (real) average working time (incl. vacation days and sick-leave) and Gini Index values, which function as inequality measures.

List of published articles in relation to this dissertation

Article I Neugebauer, Sabrina, Marzia Traverso, René Scheumann, Ya-Ju Chang, Kirana Wolf, and Matthias Finkbeiner. 2014. **Impact Pathways to Address Social Well-Being and Social Justice in SLCA—Fair Wage and Level of Education**. *Sustainability* 6: 4839–57. doi:10.3390/su6084839 **Reprinted with permission of MDPI AG** – http://www.mdpi.com/2071-1050/6/8/4839

Article II Neugebauer, Sabrina, Julia Martinez-Blanco, René Scheumann, and Matthias Finkbeiner. 2015. **Enhancing the Practical Implementation of Life Cycle Sustainability Assessment - Proposal of a Tiered Approach**. *Journal of Cleaner Production* 102: 165–176. http://dx.doi.org/10.1016/j.jclepro.2015.04.053 **Reprinted with permission of Elsevier B.V.** – https://www.elsevier.com/about/company-information/policies/copyright

Article III Neugebauer, Sabrina, Silvia Forin, and Matthias Finkbeiner. 2016. **From Life Cycle Costing to Economic Life Cycle Assessment—Introducing an Economic Impact Pathway**. *Sustainability* 8 (5): 428. doi:10.3390/su8050428 **Reprinted with permission of MDPI AG** – http://www.mdpi.com/2071-1050/8/5/428

Article IV Neugebauer, Sabrina, Yasmine Emara, Christine Hellerström, and Matthias Finkbeiner. 2016. **Calculation of Fair Wage Potentials throughout Products´ Life Cycle – Introduction of a New Midpoint Impact Category for Social Life Cycle Assessment**. *Journal of Cleaner Production (in press)*. http://dx.doi.org/10.1016/j.jclepro.2016.11.172 **Reprinted with permission of Elsevier B.V.** – https://www.elsevier.com/about/company-information/policies/copyright