23 October 2020

A review of Absolute Life Cycle Assessment methods and applications

And their potential for benchmarking absolute product-level contributions to the UN Sustainable Development Goals

MASTER THESIS REPORT

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Word count body: 21819

Acknowledgements

After months of researching, analyzing and writing time my master thesis is finished. During this process I have learned a lot, developing both my scientific and personal skills. I have learned not only to set up a valid and reliable research project, but also to better evaluate, improve and value my work. I would like to thank the people who have helped and supported me during my research.

First, I want to thank my supervisor Jeroen Guinée from the University of Leiden for guiding me during the different phases of the research and making time for reading and providing constructive feedback on the many different drafts. Although it took some time to find the right topic and research format, I eventually opted for a systematic literature review and through his guidance I was able to successfully conduct this undertaking. Through his extensive experience and deep understanding of the subject he was able to give substantive feedback. Besides, he provided clarity and insight in times I did not have a clear overview of certain aspects. In addition, I want to express my gratitude for Lydia Stougie, being the second reader from the TU Delft, for providing me with a lot of useful feedback.

Second, I am thankful that I could combine my master thesis with a graduation internship at PRé Sustainability in Amersfoort. This company appeals to me because of its position as a frontrunner in the sustainability field, but also because of the values and vision of this company. I want to thank PRé Sustainability for providing me this opportunity to gain both new scientific skills and giving me an insight into what working in the consultancy field is like. I am grateful to all the kind employees for the positive and welcoming atmosphere in the office. I especially would like to thank my supervisor Rosan Harmens, for her highly professional support and feedback.

Finally, I would like to thank my girlfriend, family and friends for their support during the past period. Sharing my wins and setbacks helped me to organize my thoughts and gave me confidence that the project was going in the right direction.

Executive summary

As of 2016, governments globally adopted the task to achieve social, economic and environmental sustainability by committing to the targets from the UN Sustainable Development Goals (SDGs). The SDGs incorporate a set of 17 goals and 169 targets accompanied with more than 200 indicators that can guide towards achieving sustainable development by 2030. Sustainable development and human wellbeing fundamentally rest on the capacity of the biosphere to sustain us. In other words, the economy or society related SDGs can only be reached if the biosphere related SDGs, in which they are embedded, are respected. To ensure the achievement of all SDGs, the environmental impact as a result of human activity needs to be reduced to safe levels. Doing so requires quantification of both impacts and safe operating spaces in the environmental domain. However, from the SDG framework it does not become clear what safe operating spaces are because for many of the environmental issues addressed, quantitative targets based on ecological boundaries are lacking.

Life-Cycle Assessment (LCA) is a method that enables holistic analysis of the environmental impact of product-systems by analyzing the impacts over the complete life cycle. Yet, as a comparative method it can only identify the most sustainable product system relative other alternative product-systems. In contrast, there have been developments to develop Absolute Life Cycle Assessment (ALCA), in which the environmental impact of a product-system is compared against a benchmark based on the earth's ecological carrying capacity, in order to define if the system is absolutely sustainable. Such a benchmark is obtained by allocating a share of the environmental carrying capacity to the product system, using a specific allocation principle. The most recognized expression of environmental carrying capacity has been provided by the planetary boundary (PB) framework, offering a set of quantitative biophysical limits for nine critical earth system processes (ESP). The functioning of these ESPs is critical to keep the earth in its stable Holocene state, which is required for anthropogenic prosperity.

Using the LCA method to quantify impacts, and the PB framework to provide quantitative ecological boundaries, ALCA could be useful to identify absolutely sustainable product-systems and support contributions from product-systems towards environmental SDG targets. Yet, an overview showing the availability of different ALCA methods and their applicability at the product level is lacking. Therefore, this master thesis provides a systematic literature review of ALCA methods and applications, that use the planetary boundary (PB) framework as an implementation of carrying capacity. The main research question is formulated as: To what extent is absolute life cycle assessment possible and does it enable a comparison of environmental impact against product-level benchmarks based on the PB-framework, to support the identification of absolute sustainable products contributing to the UN SDGs?

With a database search on Web of Science (WoS) and a snowballing approach, possibly relevant publications were identified. Afterwards, 14 key publications were selected that entail either an ALCA method or application. The review was conducted with criteria primarily based on an absolute environmental sustainability assessment (AESA) framework identified from literature. The criteria cover aspects related to LCA, the PB framework and allocation approaches needed to obtain benchmarks at the product-level.

The results showed that there are 5 dominant methods, and 9 applications of these methods. Only one of these methods includes a direct comparison of impact against a benchmark specifically allocated to the assessed product-system. Therefore, we concluded that only one method can truly be considered as an ALCA method that is also potentially usable in the context of SDGs. However, even claims of absolute sustainability that are made using this method are not fully conceptually

consistent because a comparison is made between an annual benchmark (derived from the PB framework) and LCA impacts that are in reality exerted over many years. Other methods were considered usable for different purposes. Some methods only facilitate a comparison of impact against a per-capita benchmark, representing the occupation of an individual's environmental budget by the product-system. These methods are rather usable for identifying sustainable consumption patterns. Some methods only enable the determination of impact reduction targets against which future impact reductions might be compared. Others do not involve any form of absolute sustainability comparison and are rather usable in conventional comparative LCA.

We provided a terminology proposition for PB related concepts because there seemed to be inconsistencies across publications regarding the use of PB-related concepts and their terminology. Also, there were inconsistencies in the terminology for different allocation principles. We stated that all allocation principles could be classified in three main categories. Yet, further research is recommended to find common ground on the choice for specific allocation principles to obtain benchmarks for product-systems. Also, we recommend further research to focus on getting insights in linkages between LCA impact categories, PB's and SDGs and combining these insights with the knowledge on ALCA methods that has been provided in this thesis. Such a combination would be the next step to find the potential of ALCA methods for supporting contributions from product-systems towards environmental SDG(-target)s.

Abbreviations

ALCA	Absolute Life Cycle Assessment
AESA	Absolute Environmental Sustainability Assessment
AESR	Absolute Environmental Sustainability Reference
AoP	Area of protection
CC	Carrying Capacity
CF	Characterization factor
DPSIR	Driver Pressure State Impact Response
ESP	Earth System Process
GDP	Gross Domestic Product
GHG	Green House Gas
GVA	Gross Value Added
ILCD	International Reference Life Cycle Data System
LCA	Life Cycle Assessment
LCIA	Life Cycle Impact Assessment
LCSA	Life Cycle Sustainability Assessment
PEF	Product Environmental Footprint
PEFCR	Product Environmental Footprint Category Rules
PSIA	Product Social Impact Assessment
SDG	Sustainable Development Goal
SLCA	Social Life cycle Assessment
SOS	Safe operating space
SoSOS	Share of Safe Operating Space
UN	United Nations

Table of contents

Foreword

This thesis research project has been written for the master program Industrial Ecology from Leiden University and TU Delft. Industrial Ecology is an interdisciplinary scientific field that takes a system approach to sustainability problems, integrating a technical, environmental and social perspective. Industrial Ecology is about understanding a society's metabolism – material and energy flows – from a socio-technical systems perspective (Lifset & Graedel, 2015). This enables identifying, designing and critically evaluating sustainability solutions and their implementation. This thesis positions itself in – and adds to the field of Industrial Ecology by exploring the connection between one of its key methods, Life Cycle Assessment (LCA), and the societally relevant UN Sustainable Development Goals (SDGs). The findings can be useful for other scientists in the field, business actors, policy makers, and other actors involved in sustainability challenges in general.

The author has written this thesis, as a graduation intern, at PRé Sustainability, a consultancy and software development company having sustainability as its core business. The results of this thesis contribute to a project focused on linking LCA and the SDGs, commissioned by the UN Life Cycle Initiative (UNEP, 2018), and taken up by PRé Sustainability. UNEP (2018) has launched this LCA-SDG project to develop a clear linkage between the top-down process that led to the creation of the SDG's and bottom-up knowledge, data and methods in the Life Cycle Sustainability Assessment area. The project was initiated because the Business and Sustainable Development Commission (BSDC, 2017) reports there is a need to re-interpret the SDGs and to link them to business, especially to decisions around product strategy and development. The project is taken up by PRé Sustainability and 2.0 LCA Consultants, each focusing on a different approach. PRé Sustainability screens if "standard" Environmental and Social LCA results can be the basis for claiming a contribution to a specific SDG, in a qualitative way. 2.0 LCA consultants investigates where the SDG indicators fit in a cause-effect chain between pressure indicators and the endpoint "human wellbeing" in a fully quantified way.

The approach developed by PRé Sustainability is described in more detail in (Weidema et al., 2020). In short, the main steps will be explained hereafter. The approach starts with finding qualitative linkages between targets or indicators from the SDGs and impact midpoints from ReCiPe2016 (Huijbregts et al., 2016) or social impact topics from Product Social Impact Assessment (PSIA) methodology (Goedkoop et al., 2018). After the identification of such linkages, the results from environmental and social LCA can be used to obtain semi-quantitative performance scores, supporting or invalidating SDG contributions. This distinction between whether a product has a beneficial or deteriorating effect on SDG achievement is determined by comparing the LCA results against a certain benchmark. Opposed to PSIA, where benchmarks are often based on compliance with local laws or international standards, environmental benchmarking is much less straightforward. Therefore, this thesis presents the results of scientific research on key aspects of benchmarking environmental LCA results.

1. Introduction

1.1 UN sustainable development goals and the environment

As of 2016, governments globally formally adopted the task to achieve social, economic and environmental sustainability by committing to the targets from the UN Sustainable Development Goals (SDGs) (United Nations, 2019). Thereby, the SDGs are claimed to be a democratically legitimated and globally consensual framework (Kühnen et al., 2019). The SDGs incorporate a set of 17 goals and 169 targets accompanied with more than 200 indicators that can guide towards achieving sustainable development by 2030.

Some general trends can be observed that are not in line with ambitions set by the UN. Often, economic growth and social development come at the expense of ecosystem destruction, severely compromising the ability of future generations to obtain benefits from these ecosystems (Millenium Ecosystem Assessment, 2005; Raudsepp-Hearne et al., 2010). Where significant improvements have been made regarding poverty eradication, health and education improvement, many environmental problems such as climate change and biodiversity loss and nutrient loss have become worse (Ritchie et al., 2018; United Nations, 2019). Yet, all SDGs benefit to some degree from ecosystem protection, restoration and sustainable use of resources (ICSU ISSC, 2015). Long term social and economic progress can be achieved within a healthy biosphere (Folke et al., 2016), making environmental sustainability a constraint for all anthropogenic activities. Therefore, to ensure the achievement of the SDGs, the environmental impact as a result of human activity needs to be reduced to safe levels. Doing so requires quantification of both impacts and safe operating spaces in the environmental domain.

Folke et al. (2016) visualized a multi-level framework (Figure 1) in which an economy layer is positioned within a society layer, in turn positioned within a biosphere layer. This fits within the conventional conception that there are three (social, economic and environmental) pillars of sustainability, as originally outlined by Elkington (1996) in the triple bottom line sustainability theory. Folke et al. (2016) urge for a social-ecological resilience approach in which it is recognized that human wellbeing fundamentally rests on the capacity of the biosphere to sustain us. In other words, the economy or society related SDGs can only be reached if the biosphere related SDGs, in which they are embedded, are respected.

Figure 1: Sustainable development goals classified in biosphere, society and economy (copied from Folke et al., 2016)

1.2 Quantifying product environmental impact

From the SDG framework, it does not become clear what safe environmental levels are because for many of the environmental issues addressed, quantitative targets based on ecological boundaries are lacking (Laurent et al., 2019; Stafford-Smith, 2014; Verboven & Vanherck, 2016). An example is target 2.4: ''By 2030, ensure sustainable food production systems…''. Terms as 'sustainable' leave room for multiple interpretations. Also, the target is not related to the important constraints on nitrogen phosphorus or water cycles (Stafford-Smith, 2014). Another example is target 6.4: ''By 2030, substantially increase water-use efficiency across all sectors…''. The absence of quantitative targets is understandable due to large uncertainties in the determination of such safe environmental levels (Steffen et al., 2015) and the lack of consensus on the extent to which environmental problems should be combatted, and who has the responsibility to do so. Nonetheless, without quantitative targets, the problem arises that it is impossible to claim that sustainability efforts are genuinely and sufficiently contributing to preventing or even reversing environmental problems (Stafford-Smith, 2014).

Also, McArthur & Rasmussen (2019) showed that many SDGs are not quantitative or measurable at country level, making it problematic to assess which countries are contributing to SDG achievement. Yet, having quantitative targets is important because only those can truly be achieved and allow the creation of pathways towards achievement based on the gap from the current situation, whereas qualitative targets containing words as ‘substantial’ are an ever-going process which is also open to multiple interpretations and might result in less commitment. Therefore, it is of crucial importance to quantitatively define ambiguous terms such as ‘sustainable’, ‘efficient’ and ‘substantial’ in order to overcome vagueness (Stafford-Smith, 2014) and make the goals measurable, comparable and achievable (Lu et al., 2015). An attempt to do so can be to connect the SDG framework to other frameworks from environmental science in which safe environmental impact levels are actually quantified, and environmental impacts can be measured in a consistent way.

Thus, the SDGs represent consensual targets on a global scale when pursuing positive contributions to sustainable development (Schaubroeck & Rugani, 2017). The SDGs have a top-down nature and the accompanying targets and indicators mainly have a national and policy orientation. Yet, the usability of the SDGs for nations and policymakers is questionable because there is a difficulty in supporting claims of contributions to SDGs, due to the absence of quantitative and measurable targets. This is already prevalent at large geographical scales, but becomes even more challenging at smaller scales since the SDGs are not per se designed to evaluate contributions at for example organizational or product level (Kühnen & Hahn, 2017). For capturing product level contributions, convincing approaches and indicator systems need to be developed (Laurent et al., 2019; Verboven & Vanherck, 2016). The production and consumption of goods and services are key contributors to environmental impacts. Bradshaw et al. (2010) found that the correlation between wealth and proportional (relative to resource availability per country) environmental impact[1] is found to be stronger than that between population growth and proportional environmental impact. This emphasizes that for SDG achievement, identification and adoption of sustainable products and sustainable consumption patterns is at least equally important as limiting population growth. Therefore, in order to draw conclusions about the relationship between products and SDGs regarding environmental performance, it is necessary to quantitatively analyze and compare the environmental performance of product-systems.

Considering the wide range of environmental problems that the SDGs cover, such analyses require a method that also considers multiple areas of environmental impact. Moreover, the analyses need to include the full life cycle of products (complete upstream and downstream chains), to ensure that stages such as production and disposal are also part of the environmental performance results. The analyses would have to allow exposing trade-offs between different environmental impacts and between the different pillars of sustainability, to avoid problem shifting.

Life-Cycle Assessment (LCA) is a method that enables holistic analysis of the environmental impact of product-systems by analyzing the impacts over the complete life cycle; including material extraction, production, use and disposal processes (Guinée et al., 2002; ISO, 2006; Hellweg & Canals, 2014). The method is particularly useful for comparing product-system alternatives, identifying hotspots of impact within life cycles, and providing trade-off insights in order to avoid problem-shifting. For example, shifting from one phase of the life-cycle to another, from one region to another, or from one environmental problem to another (Finnveden et al., 2009). The ability of the method to give insights into trade-offs is particularly important in the context of SDGs because achieving one SDG at the expense of another – or at the expense of shifting impacts across regions - is undesirable. Moreover, LCA is considered as a well-established method that has been widely used in industry, has been standardized by the International Standards Organization (ISO, 2006a&b) and has gained a prominent role within renowned institutions like The World Resource Institute and the European Commission (European Commission, 2020; Gaasbeek & Meijer, 2013). To improve the harmonization and

[1] Bradshaw et al. (2010) defined environmental impact as natural forest lost, habitat conversion, marine captures, fertilizer use, water pollution, carbon emissions and proportion of threatened species.

comparability of numerous LCAs annually conducted, the European Commission has initiated multi-year Product Environmental Footprint (PEF) projects in which category rules (PEF-CR) are composed that apply for LCAs concerning specific product groups (European Commission, 2020). With its trade-off strength and industry-wide applicability, LCA initially seems a suitable method to use for assessing the extent to which products contribute to environmentally related SDGs.

1.3 Set up of the report

This thesis is structured as follows, chapter 2 introduces a problem statement, derives several knowledge gaps and proposes research questions. Thereafter, chapter 3 explains the approach to answer the research questions. This entails describing the steps of conducting a systematic literature review, including a literature search, selection, and the definition of review criteria. Then, the main results from the literature review are presented in chapter 4. Further, a discussion provided in chapter 5, consisting of analysis and interpretation of, and a reflection on the results. Additionally, recommendations are provided. Finally, chapter 6 entails a final conclusion in which answers to the research questions are formulated.

2. Problem statement, knowledge gaps and research questions

Above we identified that for relating the environmental performance of products to relevant SDGs, it is necessary to quantitatively analyze the environmental performance of product-systems and compare this to a benchmark. We also identified LCA to be a suitable method for the former. Here, we explain the problems regarding the determination of benchmarks usable for the comparison against product-systems environmental performance.

2.1 Comparative Life Cycle Assessment

Commonly LCA is a comparative method, meaning that it compares among products or services with equivalent functionality, aiming to identify which has the best overall performance based on aggregation of indicator scores across space, time and environmental issues (ISO, 2006; Bjørn, Richardson, et al., 2019). This means that a benchmark is already an inherent part of LCA, because a product is benchmarked against an equivalent product alternative or even an average of many equivalent product alternatives.

In comparative LCA, the outcome of whether a product-system can be considered sustainable is always relative because it fully depends on the product alternative that is chosen as a benchmark. Yet, such relative benchmarks do not ensure that sustainability (and SDGs) is achieved on an absolute basis. For example, in a hypothetical situation where the entire energy supply of the world would be provided by one energy generation source, an LCA could be conducted to compare two alternatives of coal power stations. This comparison would tell the practitioner which station out of the two is the most sustainable but would not clarify whether the overall energy generation is sufficiently sustainable at a global scale (i.e. not increasing climate change due to high greenhouse gas (GHG) emissions). To determine whether a product-system is sufficiently sustainable, its environmental performance has to be compared against a benchmark based on a measure of the earth's capacity to handle environmental impact. Therefore, opposite to comparative LCA, some developments have been made to develop Absolute Life Cycle Assessments, which will be explained in the next section.

2.2 Absolute Life Cycle Assessment to support absolute product contributions to SDGs

2.2.1 Definition of absolute Life Cycle Assessment

According to Bjørn et al, (2019)**,** an absolute environmental sustainability assessment (AESA) can be used to study production or consumption activities of different types of entities (such as nations, companies, and individuals) and compare it with an allocated environmental carrying capacity to analyze whether this activity can be considered environmentally sustainable with respect to the chosen allocation principle. Instead of assessing a production or consumption activity, an AESA can also encompass the functional unit of a product or service system, as referred to in LCA. Under the umbrella of AESA, an increasing number of LCA studies have compared the performance of a product or service against a benchmark based on the earth's environmental carrying capacity (Bjørn et al., 2015; Chandrakumar et al., 2019; Ryberg, 2018). Such a benchmark is often referred to as Absolute Environmental Sustainability Reference (AESR) (Andersen et al., 2020; Ryberg, 2018). A specific name for AESAs involving LCA could not be identified in literature and are therefore in this thesis referred to as Absolute Life Cycle Assessment (ALCA) studies. ALCA is thus a subset of AESA, because not every AESA necessarily uses LCA.

In Figure 2, we have visualized a framework for ALCA. The framework shows that in order to define whether a system can be considered sustainable or not, its impacts, quantified using a certain life cycle impact assessment method (LCIA) have to be compared against a certain benchmark, which in ALCA has to be based on environmental carrying capacity. ALCA can thus be defined as: *A subset of absolute environmental sustainability assessment methods that implement a comparison of a system's life-cycle* *based impacts applying LCA against a carrying capacity-based benchmark, specifically allocated to that system, in order to identify whether the product-system is absolutely sustainable*.

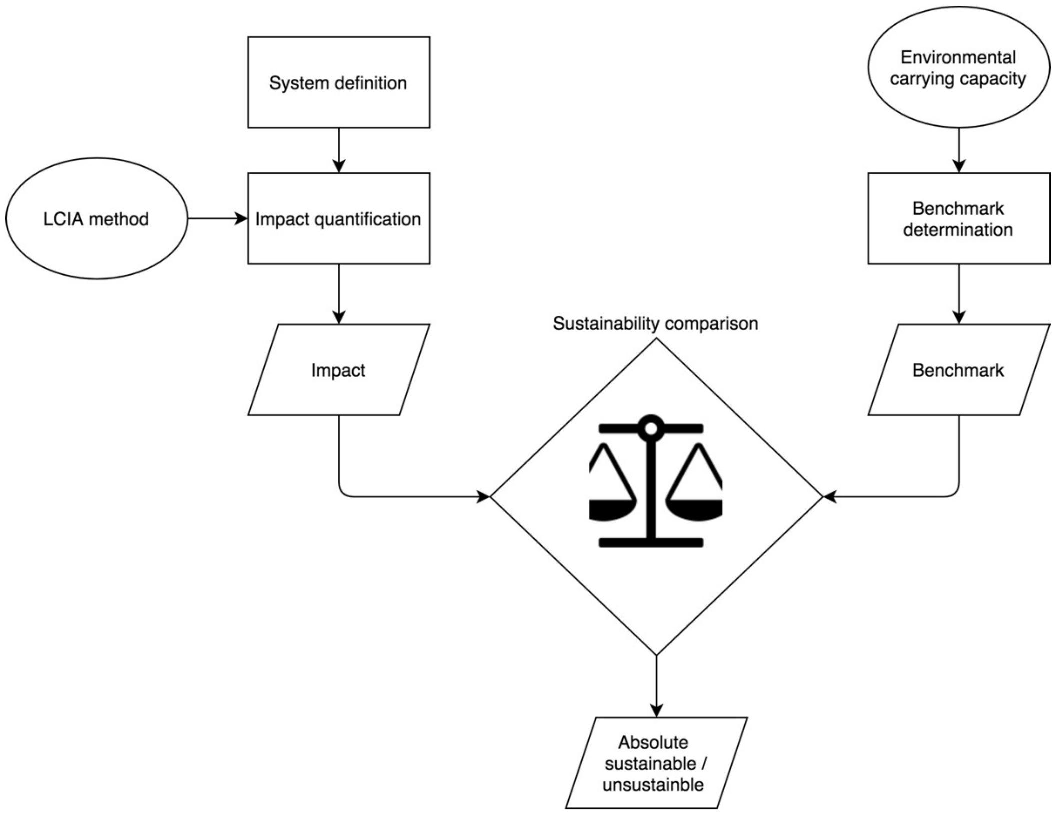

Figure 2: Basic framework for ALCA

2.2.2 General problem statement

Some researchers have already made an effort to investigate the availability of ALCA methods that use environmental carrying capacity as a basis for deriving absolute benchmarks. For example, Ryberg, (2018) introduced a review of ALCA studies. However, many of the publications included were focused on rather large geographical scales (i.e. national, regional, or sectoral), although LCA is originally designed for identifying sustainable product-systems. Chandrakumar et al. (2019) and Hameleers (2019) included a short review of AESAs complementary to their case studies. Chandrakumar et al. (2019) listed studies that 'explore the complementary linkages between environmental sustainability assessment methods to develop AESA methods' but it is not clear whether these methods are also ALCA and how they are different from each other. (Hameleers, 2019) reviewed some ALCA methods, and concluded that there are at least four methods that each implement a different adaptation of the LCA framework.

Although there has been some dispersed research on AESA and ALCA, there is no extensive systematic literature review on available ALCA methods as a specific subset of AESA. Therefore, there is still missing knowledge on several aspects in this scientific field:

- The availability of ALCA methods.
- The extent to which ALCA methods differ from each other and the traditional LCA framework.
- How these methods define the environmental carrying capacity and translate it to the product-level in order to obtain benchmarks for specific product-systems.
- Whether these methods can therewith identify absolutely sustainable product-systems.

- To what extent the methods have been applied in case studies
- What lessons can be learned from these applications

2.3 The Planetary Boundary framework as an expression of carrying capacity

As mentioned in the previous section, benchmarks should be based on ecological carrying capacity (CC). CC can be defined as "The maximum sustained environmental intervention a natural system can withstand without experiencing negative changes in structure or functioning that are difficult or impossible to revert" (Bjørn & Hauschild, 2015, p1005). There are multiple ways to express environmental CC. Therefore, the term CC can be seen as an umbrella concept.

One of the most widely recognized frameworks to quantify the earth's CC is the Planetary boundary (PB) framework (Rockström, et al., 2009; Steffen et al., 2015). Looking at the review publications mentioned in 2.2.2, this framework also seems to be the standard as an expression of CC in ALCA. The PB framework entails a set of quantitative biophysical limits for nine critical earth system processes (ESP). These earth system processes are essential for keeping the planet in a stable Holocene state that is required for human prosperity. Transgressing these global biophysical boundaries leads to an increased risk of large scale irreversible environmental change that will undermine the stability of the earth. The nine earth system processes and the quantified PBs (dotted line) can be seen in Figure 3. It can be observed that 5 PBs have already been transgressed, of which 3 are already in the high-risk zone.

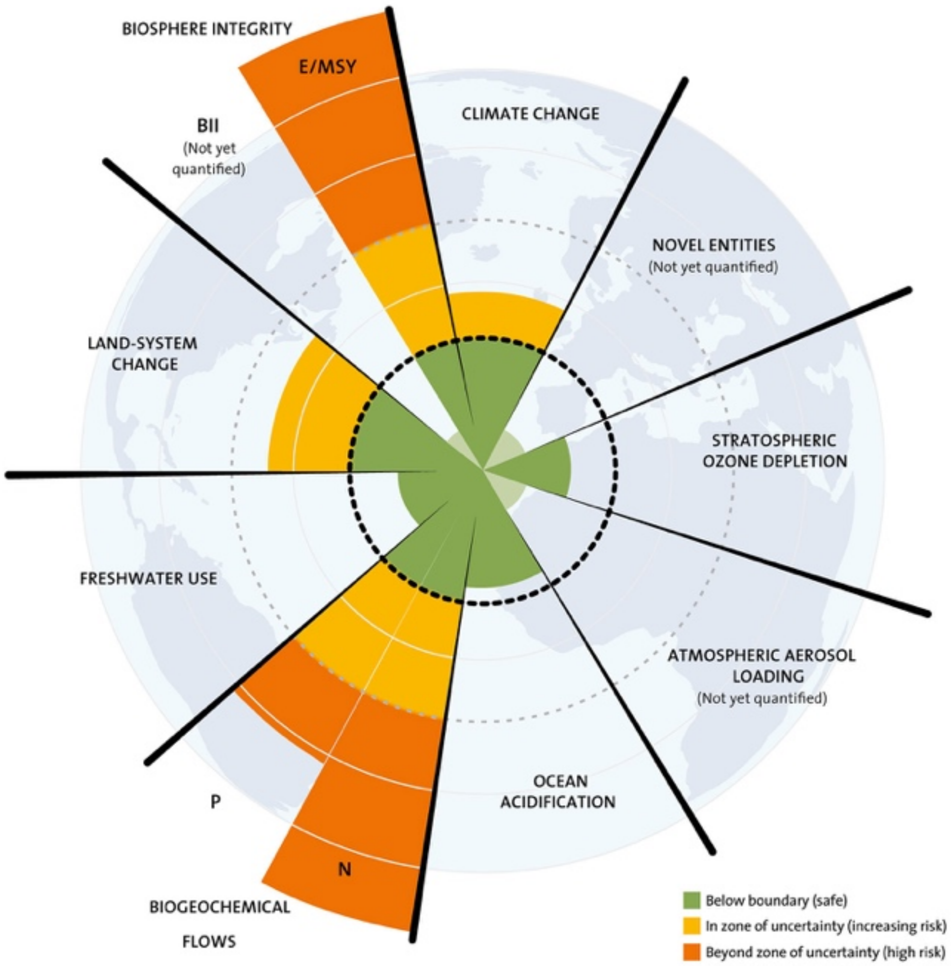

Figure 3: The planetary boundary framework (Stockholm Resilience Centre, n.d.)

Each ESP is complimented with control variables and response variables. The control variables are quantifiable indicators in which impacts and a limit in a certain ESP can be expressed. An example of a control variable for the ESP 'climate change' is the 'atmospheric CO2 concentration'. The control variable influences a certain response variable. Remaining within the ESP climate change, the response variable might be the 'extent of land-ice'. If the value of the control variable increases, the functioning of the response variable decreases. For example, if the atmospheric CO2 concentration (control variable) increases, the extent of land ice (response variable) decreases due to the enhanced greenhouse effect.

For many control variables, Steffen et al. (2015) have quantified certain thresholds. Bjørn et al. (2016) provided a definition for these thresholds: 'a numerical value of a control variable a natural system can withstand without experiencing negative changes in structure and/or functioning that are difficult or impossible to revert'. In other words, if the threshold of a control variable is transgressed, there is an accelerated decrease in the functioning of the response variable, as shown with the descending line in Figure 4. However, there is a certain degree of uncertainty within the determination of these global thresholds as represented by the zone of uncertainty in Figure 4. This means that in reality, the threshold can be at the beginning or end of this zone of uncertainty. Therefore Steffen et al. (2015) decided to a apply a precautionary approach, meaning that humanity should not let the value of the control variable exceed the safe/lower end of the zone of uncertainty, in order to minimize the risk of exceeding the actual threshold. Accordingly, these precautionary values are called the 'planetary boundaries'. Interestingly, Steffen et al. (2015) did not provide an explicit definition for a planetary boundary and seem to use the term in two ways. On the one hand, the term PB describes the *general concept* (framework) including its elements such as ESPs, control variables and tresholds. On the other hand, the term PB represents the *numerical value of a control variable*, positioned at the safe end of a threshold's uncertainty range using the anthropogenically chosen precautionary approach. In this thesis, the term 'PB' is used to describe the former. The term 'PB value' is used to describe the latter.

Using the concepts above, Steffen et al. (2015) distinguished three areas that represent the risk of impacts, depending on the value of the control variable. The first area is the Safe Operating Space (SOS), in Figure 4 the green area below the planetary boundary. In this area, there is little to no risk that the functioning of the response variable is disrupted. The second area is the aforementioned zone of uncertainty, in Figure 4 the yellow area representing the uncertainty of the position of the threshold. In this area, there is an increased risk that the functioning of the response variable is disrupted due to the possible transgression of the threshold. The third area is the high-risk zone, in Figure 4 the red area following the zone of uncertainty. In this area there is a high risk that the threshold is exceeded leading to a strong decrease of the functioning of the response variable, in turn resulting in a high likelihood that the earth destabilizes from its stable Holocene state.

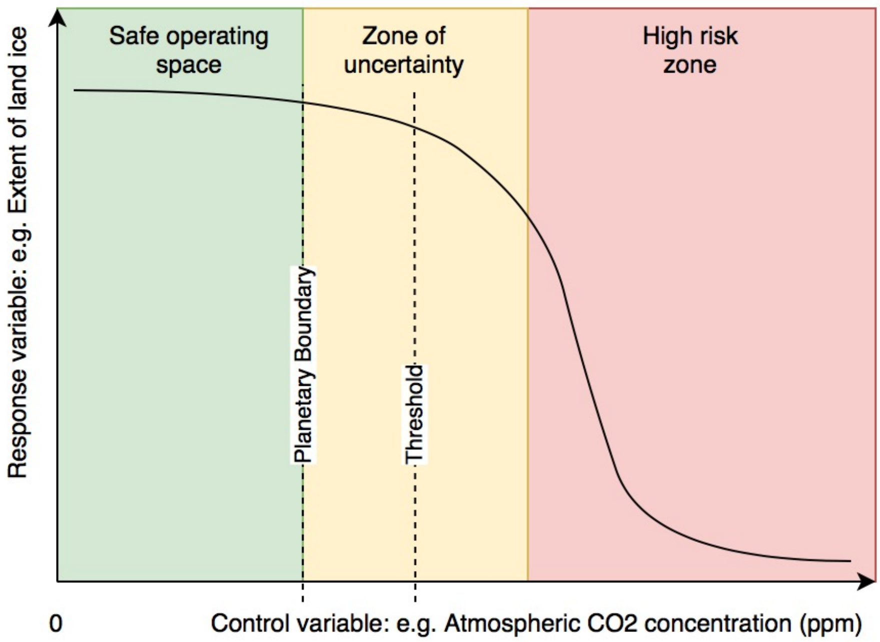

Figure 4: The planetary boundary approach, adapted from (Steffen et al., 2015).

2.4 Main problems when adopting PBs as benchmarks for ALCA

It was earlier concluded that, as a comparative method, LCA is not suitable to define absolute sustainable systems or absolute contributions from products towards the SDGs, because it lacks absolute benchmarks. ALCA, using the LCA in combination with the PB framework, provides the possibility to overcome the limitations of comparative LCA and support absolute product contributions to environmental SDGs. The PB framework and its quantitative boundaries were even originally meant to be included in the SDGs (Rockström & Sukhdev, 2014), indicating that it is also a suitable CC expression in an SDG context. Assuming that ALCA is the way forward for identifying absolute sustainable products that contribute to the SDGs, there is a need to investigate the compatibility of the PB framework and LCA. On the one hand, there is LCA, being a product-level environmental impact assessment method with its own impact categories and indicators. On the other hand, the PB framework is defined at a global scale and has its own control variables and response variables, which are used to define thresholds and a SOS for humanity. Regarding the adoption of the PB framework in ALCA we can identify four problems:

1. Allocation problem
2. SOS definition problem
3. Indicator mismatch problem (including ESP vs LCA-IC)
4. Area of protection coverage problem

Each of these problems are shortly described below.

Allocation problem

The SOS from the PB framework is not directly usable in an ALCA context. The SOS is generally defined at the global level, whereas ALCA requires a benchmark at the product level. Therefore, the previous section already suggested that the SOS somehow needs to be allocated to lower levels. In other words, the global SOS has to be downscaled to – or shared among - competing anthropogenic systems, leading to a specific benchmark for those systems. Therefore, benchmarks in ALCA are sometimes referred to as Share of Safe Operating Space (SoSOS).

SOS definition problem

From the PB framework (Steffen et al., 2015) we interpret the SOS as the “full range of control variable values below the PB value”. However, for some ESPs there is no SOS remaining because the current value of the control variable has already exceeded the PB value (climate change, nitrogen and phosphorus cycles, biodiversity). This would lead to complications if the SOS needs to be used as a basis for determining benchmarks.

Indicator mismatch problem

There is a general mismatch between the ESPs and LCA impact categories (LCA-ICs), and therefore also between the PB indicators and the LCA indicators (Hameleers, 2019). The PBs are quantified with control variables, which are indicators representing the earth system process. For example, for the earth system process ‘climate change’ a control variable is ‘atmospheric carbon dioxide concentration’ (ppm). On the other hand, the LCA indicator for climate change is ‘radiative forcing’ (W/m^2). Here, and also for many other impacts, the control variable and LCA indicator have a different indicator and unit. This means that the use of the SOS to determine a benchmark first requires some sort of indicator-unit conversion step, to ensure that the SOS is expressed in the same unit as the LCA impacts. Only then a correct comparison can be made between the benchmark and impact.

Apart from differences in units, the control variables and LCA indicators are different regarding their position in the related impact pathway. Some researchers (Chandrakumar & Mclaren, 2018; Dong & Hauschild, 2017) mapped both LCA indicators and PB indicators on to a Driver, Pressure, State, Impact, Response (DPSIR) framework. This framework show impact pathways in which anthropogenic drivers are responsible for environmental ‘pressures’, leading to altered environmental ‘states’ which in turn cause environmental ‘impact’, finally resulting in ‘responses’ within society. These mapping studies showed that PB indicators are sometimes positioned at a different place than LCA indicators. For example, the PB indicators on biochemical flows (nitrogen and phosphorus flows) are pressure indicators. Their LCA counterpart for eutrophication, the indicator ‘Accumulated Exceedance’ is a state indicator.

Flux-pulse problem

In any ALCA method that attempts to link the PB framework to LCA, the problem will arise that LCA results are conventionally expressed as impact pulses (without a time dimension) whereas the PB framework proposes limits of impacts in annual fluxes (with time dimension). This might be especially problematic if a comparison is made between an allocated SoSOS and the impact result. Then, both components need to be consistent in being fluxes or pulses.

Area of protection coverage problem

The PB framework only describes areas of global environmental impact which might endanger the earth’s ecological stability whereas LCA (and the SDGs) also cover two other areas of environmental impact related to use of resources and human health. In LCA, such areas of environmental impact are generally referred to as Areas of Protection (AoP). For the resource use and human health AoPs, benchmarks cannot be determined using the PB-framework. Therefore a PB-based ALCA might be inadequate for addressing absolute sustainability on a global level (Chandrakumar & Mclaren, 2018). This problem will not be addressed further in this thesis because the scope is on the ecological AoP and SDGs.

2.5 Knowledge gaps

Based on the problems identified in the previous section we identify four main knowledge gaps below. These knowledge gaps need to be filled to get insight in how ALCA allows a comparison of impact against CC-based benchmarks, and whether this is usable for absolute environmental sustainability conclusions and product level SDG assessments.

1. An overview showing the availability of different ALCA methods and their applicability at the product level is lacking
2. Considering the 'SOS definition problem', it is unclear how ALCA methods can use the SOS from the PB framework as a basis for deriving product-system specific benchmarks
3. Regarding the allocation of SOS to product level benchmarks, knowledge is lacking on the availability of allocation approaches and their normative foundations, as well as their use within ALCA methods and across applications of methods.
4. It is not yet clear how different ALCA methods deal with the mismatch between PB and LCA indicators, if or how methods implement a translation across DPSIR pathways, if or how methods deal with the flux-pulse problem.

2.6 Research questions

Based on the problem statement and defined knowledge gaps, the following main research question was formulated:

To what extent is absolute life cycle assessment possible and does it enable a comparison of environmental impact against product-level benchmarks based on the PB-framework, to support the identification of absolute sustainable products contributing to the UN SDGs?

The main research question is subdivided into two sub-questions. The first sub-question covers the variety of ALCA methods and how they link PB and LCA indicators:

SQ1: Which ALCA methods enable linking of planetary boundaries to LCIA midpoint indicators and which challenges can be expected when actually linking them?

The second sub-question touches upon the different approaches available to allocate PBs to benchmarks at the product level:

SQ2: What are the principles, normative foundations and practical differences of available methods for allocating planetary boundaries to product-level benchmarks allowing for comparisons with LCA characterization results?

3. Approach

To answer the formulated research questions, a systematic literature review is conducted. The purpose of this literature review is to identify scientific publications that involve ALCA methods/applications and allocation of PBs and review them on criteria related to LCA, PBs and allocation.

The method for doing this review consists of three parts. First, the search method for finding possibly relevant articles is described in section 3.1. Then, in section 3.2, a selection is performed to filter out non-relevant articles and a completeness check is done to ensure the inclusion of articles that were missed in the search. Finally, the review approach and criteria that will be used for the actual review are provided in section 3.3.

3.1 Search method

In order to find the relevant scientific literature, specific keywords were used in two search engines.

A search query in the Web of Science (WoS) database:

TS = ("life cycle assessment" OR "life cycle analysis" OR "lca") AND TI = (carrying capacity* OR "share" OR "sharing" OR "scaling" OR "downscaled" OR "downscaling" OR "absolute" OR planetary boundary* OR ecological boundary* OR "safe operating space")

Clarifications:

- TS indicates that the keywords between brackets should be defined as the article topic.
- TI indicates that the keywords between brackets should be present in the article title.
- The OR statement indicates that the use of only one of the keywords is sufficient
- The AND statement indicates that in both TI and TS one of the defined topics as defined respectively must be present.
- A * symbol indicates that alternative versions of the keyword such as the plural are also included.
- The timespan was set from 2009 – 2020[2] (since the planetary boundary framework was introduced in 2009).
- The language was set to English.
- The reasoning to execute the search such that most keywords should be present in the title instead of the topic, is that a topic search with the above combinations led to hundreds or thousands of articles, which is undoable to review considering time limitations for this thesis.

This search resulted in 58 articles, which will be subjected to two iterations of selection as described in the next *selection and completeness* section.

3.2 Selection and completeness

3.2.1 First selection iteration

For the obtained set of 58 articles, a first selection step was performed to filter out the publications that were not within the research boundaries. For example, a paper about “life cycle analysis of car sharing systems” will pop up in the search due to the keyword ‘sharing’, but this publication is not related to this thesis. During this filtering step, only the title, keywords and abstracts of the publications have been read. The selection step resulted in a set of 15 articles, as listed in the first column of Table 1.

[2] The search was done in April 2020, so not the full publishing year 2020 was included

Literature search was then extended with a snowballing approach. This entailed scanning the full text and reference lists of these articles in order to check if other important publications had been missed in the first database search. The snowballing step provided 13 more articles related to both LCA and absolute sustainability, as listed in the second column of Table 1.

Table 1: First literature selection

Selected from search (#15)	*Obtained with snowballing (#13)*
(Andersen et al., 2020)	(Algunaibet et al., 2019)
(Bjørn & Hauschild, 2013)	(Clift et al., 2017)
(Bjørn et al., 2016)	(Doka, 2016)
(Bjørn & Hauschild, 2015)	(Downing et al., 2019)
(Bjørn et al., 2015)	(Fantke & Illner, 2019)
(Bjørn, Richardson, et al., 2019)	(González-Garay et al., 2019)
(Bjørn, Sim, et al., 2019)	(Kara et al., 2018)
(Bjørn, Sim, King, et al., 2020)	(Pelletier et al., 2019)
(Bjørn, Sim, Boulay, et al., 2020)	(Sandin et al., 2015)
(Brejnrod et al., 2017)	(Ryberg et al., 2018b)
(Chandrakumar & Mclaren, 2018)	(Tuomisto et al., 2012)
(Chandrakumar et al., 2019)	(Vanham et al., 2019)
(Ritzen et al., 2019)	(Wolff et al., 2017)
(Ryberg et al. 2018b)	
(Świader et al., 2018)	

3.2.2 Second selection iteration

After full reading, the 28 articles in total could be distinguished into two general categories:

(1) Articles that discuss, explore and comment on the LCA methodology in combination with absolute sustainability and PBs.
(2) Articles in which methods at the intersection of LCA and PBs are developed (ALCA methods) or applied in case studies.

Only the 14 articles within the second category (Table 2) are subjected to the review criteria as described in 3.3. The articles within the first category are useful for understanding the context and have contributed to writing chapters 1, 2 and 5.

Table 2: Final literature selection

Author and year	*Title*
(Algunaibet et al., 2019)	Powering sustainable development within planetary boundaries
(Andersen et al., 2020)	Assessment of absolute environmental sustainability in the built environment
(Bjørn & Hauschild, 2015)	Introducing carrying capacity-based normalization in LCA: framework and development of references at midpoint level
(Brejnrod et al., 2017)	The absolute environmental performance of buildings
(Chandrakumar et al., 2019)	A Benchmarking Approach to Operate Agri-food Systems within the 2°C Global Carbon Budget
(Doka, 2016)	Combining life cycle inventory results with planetary boundaries: The Planetary Boundary Allowance impact assessment method Update PBA'06
(González-Garay et al., 2019)	Plant-to-planet analysis of CO2-based methanol processes
(Ritzen et al., 2019)	Sustainable Energy Technologies and Assessments Carrying capacity based environmental impact assessment of Building Integrated Photovoltaics
(Ryberg et al. 2018a)	How to bring absolute sustainability into decision-making: An industry case study using a Planetary Boundary-based methodology
(Ryberg et al. 2018b)	Development of a life-cycle impact assessment methodology linked to the Planetary Boundaries framework
(Sandin et al., 2015)	Using the planetary boundaries framework for setting impact-reduction targets in LCA contexts
(Świader et al., 2018)	Application of ecological footprint accounting as a part of an integrated assessment of environmental carrying capacity: A case study of the footprint of food of a large city
(Tuomisto et al., 2012)	Exploring a safe operating approach to weighting in life cycle impact assessment - a case study of organic, conventional and integrated farming systems
(Wolff et al., 2017)	Detecting unsustainable pressures exerted on biodiversity by a company. Application to the food portfolio of a retailer

3.3 Review approach and criteria

In this section, the approach for systematically analyzing the final literature set will be defined. To analyze and compare the approaches in the literature a clear structure is needed. Such a structure could be extracted from existing frameworks: such as the framework for AESA proposed by Bjørn et al. (2019). The authors state that this framework is intended for researchers that want to compare existing AESA methods and communicate their differences to peers and potential users requiring guidance on method selection. Since we consider ALCA as a subset of AESA, we consider this framework suitable as a structural basis for conducting the literature review. Moreover, the framework covers several aspects that were previously proposed within the research questions, such as impact quantification (in this thesis LCA), sustainability identification, CC definition (in this thesis the PB framework) and allocation approach. In section 3.3.1, the framework and its components are first explained. Then, in section 3.3.2, the framework is used as a basis to define a set of specific review criteria on which the set of publications from the refinement step will be analyzed.

3.3.1 Framework for AESA methods (Bjørn, Richardson, et al., 2019)

Bjørn, Richardson, et al. (2019) have developed a framework for AESA methods that includes four succeeding assessment steps and involves six methodological choices (Figure 5).

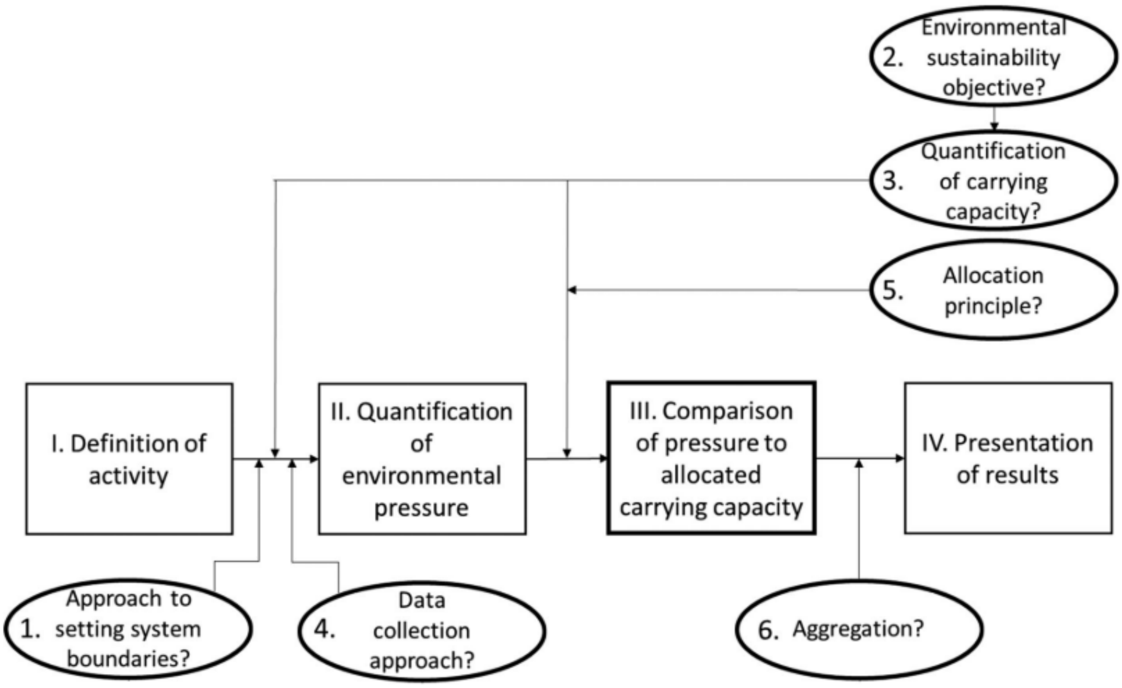

Figure 5: Framework for AESA (Bjørn, Richardson, et al., 2019).

In the framework, the boxes are the four assessment steps, of which I, II and IV are involved in any sustainability assessment method. Step III, the comparison of pressure to allocated CC is unique to AESA methods. This is in accordance with our line of reasoning in section 2.2. There it was already highlighted that, in contrast to comparative LCA, ALCA methods implement benchmarks based on predefined environmental CCs (i.e. using the PB framework).

A short explanation of the methodological choices (the 6 ellipses) will follow below.

- *Choice 1*: To progress from the definition of activity (step I) towards the quantification of environmental pressure (step II), a decision is needed regarding how system boundaries are set. This can be either a territorial approach (only include the territorial extension of the activity itself) or a consumption-based approach (enclose all production processes that are needed for the defined activity, regardless of the location).
- *Choice 2*: Here, the environmental sustainability objective needs to be defined to clarify what should be protected for achieving environmental sustainability.
- *Choice 3*: After the definition of the environmental sustainability objective, it needs to be decided how it is translated to one or multiple quantified environmental CCs, representing the

level of anthropogenic pressure that the environment can withstand while remaining its functional integrity.

- *Choice 4*: the chosen approach for the collection of data that is needed to quantify environmental pressure corresponding to the defined activity. This choice depends on system boundary determination from choice 1.
- *Choice 5*: A choice must be made on how a part of the quantified CC is allocated to the defined activity in case multiple systems are occupying the CC. Only after this, it is possible to execute the comparison (step III).
- *Choice 6*: Aggregation techniques can be applied to facilitate interpretation of assessment results, specifically useful to identify the activity with the best overall performance in a comparative environmental assessment.

Bjørn, Richardson, et al., (2019) have already applied the framework in an analysis of five AESA methods. Those AESA methods were however not related to LCA and also did not apply any form of allocation because all global activities were assessed (making choice 5 on allocation unnecessary). Thus, the influence of various allocation principles and their ethical foundations on the results, as well as the integration of AESA framework elements with the LCA framework still needs to be investigated. Bjørn, Richardson, et al. (2019) also mention that the five AESA methods can also be used to assess various activities at a sub-global level, and therefore refer to PBs–related methods applied at national scale (Cole et al., 2014; Dao et al., 2018; Nykvist et al., 2013) and at the scale of industrial sectors (Sandin et al., 2015). Application at such lower levels will clearly require a methodological choice on how CC is allocated.

3.3.2 Review criteria

In this section the review criteria are formulated and explained, which will be used to analyze the final literature selection from 3.2.2. As previously mentioned, the review is conducted on ALCA publications and ALCA can be considered as a subset of AESA. Therefore, some of the components from the AESA framework (Bjørn, Richardson, et al., 2019) can directly be used as criteria. Yet, other components from this AESA framework are changed in order to become more relevant criteria in ALCA context. Also, some additional criteria are added. This led to a set of criteria that can be arranged in three coherent groups:

1. LCA related criteria (listed, explained and supported in Table 3)
2. PB-related criteria (listed, explained and supported in Table 4)
3. Allocation related criteria (listed, explained and supported in Table 5)

Table 3: LCA related review criteria

	Review criteria:	*Explanation*	*Clarification for inclusion*
C0	Method / Application	Does the publication entail an ALCA method proposal, an application (case study), or both?	This criterion provides insights on the availability of methods and the extent to which they have been applied in case studies.
C1	Scale / object study	What is the geographical scale of study and object of study within an ALCA application? How is the system defined?	This criterion is only relevant for publications involving a case study. It was included because 'system definition' is the first step in the AESA framework.
C2	LCA adjustment	Does a method/application implement standard LCA steps or does it adjust the LCA framework?	The second assessment step in the AESA framework is 'quantification of environmental pressure'. Since this review is focused on ALCA, it is expected to see that the impact quantification is done with some form of LICA. Hameleers (2019) already pointed out that some ALCA methods make adjustments to the conventional LCA framework.
C3	Flux/pulse	Is a functional unit defined as pulse (without time dimension) or as a flux (with time dimension)?	In any ALCA method that attempts to link the PB framework to LCA, the problem will arise that LCA results are conventionally expressed as impact pulses (without a time dimension) whereas the PB framework proposes limits of impacts in annual fluxes (with time dimension).
C4	Absolute sustainability comparison	Does the method (or application) involve a comparison of impact against an absolute benchmark to determine absolute sustainability?	This criterion relates to the third step from the AESA framework, 'comparison of pressure against allocated carrying capacity', which is unique to AESA methods.
C5	Results presentation	How are the results from the LCA and absolute sustainability comparison presented?	This criterion was included because it is the final assessment step from the AESA framework and it provides insight in which statements are made based on the results.

Table 4: PB related review criteria

	Criteria	*Explanation*	*Clarification for inclusion*
C6	Sustainability objective	Which general environmental sustainability objective is adopted?	This is one of the methodological choices in the AESA framework. Since our review is focused on the PB framework, it is expected that publications frame the sustainability objective as avoiding transgression of PBs.
C7	Planetary boundaries included?	Which of the PBs formulated by Rockström et al. (2009) or Steffen et al. (2015) are included in the ALCA methods or applications?	This criterion will provide insights in how many ESPs can be covered In the ALCA method at stake. It will also provide insights in how methods can deal with mismatches between LCA indicators and control variables, and the possibly required conversions across impact pathways, since that will likely be the determining factor for covering an ESP in an ALCA method or not.
C8	LCA-ICs covered	Which LCA-ICs can be covered in terms of impact quantification and benchmark determination, within methods or applications?	LCA impacts are generally quantified in several LCA-ICs at midpoint level. To define absolute sustainability, benchmarks are also needed for each LCA-IC. Therefore, this criterion will show in which LCA-IC absolute sustainability can be defined across methods and applications. At the same time, this criterion will also provide insight in how methods deal with mismatches between LCA indicators and control variables, and possibly required conversions across impact pathways.
C9	Quantification of SOS	How is the SOS quantified and used within ALCA methods/applications?	This criterion comes from the methodological choice 'quantification of carrying capacity' in the AESA framework. In our review, ALCA publications using PB framework are analyzed and it is therefore expected that the CC is expressed as SOS.

Table 5: Allocation related review criteria

	Criteria	*Explanation*	*Clarification for inclusion*
C10	Basis of allocation	On which basis is the quantified SOS allocated to a benchmark? For example, a SoSOS might be derived for a individuals, products or sectors.	An absolute sustainability comparison requires an absolute benchmark at the product level. The SOS is however quantified by the PB framework at global level. Therefore, this criterion should provide insight in whether methods and applications implement the allocation of a SoSOS to product-systems or other entities.
C11	Allocation principle(s) used	According to which allocation principle(s) is allocation conducted, within methods and applications?	Even when the basis of allocation is clear, the allocation might still be conducted in different ways. E.g. either by allocating uniformly or giving higher/lower shares to specific groups (of people, products sectors, etc.) depending on the indicator used for the allocation.
C12	Principle documentation	Was the allocation documented in the publication, and how?	This criterion is necessary to determine whether the terminology regarding allocation principles is consistent. Also, it will give insight in whether the use of a certain allocation approach is always clarified and supported or not.
C13	Compatibility allocation principles	Is it possible, to use other allocation principles apart from the ones that are used in publications?	This criterion was included to investigate the compatibility with different allocation principles across methods/applications.

All the publications selected in section 3.2.2 are reviewed according to these criteria. The individual reviews of these publications can be found in Appendix A. The next chapter summarizes the main results from these reviews.

4 Results

4.1 Introduction

In this chapter, the main findings from reviewing the literature selection are brought together. First, section 4.2 provides an overview of different methods and case studies, covering criteria C0 (methods/applications) and C1 (scale / object study). Then, in 4.3, there is an analysis of how the main methods identified from the overview deal with the remaining review criteria. This analysis is done in three different parts, following the three groups of criteria as defined in the previous section.

4.2 Overview of ALCA methods and case studies

Methods/applications

During the review of selected publications, several ALCA methods and case studies applying these methods have been observed. In the top part of Table 6, 4 ALCA methods are distinguished in the 'methods' row, each providing a different 'primary LCA adjustment'. The blue arrows in the Table represent that the publications below the arrow involve case studies in which the method above the arrow is used. Consequently, the lower part of the Table shows different case studies included in the review, each providing an application of ALCA at one or multiple scales.

Scales/objects of study

Based on table 6 we can identify that six applications actually analyze a product-system, most of which using the method by Bjørn & Hauschild (2015) and Ryberg et al. (2018b). For two applications it was debatable if the case study actually studies a product-system, or rather an entire sector. For example, Sandin et al. (2015) calculate reduction targets for the entire clothing sector and assume that these targets are applicable for every product in the sector. In contrast, Chandrakumar et al. (2019) specifically use LCA results of agricultural products, but also use these to estimate impacts of entire product-industries due to the lack of inventory data at this level. Two applications clearly entail an analysis at company level (Wolff et al., 2017) or sectoral level (Algunaibet et al., 2019).

Excluded publications

Two publications from the final literature selection in 3.2.2, Ritzen et al. (2019) and Świader et al. (2018), didn't really fit the ALCA domain for different reasons. The former did a case study on the sustainability of building integrated photovoltaics, but they did not follow the LCA framework properly (see Appendix A8). The latter performed a case study on the environmental impact of food consumption of a Polish city but did not perform a full LCA analysis (See Appendix A12). They only calculated the carbon-based environmental footprint (global hectares) and made a debatable comparison against biocapacity (global hectares) based on the amount of land and land-use types within the city and its municipalities. Both publications expressed CC in an alternative way that doesn't fit in our CC definition. Ritzen et al. (2019) defined CC as the ability of a system to (re) generate the resources consumed within the system itself. Therefore, they calculated the impact from 1m^2 solar systems as 'embodied land', which is the time and land (m^2*a) required for converting solar energy to total energy consumed in all life cycle stages. This embodied land divided per m^2 then represents the CC exceedance, in which any value higher than 1 reflects a transgression. Świader et al. (2018) expressed CC as biocapacity, which is the annual bio-productive ability of an area of a given land use type to provide the human needs. Thus, both publications did not use the PB framework for expressing CC and did not determine which share of SOS the assessed system is entitled to. For these reasons, the two publications are not included in Table 6, and not further treated in the remainder of this chapter.

Table 6: Overview of methods and case studies

	Primary LCA adjustment	*Authors*				
Methods	*G&S definition*					
	Life cycle inventory					
	Characterization			Doka (2016)[1]	Ryberg et al. (2018b)[2]	
	Normalization		Bjørn & Hauschild (2015)			
	Weighting	Tuomisto et al. (2012)				
	-					Sandin et al. (2015)
		↓	↓	↓	↓	↓
	Scales[3]	*Object of study (author)*				
Applications	Company		*Portfolio retailer* (Wolff et al., 2017)			
	Product	*Farming product-systems* (Tuomisto et al., 2012)	*Dwellings* (Andersen et al., 2020)		*Dwellings* (Andersen et al., 2020)	
			Dwellings (Brejnrod et al., 2017)		*Methanol synthesis* (González-Garay et al., 2019)	
					Laundry (Ryberg et al., 2018a)	
				Agri-food systems (Chandrakumar et al., 2019)		*Clothing* (Sandin et al., 2015)
	Sectoral				*Energy mix US* (Algunaibet et al., 2019)	

[1] Weighting possible but not recommended by the author (see appendix A6)
[2] Normalization against full SOS or SoSOS possible
[3] These are scales of the case studies as implied by the author of this thesis

From Table 6 becomes clear that there are just a limited number of actual methods across the reviewed publications. Most publications were applications of these methods. Table 6 also points out that each ALCA method implements an adjustment at a different place (step) in LCIA phase of the LCA framework, except the method by Sandin et al. (2015). To prevent confusion throughout the remaining report, Table 7 (third column) shows the names that are used in this thesis to refer to the methods.

Table 7: Terminology used in this thesis for different methods

	Method name in the original publication	*Name used in this thesis*
(Doka, 2016)	Planetary Boundary Allowance method (PBA'06)	$\text{ALCA-Characterization}_{\text{LCAmetrics}}$
(Ryberg et al., 2018b)	Planetary-Boundary Life Cycle Impact Assessment (PB-LCIA)	$\text{ALCA-Characterization}_{\text{PBmetrics}}$
(Bjørn & Hauschild, 2015)	Carrying capacity-based normalization	ALCA-Normalization
(Tuomisto et al., 2012)	Planetary Boundary-based weighting factors	ALCA-Weighting
(Sandin et al., 2015)	Planetary Boundary-based impact reduction targets	ALCA-Reduction-targets

Below follows a concise summary of the basic principles behind each method.

$\text{ALCA-Characterization}_{\text{LCAmetrics}}$

Doka (2016) introduced an ALCA method in which a new characterization approach is implemented. First Doka (2016) allocates the SOS into a future per-capita SoSOS, by dividing the SOS from the PB-framework by a projected population of 10 billion people in 2050. Then characterization factors (CFs) are developed such, that after multiplication with inventory results, scores are obtained that represent how much of the per-capita SoSOS is occupied by the assessed system.

For example, the global freshwater use SOS equals 4000 km^3/yr. The per capita SoSOS then equals (4000 km^3/yr / 10 E^10) = 400 (m^3/yr/ capita). Using this SoSOS, Doka (2016) develops new characterization factors expressed as a fraction of the per capita SoSOS, which for water-use equals 0.0025 ($\text{SoSOS}_{\text{per capita}}/m^3$). In the hypothetical situation where a person would consume 100 cotton shirt a year, equaling 200 m^3 of water used, the result would be expressed as: 200 (m^3)* 0.0025 ($\text{SoSOS}_{\text{per capita}}/m^3$) = 0,5 $\text{SoSOS}_{\text{per capita}}$. This means that 50% of the per-capita SoSOS for global freshwater use is occupied by shirts. This makes sense because 200 m^3 is halve of 400 m^3 available per capita, as previously mentioned.

$\text{ALCA-Characterization}_{\text{PBmetrics}}$

Ryberg et al. (2018b) propose an ALCA method with characterization factors that enable to express impact in the metrics of the PB framework (the control variables), instead of in metrics of LCA characterization methods. In traditional LCA characterization, the inventory result would, for example for global warming, be multiplied with a characterization factor, the so-called Global Warming Potential (GWP), that converts a GHG emission (kg) into CO_2-eq (kg). In the $\text{ALCA-Characterization}_{\text{PBmetrics}}$ method, the characterization factor converts a GHG emission (kg) into 'ppm atmospheric CO_2', the metrics of the control variable of the PB-framework. One reason to convert inventory results into the metrics of the PB framework is that it enables a direct comparison of impact against a SoSOS, since both now have the same unit. In this way, the indicator mismatch problem is avoided. The SoSOS can be separately determined by allocating a part the SOS to the assessed system. This parallel allocation undertaking is not described within the method itself.

ALCA-normalization

Bjørn & Hauschild (2015) proposed an ALCA method in which a new normalization approach is implemented. In traditional LCA normalization, normalization references are values that for example express per-capita impact that is currently generated in a year. The characterization results can be divided by these normalization references to express how much of the annual per-capita impact is exerted by the assessed system. These normalization references are however not based on the CC of the earth and therefore not directly relevant in ALCA.

Therefore Bjørn & Hauschild (2015) developed per-capita normalization references that are based on the thresholds from the PB-framework, by dividing the global thresholds by the current global population. In this way, the normalization references represent the maximum allowed impact per capita according to the thresholds from the PB framework. Now, the characterization results can be divided by these threshold-based normalization references to express how much of the maximum allowed annual per-capita impact is taken up by the assessed system.

In their method, the units of the threshold-based normalization references need to match the LCA-ICs. Therefore, thresholds from the PBs sometimes had to be translated across the impact pathway, see Bjørn & Hauschild (2015) for more details. For example, where the climate change control variable, and thus the threshold, was expressed in atmospheric CO2 concentration (ppm), the climate change LCA-IC expresses results in CO2-eq. A translation of units allows the user of this method to express the normalized results in LCA metrics (existing LCA-ICs).

ALCA-Weighting

Tuomisto et al. (2012) introduced an ALCA method in which a new weighting approach is implemented. In traditional LCA weighting, normalization results can be multiplied with weighting factors that represent the importance of impact categories relative to each other. This multiplication gives an aggregated single score that reflects the overall weighted impact of the system. These weighting factors can for example be determined by an expert panel. Tuomisto et al. (2012) developed weighting factors that are based on the PB framework. The weighting factors for 9 ESPs from Rockström et al (2009) were derived by dividing the current value of the control variable by the PB value of the control variable. An example of this is given in Table 8, while the complete list of PBs and weighting factors is provided in Appendix A13. In order to obtain a single score, these weighting factors can thereafter be multiplied with normalized results calculated for the LCA-ICs that relate to the ESP.

Table 8: Example of PB-based weighting factors (Tuomisto et al., 2012)

ESP	*Control variable*	*Unit*	*PB value*	*Current value (2012)*	*Weighting factor*
Climate change	Atmospheric CO2 concentration	Parts per million	350	387	1.11
Freshwater use	Global freshwater use	km3 consumed/yr	4000	2600	0.65

ALCA-Reduction-targets

The method by Sandin et al. (2015) does not include adjustments on any of the LCA steps. Rather, it entails a procedure to use global goals based on the SOS for setting case-specific impact reduction targets. The procedure consists of four steps. The first step is to identify quantified PB values within the included ESPs, which can be taken directly from the PB framework (Steffen et al., 2015). The second step is to define a global reduction target for the ESP based on the difference between the current value of the control variable and the PB value. Consequently, in ESPs such as freshwater use where the current value (2600 $km^3\ yr^{-1}$) of the control variable is lower than the PB value (4000 $km^3\ yr^{-1}$), a negative reduction target is given. The third and fourth step entail a conversion factor to translate the global reduction target into a target specifically for a global market segment and product within this segment, respectively.

The procedure can however be conducted independently of the LCA. Yet, the final percent wise impact reduction targets can be applied to characterized LCA results in several LCA-ICs, as was done in their case study (Sandin et al., 2015). The final impact reduction targets show the extent to which the impact from a system in an individual impact category related to an ESP has to be reduced in a certain time frame. Sandin et al. (2015) propose 2050 as a reasonable time frame because 35 years is generally required for large transitions.

4.3 Analysis of main methods

To keep the remainder of the results section concise, the analysis per criterion in this section will generally only include the 5 main methods that were identified earlier. Yet, at some places there will be an elaboration on the applications of methods, to show how specific aspects of a method were dealt with across case studies. The details from the applications of methods can be found in Appendix A9. Table 9 summarizes how different methods deal with the review criteria. Criterion C0 (method/application) and C1 (scale/object study) have already been covered in section 4.2 (table 6) and will therefore not be included in this section.

Table 9: Summary of criteria handling across methods

LCA related criteria				
	(Primary) LCA adjustment	Flux/pulse	Absolute sustainability comparison	Result presentation
(Tuomisto et al., 2012)	Weighting	N.A.	N.A.	LCA metrics,weighted single scores.
(Bjørn & Hauschild, 2015)	Normalization	Not treated	Impact against SoSOS allocated per-capita	LCA metrics, Normalized score, for each LCA-IC, reflecting SoSOS occupation in person equivalents.
(Doka, 2016)	Characterization	Not treated	Impact against SoSOS allocated per-capita	
(Ryberg et al., 2018b)	Characterization	LCI: flows as flux [mass /year] instead of pulses [mass]. FU: annual and continuous.	Allows comparison of impact against SoSOS allocated to the assessed system	PB metrics, characterized scores.
(Sandin et al., 2015)	None	Not treated	Achieved impact reduction (%) against required impact reduction (%)	LCA metrics, impact reduction targets, for each LCA-IC, as percentages.
Planetary boundary related criteria				
	Sustainability objective	Planetary boundaries included	LCA impact categories included	Quantification of SOS
(Tuomisto et al., 2012)	Avoid transgression PB	N.A.	2	PB value minus current value of control variable
(Bjørn & Hauschild, 2015)	Avoid transgression PB	N.A.	10	Defined by the thresholds from PB framework
(Doka, 2016)	Avoid transgression PB	N.A.	4	Defined by the PB values
(Ryberg et al., 2018b)	Avoid transgression PB	Covering 13	N.A.	PB value minus natural background level of control variable
(Sandin et al., 2015)	Avoid transgression PB	N.A.	8	PB value minus current value of control variable
Allocation related criteria				
	Basis of allocation *within method*	Allocation principle(s) used	Principle documentation	Compatibility allocation principles
(Tuomisto et al., 2012)	N.A.	N.A	N.A	N.A
(Bjørn & Hauschild, 2015)	On a per-capita basis	Egalitarian	Documented and discussed	Not suggested or discussed
(Doka, 2016)	On a per-capita basis	Egalitarian	None	Not suggested or discussed
(Ryberg et al., 2018b)	N.A.	N.A.	N.A.	N.A.
(Sandin et al., 2015)	Per global sector, then per regional sector	Outcome based, then egalitarian / grandfathering	Documented and discussed	Suggested and discussed (see appendix A11)

PB = planetary boundary. SoSOS = share of safe operating space. LCA-IC = LCA impact category.

4.3.1 LCA related criteria

Criterion: Primary LCA adjustment

Above it was already identified that each method connects to the LCA framework at a different LCA step. This point of connection to the LCA framework is further referred to as '*primary LCA adjustment*', indicating that the main adjustment takes place at that specific LCA step, which doesn't rule out variations in other LCA steps. For example, if a method proposes a variation in the LCA normalization, different forms of weighting would still be possible.

The basic principles of each method have been discussed in the previous section, but specifically the primary LCA adjustments in the methods are listed below:

- The ALCA-Characterization$_{LCAmetrics}$ method (Doka, 2016) has characterization as primary LCA adjustment, as it proposes new CFs that enable to express impact as an occupation of per-capita SoSOS. At the same time, the method not only adjusts characterization but simultaneously conducts normalization, precisely because the impacts are directly normalized in person equivalents.
- The ALCA-Characterization$_{PBmetrics}$ method (Ryberg et al., 2018b) has characterization as primary LCA adjustment, as it proposes new characterization factors that enable the conversion of inventory results into the metrics of the PB framework.
- The ALCA-normalization method (Bjørn & Hauschild, 2015) has normalization as primary LCA adjustment. They have introduced normalization references based on the PB framework that can be applied to characterization results.
- The ALCA-weighting method (Tuomisto et al., 2012) has weighting as primary LCA adjustment, as it introduces weighting factors based on the PB framework.
- The ALCA-Reduction-targets method (Sandin et al., 2015) does not include adjustments on any of the LCA steps. It rather entails a procedure for setting case-specific impact reduction targets that could be applied to characterization results in existing LCA'ICs.

Criterion: Result presentation

The ALCA-weighting method (Tuomisto et al., 2012) enables to aggregate normalization results from different LCA-ICs (thus in LCA metric) into a weighted single score. This is however only relevant for comparative LCA, because it allows a practitioner to compare the aggregated single scores of two or more product-system alternatives and thereby identify the most sustainable system.

Both the ALCA-normalization method (Bjørn & Hauschild, 2015) and ALCA-Characterization$_{LCAmetrics}$ method (Doka, 2016) enable the expression of results as normalized scores, for individual LCA-ICs (thus in LCA-metrics), reflecting SoSOS occupation in person equivalents. The authors claim that the results can be expressed as follows: if an LCA studying a product-system leads to a normalized result of 1 in a certain LCA-IC, this means that the product-system exerts the full impact available for one person in one year (or in other words 1 person-equivalent).

The ALCA-Characterization$_{PBmetrics}$ method (Ryberg et al., 2018b) enables a practitioner to express results as characterized impact scores in the metrics of the PBs (following the control variables). These characterization results might then be divided by a separately determined SoSOS (see next criterion) in order to obtain a value that reflects the degree of SoSOS occupation. Then any value below 1 would reflect that the system exerts less impact than what it is entitled to, and any value above 1 reflects that the system exerts more impact than what it is entitled to.

The ALCA-Reduction-targets method (Sandin et al., 2015) does not alter the results from the LCA but separately proposes impact reduction targets, for each LCA-IC (thus in LCA metrics), as percentages.

Criterion: Absolute sustainability comparison

Both The ALCA-Normalization method (Bjørn & Hauschild, 2015) and ALCA-Characterization$_{LCAmetrics}$ method (Doka, 2016) inherently include a comparison of impact against SoSOS allocated per capita. For example, the normalization step in which the impact is divided by a person equivalent normalization reference is in fact the same as making a comparison between both. However, these two methods do not give a determination of which share of the per capita SoSOS can be entitled specifically to the product-system of the analysis. Consequently, these methods alone cannot reveal whether an activity can be considered absolutely sustainable but can only reveal a product's occupation of SoSOS available for one individual.

In contrast, only the ALCA-Characterization$_{PBmetrics}$ method (Ryberg et al., 2018b) allows a direct comparison of impact against a SoSOS that is allocated to the assessed system. The method itself however only provides the characterization factors needed to express LCA results in the metrics of the PBs and does not provide guidance against what this impact should be compared. Yet, parallel to using the characterization approach, a practitioner can allocate a share of the full SOS from the PB framework specifically to the assessed product. Then a comparison can be made between characterization impact and SoSOS, on which can be concluded whether the individual product-system is absolutely sustainable. Ryberg et al (2018b) don't provide any further guidance for this step.

The ALCA-weighting method (Tuomisto et al., 2012) just uses the PB framework to aggregate LCA impacts in a weighted single score and does not provide any form of benchmark. Therefore, it does not allow for an absolute sustainability comparison to define absolutely sustainable systems, as would be expected from an ALCA method.

The ALCA-Reduction-targets method (Sandin et al., 2015) does not include a comparison between impact and some sort of benchmark, but only provides future impact reduction targets. Yet, over time the achieved impact reduction can be compared against such impact reduction targets to determine if the system is on track to become absolute sustainable.

Criterion: Flux/pulse handling

Only one method, the ALCA-Characterization$_{PBmetrics}$ method (Ryberg et al., 2018b), deals with the flux-pulse problem by making two adjustments: (1) Requiring that LCI flows are constant inputs (fluxes) instead of only inputs (pulses). Thus, the LCI results need to be formatted as a [mass/time] instead of [mass]. (2) Defining the FU in the LCA with a constant time duration, for example, an annual fulfillment of the function does that trick.

In this way, the method quantifies the annual impacts that occur by continuously fulfilling the FU. It should be noted that this only works under the implicit assumption of a continuous (steady-state) FU fulfillment. Only then one can assume that the impacts occur in the same year, whereas LCA impacts are in reality exerted over many years. Now, both LCA results and the SOS are quantified as annual fluxes, which allow for a just comparison. The handling of the flux/pulse mismatch within ALCA-Characterization$_{PBmetrics}$ is described in more detail in Appendix A10.

The other methods do not take care of the flux/pulse inconsistency between LCA and the PB-framework, nor do they identify it as a problem. In this way, if a method proposes an absolute sustainability comparison between impact results against SOS, it is implicitly assuming that these impacts are generated in one and the same year.

4.3.2 PB related criteria

This section gives an overview of the formulated environmental sustainability objectives, included planetary boundaries, included LCA impact categories (LCA-ICs) and variations in SOS quantification, across the publications. The criteria 'planetary boundaries included' and 'LCA-ICs included' only include publications that express the results in PB-metrics or LCA metrics, respectively. The application publications are included under the criteria 'PBs included', 'LCA-ICs included' and 'quantification of SOS' because many variations were observed, both between the applications and between the applications and used methods.

Criterion: Formulation of environmental sustainability objective

The sustainability objectives across methods were not always explicitly defined in the publications. Still, every publication somehow described the purpose of the introduced method, as listed in Table 10. Although described in different words, all these methods intend to provide insights in how transgression of the PBs/thresholds can be avoided. This is irrespective of how the SOS is used or the assessed entity to which a share of the SOS is allocated.

Table 10: Environmental sustainability objectives across methods

Method	*Sustainability objective extracted from publication*
ALCA-Normalization (Bjørn & Hauschild, 2015)	"Ecological impacts and resource intensities of product life cycles should be reduced to a level at least in line with the Earth's estimated carrying capacity." (p. 1006)
ALCA-Characterization$_{LCAmetrics}$ (Doka, 2016)	"Check if the life cycle burdens of a particular lifestyle or personal consumption pattern fits into the available planetary capacities." (p. 4)
ALCA-Characterization$_{PBmetrics}$ (Ryberg et al., 2018b)	"Quantifying the environmental performance of products and technologies in relation to Planetary Boundaries." (p. 250)
ALCA-Reduction-targets (Sandin et al., 2015)	"Respect the nine biophysical planetary boundaries to avoid risks of abrupt, non-linear environmental change causing functional collapses in ecosystems." (p. 1684)
ALCA-Weighting (Tuomisto et al., 2012)	"Meet the challenge of maintaining the stable state of the planet." (p. 148)

Criterion: Planetary boundaries included

Table 11 provides an overview of the coverage of PB control variables by the ALCA-Characterization$_{PBmetrics}$ method and its applications (denoted with an '**A**'), since these publications all express results in PB metrics.

Table 11: PBs included across publications expressing results in PB metrics

ESP	Novel entities	Climate change		Change in biosphere integrity		Stratospheric ozone depletion	Ocean acidification	Biochemical flows			Land system change		Freshwater use		Atmospheric aerosol loading	
PB Control variables	-	CO2 concentration	Radiative forcing: energy imbalance	Genetic diversity	Functional diversity	Stratospheric ozone depletion	Ocean acidification	Global, phosphorus flow	Regional, phosphorus flow	Global, fixation of nitrogen	Global original forest cover	Biome potential forest cover	Global blue water consumption	Basin, freshwater withdrawal	Global	Regional
ALCA-Characterization$_{PBmetrics}$ (Ryberg et al., 2018b)		V	V			V	V	V	V	V	V	V	V	V	V	V
A *(Ryberg et al., 2018a)*		V	V			V	V	V	V	V	V	V	V	V	V	V
A *(Andersen et al., 2020)*			V							V	V		V			
A *(González-Garay et al., 2019)*		V	V			V	V	V		V	V		V			
A *(Algunaibet et al., 2019)*		V	V			V	V	V		V	V		V			

The ALCA-Characterization$_{PBmetrics}$ method (Ryberg et al. 2018b) ensures a very large coverage of PB control variables. Most of these PB control variables were also included in the applications of this method. It can be noted that the PB control variables from the ESP 'Change in biosphere integrity' were not included in the method nor applications, which can be explained by the fact that characterization models are considered immature (Ryberg et al., 2016). The 'Novel entities' ESP was also not included because a PB value and control variable has yet to be defined (Ryberg et al., 2016).

Criterion: LCA impact categories included

Table 12 provides an overview of the coverage of LCA-ICs by the ALCA-Weighting, ALCA-Normalization, ALCA-Characterization$_{LCAmetrics}$, ALCA-Reduction-targets methods and their applications (denoted with an 'A'), since these publications all express results in LCA metrics.

Table 12: LCA-ICs included across publications expressing results in LCA metrics

LCA-IC	Climate change	Freshwater ecotoxicity	Water resource depletion	Photochemical ozone formation	Terrestrial acidification	Terrestrial Eutrophication	Freshwater eutrophication	Marine eutrophication	Land use, soil erosion	Land use, biodiversity
ALCA-Weighting (Tuomisto et al., 2012)	V		V							V*
A *(Tuomisto et al., 2012)*	V									V*
ALCA-Normalization (Bjørn & Hauschild, 2015)	V	V	V	V	V	V	V	V	V	V
A *(Brejnrod et al., 2017)*	V	V	V	V	V	V	V	V	V	V
A *(Wolff et al., 2017)*	V	V	V	V	V	V	V	V	V	V
A *(Andersen et al., 2020)*	V		V					V	V	
ALCA-Characterization$_{LCAmetrics}$ (Doka, 2016)	V		V	V						V
A *(Chandrakumar et al., 2019)*	V									
ALCA-Reduction-targets (Sandin et al., 2015)	V		V	V	V	V	V	V		V
A *(Sandin et al., 2015)*	V		V	V	V	V	V	V		V

* Tuomisto et al. (2012) used a different LCA-IC for land use: land occupation (ha).

The ALCA-Weighting method (Tuomisto et al., 2012) was introduced in 2012, before the publication of the second version of the PB framework (Steffen et al., 2015). Therefore, Tuomisto et al. (2012) build on the first version of the PB framework by Rockström et al. (2009) for the construction of PB-based weighting factors. They weren't able to solve conversion issues towards LCA-ICs, resulting in low LCA-IC coverage in their case study.

It can be noted that the ALCA-Normalization method (Bjørn & Hauschild, 2015) has a large coverage of LCA-ICs, which is also the case in this method's applications by Brejnrod et al. (2017) and Wolff et al. (2017). Andersen et al. (2020) also apply this method but include less LCA-ICs in the analysis, which could be explained by the fact that they simultaneously applied ALCA-Characterization$_{PBmetrics}$ for the sake of method comparison.

Similar to the ALCA-Weighting (Tuomisto et al., 2012), Doka (2016) was not able to include many LCA-ICs in the ALCA-Characterization$_{LCAmetrics}$ method, mainly due to the indicator mismatch problem. This problem restricts the LCA practitioner to, for example, phosphorus and nitrogen emissions at the LCI level, instead of at the acidification and eutrophication midpoint impact categories level. Chandrakumar et al. (2019) only included climate change due to lacking inventory data for the system in question.

The coverage by Sandin et al. (2015) is rather high, possibly explained by the fact that it is easier to assume that their percent wise impact reduction targets can be copied 1:1 from PBs to LCIA metrics.

Criterion: Quantification of SOS

All five methods utilized the PB framework (Rockström et al., 2009; Steffen et al., 2015) as quantification of the earth's CC. Yet, across the methods and their applications there appeared to be variation in how the SOS from the PB framework was interpreted and used. This is not necessarily problematic, since the methods with different characteristics require different concepts from the PB-framework. However, across publications there also appeared to be inconsistency in the terminology of PB related concepts, leading to confusion. Table 13 shows the inconsistencies across publications by listing the terms and providing an explanation of what the used terms actually represent in the publication.

Table 13: Inconsistencies in the terminology of PB-related concepts across publications analyzed in the review

Publication	*Term explicitly used in the publication*	*What the term actually represents in the publication*	*Comment*
(Tuomisto et al., 2012)	Safe operating space	PB value (lower limit of the uncertainty zone) of the control variable minus the current value of the control variable.	This expression of SOS deviates from the SOS as explained in the original PB framework. See section 2.3
(Sandin et al., 2015)			
(Bjørn & Hauschild, 2015)	Carrying capacity	The threshold (averages value of the uncertainty zone) for each control variable	In contrast to other methods, the threshold values are used instead of the PB values. See section 2.3
(Andersen et al., 2020)	Carrying capacity based safe operating space ($SOS_{CC,world,i}$)	The threshold (averages value of the uncertainty zone) for each control variable	This expression of SOS deviates from the SOS as explained in the original PB framework, because the threshold values are used instead of the PB values.
	Planetary boundary based safe operating space (SOS_{PB})	PB value (lower limit of the uncertainty zone) of the control variable minus the natural background value of the control variable	This expression of SOS deviates from the SOS as explained in the original PB framework. See section 2.3
(Ryberg,et al., 2018a)	Full safe operating space (SOS)		
(Ryberg, et al., 2018b)			
(Algunaibet et al., 2019)			
(González-Garay et al., 2019)			
(Wolff et al., 2017)	Environmental budget	The threshold (averages value of the uncertainty zone) for each control variable	-
(Doka, 2016)	Planetary boundary allowance	Differs for each PB and LCA-IC, but generally the PB value (lower limit of the uncertainty zone)	The planetary boundary allowance mostly corresponds to SOS as explained in original PB framework. See section 2.3

4.3.3 Allocation related criteria

This section first gives an overview of the basis of allocation within methods. Secondly, it presents the allocation principles used across methods and applications. Lastly, this section provides the documentation of allocation principles across publications. Applications are included under the latter two criteria because allocation is not always part of an ALCA method itself. Besides, it is interesting to show differences in allocation between applications of the same method.

Criterion: Basis of SOS allocation within method

When the impacts of a studied system have been quantified with one of the main methods, it can be compared against a benchmark, which generally resembles an allocated SoSOS, in order to define whether the system can be considered absolute (environmentally) sustainable.

Some methods inherently determine a benchmark and therefore also inherently apply an allocation step. For example, the ALCA-Normalization method (Bjørn & Hauschild, 2015) and the ALCA-Characterization$_{LCAmetrics}$ method (Doka, 2016) both determine a per-capita SoSOS and ensure that the results are expressed as the occupation of this per-capita SOS. The former by normalizing against per-capita SoSOS and the latter by characterizing impact such that the impact score directly reflects per-capita SoSOS occupation. In this way both methods allocate the full SOS on an equal per-capita basis amongst all individuals in a region, may it be the whole world. Here it should however be noted again that the SOS in the ALCA-Normalization method is determined with the threshold values whereas the SOS in the ALCA-Characterization$_{LCAmetrics}$ method is determined with the PB values (corresponding to the original PB framework). Also, it is important to realize that there is no allocation to a product-system, only to persons.

The ALCA-reduction-targets method (Sandin et al., 2015) does not quantify LCA impacts but determines impact reduction targets (RTs in %) against which (future) impacts can be compared. By doing so, they need to make two allocation steps. These two allocation steps entail a conversion factor to translate a global reduction target into a target specifically for a global market segment and a (regional) product within this segment, respectively. Details regarding these allocation steps can be found in Appendix A11.

The methods ALCA-Characterization$_{PBmetrics}$ (Ryberg et al., 2018b) and ALCA-Weighting (Tuomisto et al., 2012) don't provide guidance on allocation. The former only provides a new way of impact quantification and does not provide guidance on how SOS has to be allocated in order to get a benchmark for a product-system. The latter does not include a comparison against a benchmark at all and therefore no allocation is required.

Criterion: Allocation principle(s) used

Although the allocation of SOS is not involved in every method and neither is guidance on such allocation always provided, the applications of the methods did often apply an allocation of SOS in order to define whether a system can be considered as absolute sustainable. The results under this criterion, present the different allocation principles used across these applications, categorized according to the ALCA methods that were used. For the ALCA methods that were tested in multiple applications, patterns regarding allocation are identified where possible.

First, it is necessary to note that many different terms were observed across publications to describe certain allocation principles, which might lead to confusion. Therefore, Table 14, provides an overview of the explicit allocation principle terminology as observed in publications, versus how we implicitly interpreted the allocation principle (third column). These implicit terms were added because we state that all of the allocation principles can be classified into three main categories:

1. Egalitarian: Allocating the SOS equally (uniformly) among individuals.

This form of allocation can only be conducted on a per-capita basis. It wouldn't make sense to give every-product system for example an equal share.

2. Utilitarian: Allocating the SOS among competing anthropogenic entities based on an indicator that represents the utility of the activities

3. Grandfathering: Allocating SOS among competing anthropogenic entities based on their current contribution to current total environmental impact.

The name grandfathering comes from the fact that an entity inherits the right to emit in the future based on its emission in the future.

Table 14: Explicit terminology allocation principles and implicit interpretation within this thesis

Publication	*Explicit terminology for allocation principle used in the publication*	*How allocation is actually conducted in the publication*	*Implicit interpretation*
(Algunaibet et al., 2019)	Egalitarian principle	A combination of two allocation steps based on: Equal per capita Economic output measured in GVA	Combination of egalitarian and utilitarian
(Andersen et al., 2020)	Egalitarian principle	Equal per capita	Egalitarian
	Utilitarian principle	Allocation step based on either: Economic output measured in FCE Hours spent	Utilitarian
	Acquired rights principle	Allocation step based on either: Current impact activity (CO_2 emissions) relative to global impact Current energy activity relative to total energy use	Grandfathering
(Bjørn & Hauschild, 2015)	None[3]	Equal per capita	Egalitarian
(Brejnrod et al., 2017)	Egalitarian principle	Equal per capita	Egalitarian
	Allocation by economic value	Economic output measured in FCE	Utilitarian
(Chandrakumar et al., 2019)	Grandfathering principle	Current impact activity relative to global impact	Grandfathering
	Economic principle	Economic output measured in GVA	Utilitarian
	Agri-land principle	Land occupation	Utilitarian
	Calorific content principle	Calorific content	Utilitarian

[3] There is only a textual explanation that the CC is shared equally amongst individuals, see Appendix A3

(Doka, 2016)	None	Equal per capita	Egalitarian
(González-Garay et al., 2019)	Status quo principle	Current impact activity relative to global impact	Grandfathering
(Ryberg et al. 2018a)	Egalitarian	Equal per capita	Egalitarian
	Egalitarian	Economic output measured in FCE	Utilitarian
	Egalitarian	Economic output measured in GVA	Utilitarian
	Status quo	Current impact activity relative to global impact	Grandfathering
(Sandin et al., 2015)	Individual rights	Equal per capita	Egalitarian
	Historical rights market segment	Current impact activity relative to global impact	Grandfathering
	Historical rights individuals	Current impact citizens of a region relative to global impact	Grandfathering
	Historical debts	Equal per capita (cumulative population)	Egalitarian
(Wolff et al., 2017)	Individual ecological budgets principle	Equal per capita	Egalitarian
	Grandfathering principle	Current impact activity relative to global impact	Grandfathering
	Market share principle	Utility of company based on their consumer base	Utilitarian

Visualizations (presented in the following pages) have been made to show the subsequent allocation steps and allocation principles that were used during these steps, across publications. These visualizations first require some clarifications:

- The blue boxes are the entities among which the SOS has to be allocated (size is not on scale)
- Each green lane represents an allocation approach. Within such an approach there is a specific allocation principle for each translation from one entity to the next, represented by the white arrows. The allocation principles translate the PB global budgets to specific budgets for the systems analyzed in case studies.
- The dotted lines represent that the sum of the entities on the right equals the previous entity on the left.
- Table 15 clarifies the ID's that were used in these visualizations, representing a general allocation and allocation basis, in accordance with Table 14.

Table 15: ID clarification within visualizations of SOS allocation

ID	*General allocation principle*	*Allocation basis*
E1	Egalitarian	Equal per capita (current population of a region)
E2	Egalitarian	Equal per capita (cumulative population of a region)
G1	Grandfathering	Current impact of a specific activity (i.c. product system) relative to the total global impact of all activities (i.c. all product systems) in a specific year.
G2	Grandfathering	Current energy use of a specific activity (i.c. product system) relative to total energy use.
G3	Grandfathering	Current impact of a population in a region relative to the total global impact of citizens globally.
U1a	Utilitarian	Annual economic output of the product system relative to total global annual economic output (measured in GVA)
U1b	Utilitarian	Annual economic output of the product system relative to total global annual economic output (measured in FCE)
U2	Utilitarian	Annual land occupation of a product system relative to total global fertile land.
U3	Utilitarian	Calorific content of a product system relative to total global calorie supply (annual)
U4	Utilitarian	Average hours spent on using the product-system relative to a full day

Allocation within the applications of ALCA-normalization method (Bjørn & Hauschild, 2015)

The normalization references in this method were obtained by dividing (allocating) the SOS (defined by threshold values) by the current population of a region (e.g. the world or Europe). By doing so the SOS is already uniformly distributed amongst individuals, which corresponds to allocation based on the egalitarian allocation principle. The normalization references, which are actually SoSOS, are thus determined by an egalitarian allocation step that is already integrated in the method. Therefore, it is expected to see this first allocation step always across applications.

Figure 5, 6 and 7 visualize the allocation principles and their different allocation steps that were used to determine the benchmarks in Andersen et al. (2020), Brejnrod et al. (2017) and Wolff et al. (2017), respectively. Andersen et al. (2020) tested 6 allocation principles, whereas Brejnrod et al. (2017) and Wolff et al. (2017) tested only one allocation principle.

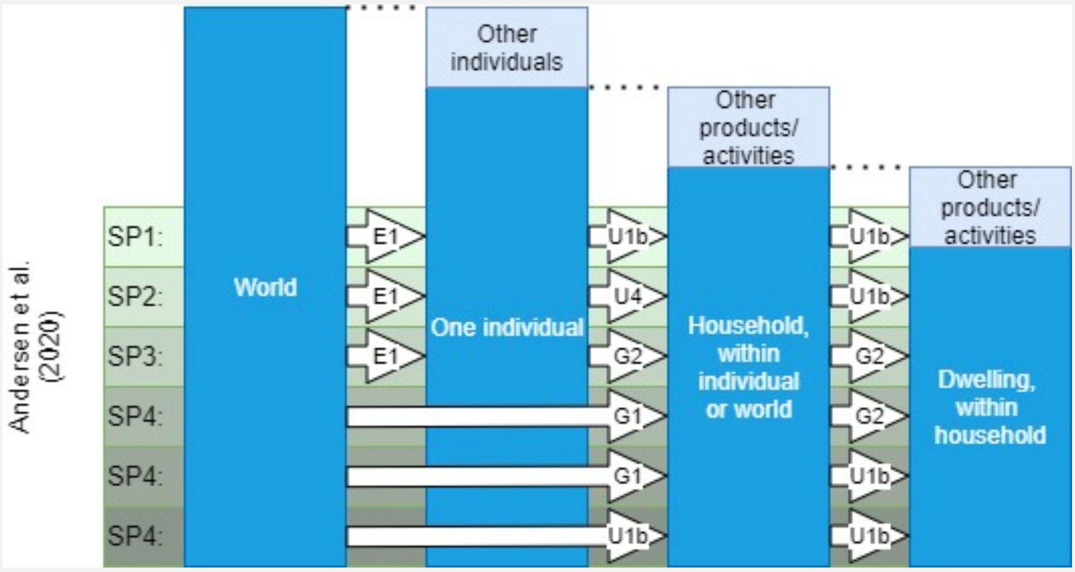

Figure 5: allocation principles (Andersen et al., 2020)

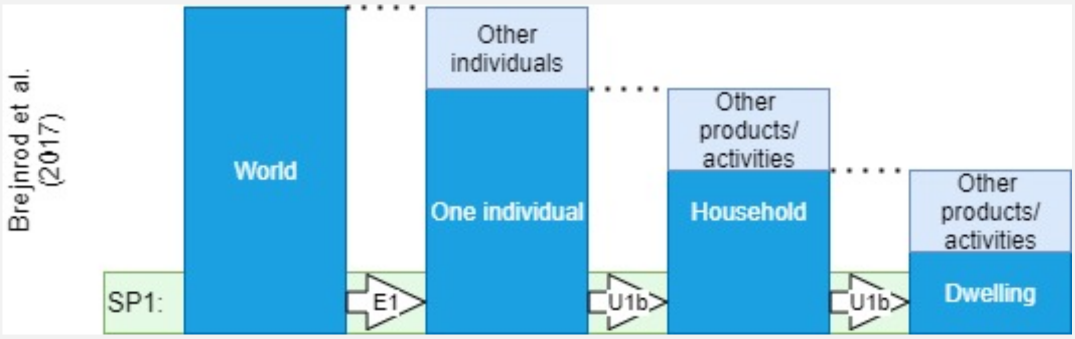

Figure 6: allocation principles (Brejnrod et al., 2017)

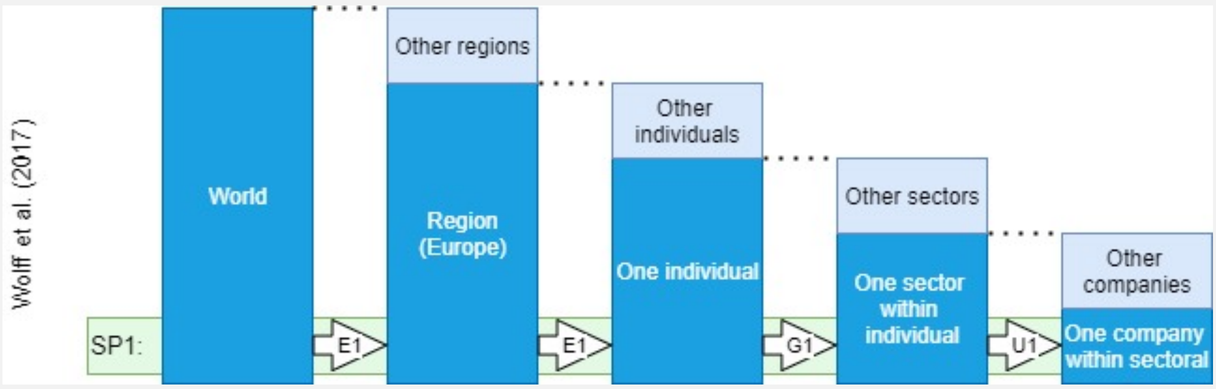

Figure 7: allocation principles (Wolff et al., 2017)

Patterns:

Allocation does not exist of just one step but rather can involve at least 3 and up to 5 different steps, each requiring a choice of allocation principle and allocation equation.

It can be noted that across all of these applications, except for three allocation principles (G1, G1 and U1b) in Andersen et al. (2020), the first step was always per-capita allocation based on the egalitarian principle. After the SOS had been allocated to one individual's SoSOS, further allocation steps were observed to obtain a benchmark within the individual SoSOS, specifically for the studied system. These subsequent allocation steps were conducted according to different variations of the utilitarian and grandfathering allocation principle.

Allocation within the applications of ALCA-Characterization$_{\text{LCAmetrics}}$ (Doka, 2016)

The characterization factors in this method are determined such that impact is expressed as an occupation of the per-capita SoSOS. In the summary of this method (section 4.2) we already identified that a per-capita SoSOS is first derived in the method by uniformly distributing the SOS amongst the population of a region (e.g. the world or Europe). However, instead of using the current population, Doka (2016) uses a predicted future population of 10 billion people, in order to ensure that the SoSOS of current citizens is equal to the SoSOS of future citizens. Allocating the SOS uniformly among individuals corresponds to allocation based on the egalitarian allocation principle. Since this egalitarian allocation step is integrated in the method, it is expected to see this first allocation step always in applications.

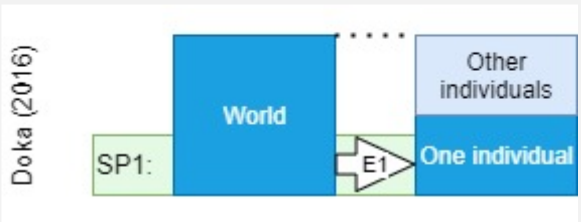

Figure 8: allocation principles (Doka, 2016)

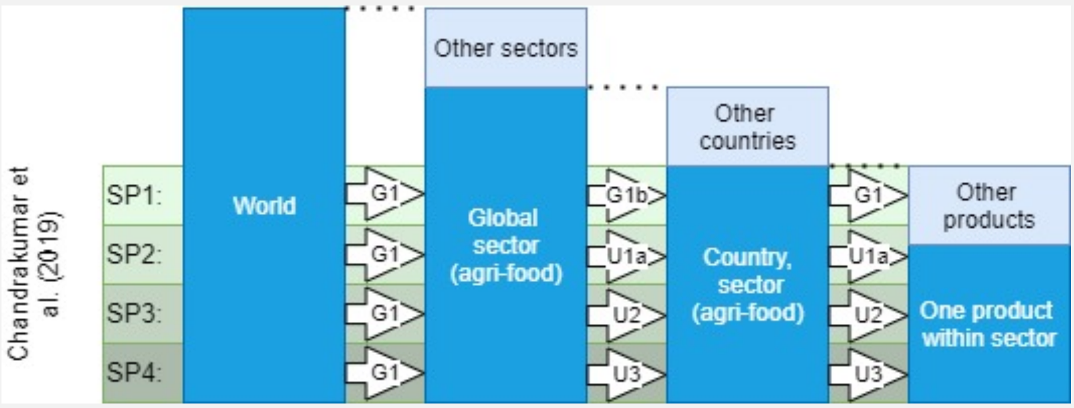

Figure 9: allocation principles (Chandrakumar et al., 2019)

Although applying the ALCA-Characterization$_{LCAmetrics}$ method, Chandrakumar et al. (2019) did not apply the egalitarian principle in their first or any other allocation step. Rather, combinations of the grandfathering and utilitarian principles were used.

Allocation within the applications of ALCA-Characterization$_{PBmetrics}$ (Ryberg et al., 2018b)

As explained under the criterion "basis of SOS allocation within method'', there is no guidance on allocation in the ALCA-Characterization$_{PBmetrics}$ method. Therefore, a practitioner can freely choose which allocation steps and allocation principles are applied to determine the benchmark for a system.

Figure 10, 11, 12 and 13 visualize the allocation principles and their different allocation steps that were used to determine the benchmarks in Algunaibet et al. (2019), Andersen et al. (2020), González-Garay et al. (2019) and Ryberg et al. (2018a). Andersen et al. (2020) and Ryberg et al. (2018) tested 6 and 4 allocation principles, respectively, whereas both Algunaibet et al. (2019) and González-Garay et al. (2019) tested only one allocation principle.

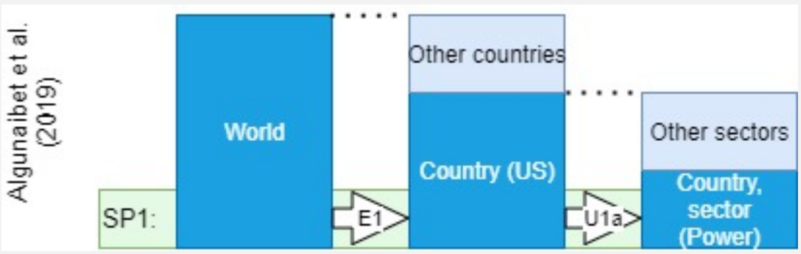

Figure 10: allocation principles (Algunaibet et al., 2019)

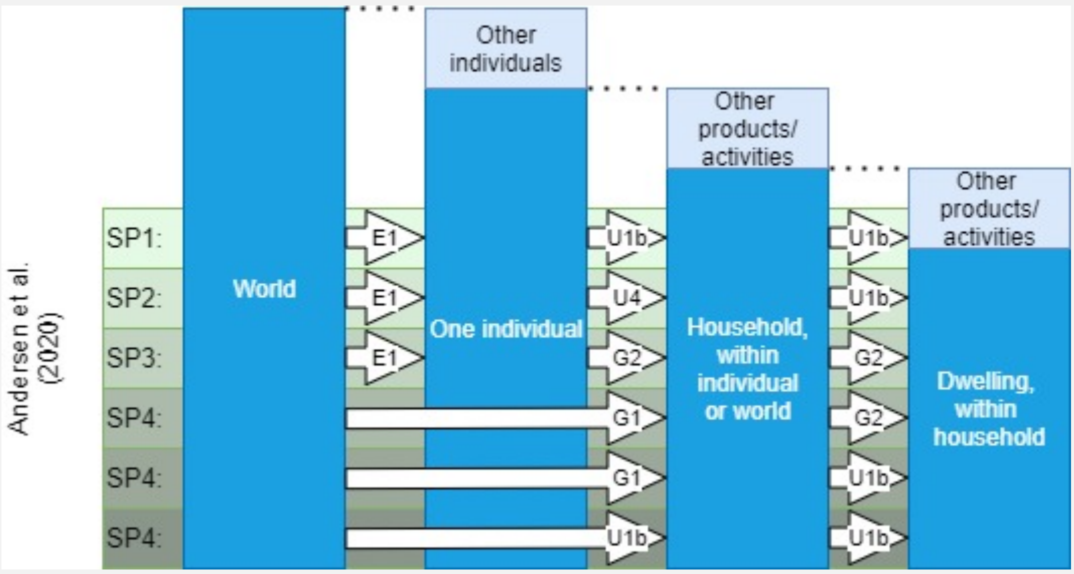

Figure 11: allocation principles (Andersen et al., 2020)

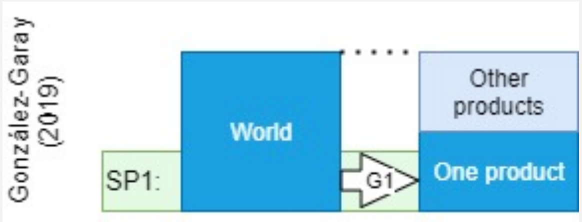

Figure 12: allocation principles (González-Garay et al., 2019)

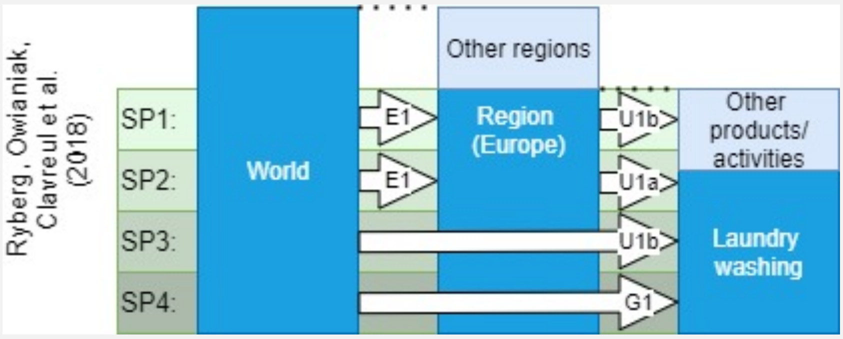

Figure 13: allocation principles (Ryberg et al. 2018a)

Patterns:

It can be noted that across these applications, it is common to do the first allocation step capita based with an egalitarian allocation principle (whether the SOS is allocated to the population of a region or directly to an individual). Only the three allocation principles in Andersen et al. (2020) and the sole allocation principle used in González-Garay et al. (2019) first allocated based on a grandfathering or utilitarian allocation principle. In most applications, the first allocation step was followed by one or two subsequent allocation steps according to different variations of the utilitarian and grandfathering allocation principle.

Allocation within the applications of ALCA-reduction-targets (Sandin et al., 2015)

The ALCA-reduction-targets method (Sandin et al., 2015) is in itself a procedure to determine the benchmark. This benchmark is however not a certain quantity of impact but a percent wise impact reduction target. In their publication, Sandin et al. (2015) also apply the method to a case on the Swedish clothing sector, for which they used 4 different allocation principles to translate global reduction targets to sector-specific reduction targets. These allocation principles were based on two variations of the egalitarian and grandfathering allocation principle.

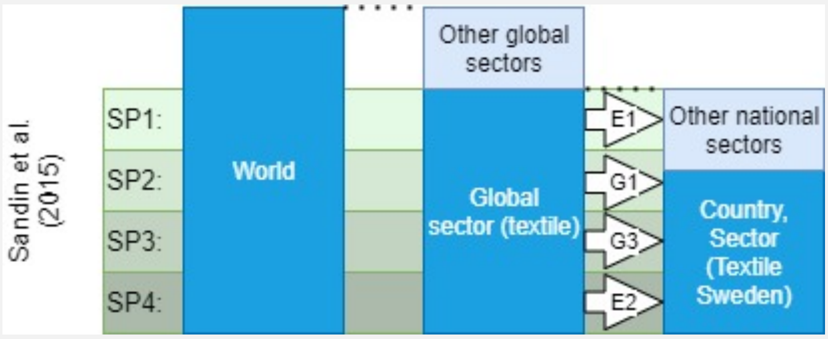

Figure 14: allocation principles (Sandin et al., 2015)

Criterion: Documentation of principle(s)

As shown in Figure 15, the explicit documentation of the choice of allocation principles was present in most publications, meaning that the authors wrote which allocation principle and allocation basis was used to determine the benchmark. Note that this doesn't imply that the limitations and subjectivity of principles was also always explained across all publications.

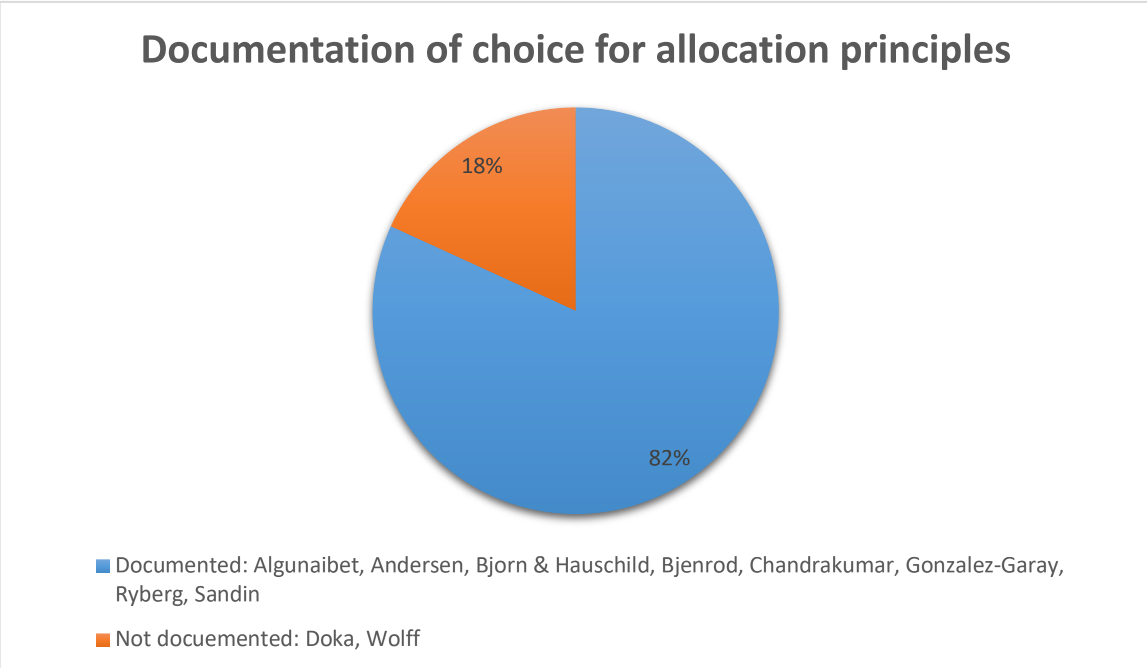

Figure 15: Documentation of used allocation principles across publications.

5 Discussion

This chapter presents a discussion and reflection on the results. In section 5.1, we first provide a terminology proposition to take away confusion due to inconsistent use of PB-related terms across publications. Then, section 5.2 presents a discussion on the extent to which methods comply with the definition of ALCA and the type of questions they can answer. Additionally, a final overview of ALCA based on the methods is provided in this section. Thereafter, 5.3 provides a discussion on the use of allocation principles across methods and applications. In 5.4 the consequences of the flux-pulse inconsistency in ALCA methods are discussed. In 5.5 there is an overview of the potential of ALCA methods in the context of SDGs. Finally, 5.6 and 5.7 provide recommendations for the scientific domain and PRé Sustainability, respectively.

5.1 Use of the PB-framework and terminology

From Table 13, it became clear that there are inconsistencies in the use of PB related terms across publications that were included in the review. To clarify how different PB related concepts relate to - or result from - each other, we created a visualization (Figure 16) that has been adjusted from Steffen et al. (2015).

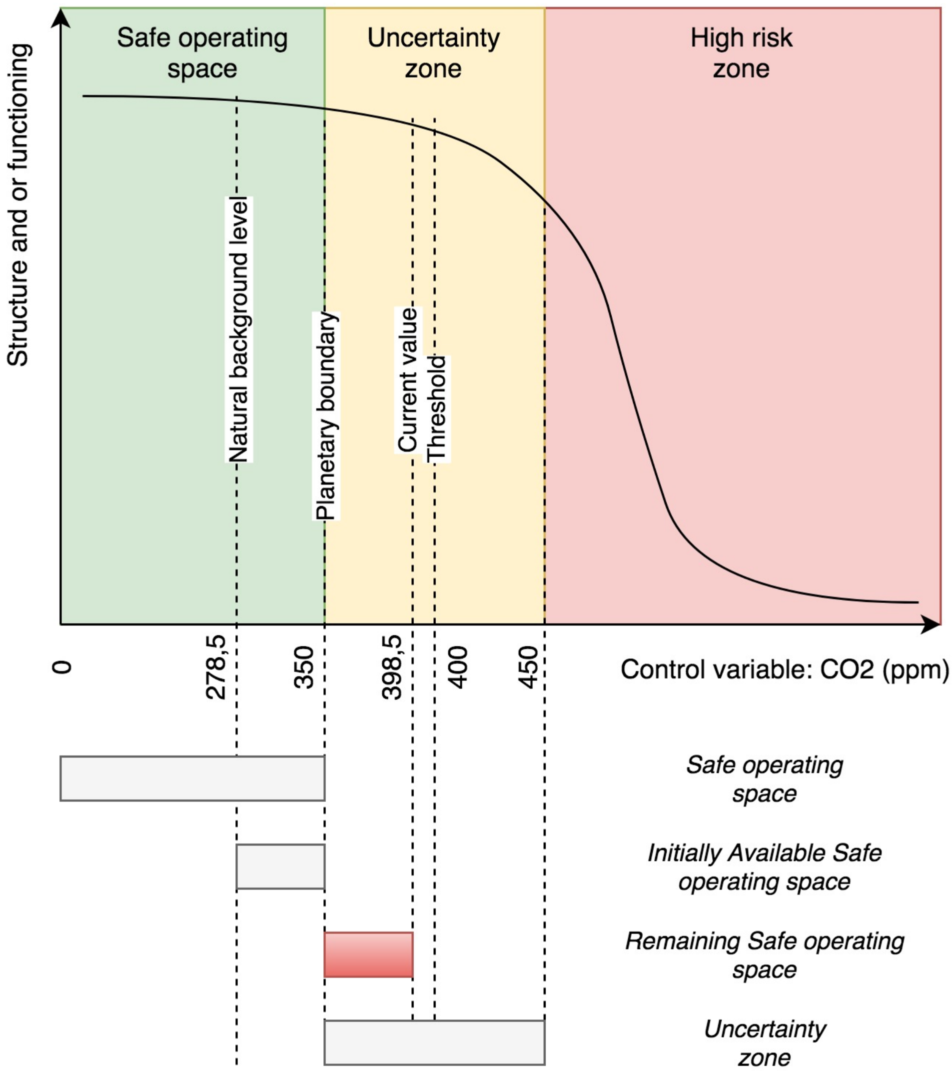

Figure 16: Visualized terminology of PB related concepts, adjusted from Steffen et al. (2015). (The bar representing remaining safe operating space is colored in red to indicate that it is negative because the current value exceeds the planetary boundary).

Complementing to the visualization, Table 16 provides a proposition for definitions and abbreviations for these varying PB related concepts. Definitions were either formulated or adopted from other publications and referenced as such. Each term is also accompanied with an example from the PB framework.

Table 16: Terms, abbreviations and definitions of PB related concepts

Term	*Abbrev.*	*Definition*	*Example*
Carrying capacity	CC	The maximum sustained environmental intervention a natural system can withstand without experiencing negative changes in structure or functioning that are difficult or impossible to revert (Bjørn & Hauschild, 2015) *Note: Should be seen as an umbrella concept. Thus, the PBs are just one form of expressing CC.*	PBs represent one possible implementation of CC
Earth system process	ESP	A biophysical subsystem or process of the earth that has a critical function in maintaining the earth's Holocene state, and of which its function can be disturbed if subjected to excessive anthropogenic pressures.	Climate change
Control variable	-	A quantifiable indicator in which impacts and a limit in a certain ESP can be expressed.	Atmospheric CO_2 concentration
Unit	-	The unit used to express the dimension of the control variable. *Note: A control variable might however also be dimensionless, for example a percentage.*	Parts per million (ppm)
Threshold	-	The maximum numerical value of a control variable that expresses a limit above which the function or structure of earth system process might be irreversibly disturbed. *Note: this definition was adjusted from Bjørn et al. (2016)*	400 ppm CO_2 (Steffen et al., 2015)
Uncertainty zone	-	The range of uncertainty in the determination of the threshold. *Note: The zone represents an area of increasing risk.*	350 –> 450 ppm CO_2 (Steffen et al., 2015)
Planetary Boundary value	PB	The value of a control variable, corresponding to the lower value of the uncertainty zone, that, depending on the risk humanity is willing to take, is chosen as a boundary level which shouldn't be transgressed. *Note: Within Rockström et al. (2009) and Steffen et al. (2015) a precautionary principle is used, meaning that for control variables for which a higher value represents an increased risk, the lower value of the uncertainty zone is chosen as the PB value (and vice versa).* *Note that 'PB value' is different from the previously defined 'PB', representing the general concept.*	350 ppm CO_2 (Steffen et al., 2015)

Current value	-	The current numerical value of a control variable. *Note: The word 'current' might be misleading if the value actually reflects the situation of a year in the past, which emphasizes the need to communicate the year that corresponds to the value.*	398,5 ppm CO2 (Steffen et al., 2015)
Natural background level	NB	The value of a control variable representing the situation before the pre-industrial revolution. *Note: This is under the assumption that, before the pre-industrial revolution, anthropogenic pressures had a negligible effect on the control variable.*	278,5 ppm CO2 (Ryberg et al., 2018a)
Safe Operating Space	$SOS_{0>PB}$	The full range of possible numerical values of a control variable from zero until the PB value. *Note: This is how SOS was originally presented in the PB framework* (Steffen et al., 2015).	0 -> 350 ppm
Initially Available Safe Operating Space	$SOS_{in,av}$	The part of the SOS that was initially available for anthropogenic activity since the beginning of the Anthropocene, defined as the PB minus the NB. $SOS_{in,av}$ = PB – NB	350-278,5 = 71,5
Remaining Safe Operating Space	SOS_{rem}	The part of the available safe operating SOS_{av} that is still remaining in a certain year, defined as the PB minus the current value. SOS_{rem} = PB - current value *Note: This value can thus be negative if the PB has already been transgressed.*	350-398,5 = -48,5
Share of Safe Operating Space	$SoSOS_i$	A share of the SOS that is assigned to a specific anthropogenic activity. The sum of SoSOS should equal the SOS from which they are derived. $SOS_i = \sum SoSOS_i$ *Note: The 'i' in the abbreviation denotes that also any of the above listed variations of SOS can be used ($SOS_{0>PB}$ or $SOS_{in,av}$ or SOS_{rem})*	-

To show that this terminology proposition is adequate for describing research in the PB and ALCA domain, Table 17 again lists the terminology inconsistencies across the publications reviewed but is now complemented with a fourth column in which the abbreviations from our own proposition are given.

Table 17: Corrected terms (abbreviations) following terminology proposition

Publication	*Term explicitly used in the publication*	*What the term actually represents in the publication*	*Correct term according to our proposition*
(Tuomisto et al., 2012)	Safe operating space	PB value (lower limit of the uncertainty zone) of the control variable minus the current value of the control variable.	SOS_{rem}
(Sandin et al., 2015)			
(Bjørn & Hauschild, 2015)	Carrying capacity	The threshold (average value of the uncertainty zone) for each control variable	Threshold
(Andersen et al., 2020)	Carrying capacity based safe operating space ($SOS_{CC,world,i}$)	The threshold (averages value of the uncertainty zone) for each control variable	Threshold
	Planetary boundary based safe operating space (SOS_{PB})	PB value (lower limit of the uncertainty zone) of the control variable minus the natural background value of the control variable	$SOS_{in,av}$
(Ryberg et al., 2018a)	Full safe operating space (SOS)		
(Ryberg et al., 2018b)			
(Algunaibet et al., 2019)			
(González-Garay et al., 2019)			
(Wolff et al., 2017)	Environmental budget	The threshold (averages value of the uncertainty zone) for each control variable	Threshold
(Doka, 2016)	Planetary boundary allowance	Differs for each PB and LCA-IC, but generally the full SOS	$SOS_{0>PB}$

To prevent confusion, it's important for the ALCA community to find consensus within the use of terms and to apply them consistently. Especially because methods involve a combination of LCA and PB research which both have their own terminology. Inconsistencies in terminology were mostly found for PB related concepts. Recently, a review article has been published by Bjørn, et al. (2020) in which some terms have been defined and accompanied with synonyms. Similar definitions were given compared to our definitions for ALCA and CC. However, they do not use PB-related concepts. For example, they used the general term 'assigned carrying capacity' where we use the term 'SoSOS'.

With the terminology proposition, we are able to distinguish four different variations in which the PB framework was used across methods:

1. The remaining safe operating space (SOS_{rem}) was used in ALCA-Reduction-targets and ALCA Weighting
2. The initially available safe operating space ($SOS_{in,av}$) was used in ALCA-Characterization$_{PB\text{-}metrics}$
3. The full safe operating space delimited by the PB values ($SOS_{0>PB)}$) was used in ALCA-Characterization$_{LCA\text{-}metrics}$
4. Fourth, the threshold values were used in ALCA-Normalization.

Considering these differences in using the PB framework, it is likely that the methods will generally provide different conclusions on absolute sustainability of a system, if they are applied in the same assessment. This was also the case in the one application (Andersen et al., 2020), that used two methods, ALCA-normalization and ALCA-Characterization$_{\text{PB-metrics}}$. Knowing that the threshold is a larger value than the PB value, the SoSOS in the ALCA-normalization will be larger than the SoSOS in ALCA-Characterization$_{\text{PB-metrics}}$. This is argued by Andersen et al. (2020) as a possible cause for the fact that ALCA-normalization finds more product-systems (dwellings) to be absolutely sustainable in their case study.

There are several flaws of using SOS$_{rem}$ according to Ryberg et al. (2018):

1. SOS$_{rem}$ is not relevant for assessing whether a product-system contributes to humanity's ability to maneuver in the full safe operating space. By using SOS$_{rem}$ a practitioner actually pre-allocates a share of the SOS to existing anthropogenic activities according to grandfathering allocation, leaving the SOS$_{rem}$ for new activities.
2. For PBs that have already been transgressed, the SOS$_{rem}$ will be negative, meaning that all new activities would be absolute unsustainable if they exert any net-positive impact. This would then discourage the sustainability transition.

We argue, however, that using SOS$_{rem}$ is not necessarily problematic in all cases, because these flaws don't apply to ALCA-Reduction-Targets and ALCA-Weighting use. Setting impact reduction targets and the determination of weighting factors should be based on the current state of the environment in order to represent which ESPs or impact categories are most critical in the present. Using the SOS$_{rem}$ results in impact reduction targets of 100% for PB values that have already exceeded but it is not unrealistic that such reduction can eventually be achieved, although likely not overnight. Using the full SOS here would neglect that there is no more room left for impact in certain PB's.

Due to the general mismatch between PBs and LCA-ICs, there also needs to be common ground in defining the impact categories used in ALCA research. This is complicated even more due to the existence of different LCIA methods each having their own ICs. A steppingstone for finding such common ground could be the mapping of PBs and their LCA equivalents (at either LCIA or LCI level) on a DPSIR framework (Chandrakumar & Mclaren, 2018), to expose which categories require conversions which in turn likely lead to terminology confusion. It should be noted that most, but not all ALCA methods, have to deal with conversions across DPSIR due to the PB and LCA-IC mismatch. This was already mentioned as one of the advantages of ALCA-Characterization$_{\text{PB-metrics}}$ (Ryberg et al., 2018b).

5.2 Discussion of ALCA methods

The results showed that there are 5 main methods in the ALCA domain. In this section, there is a reflection on the degree to which these 5 main methods can be regarded as actual ALCA methods, in consideration of the ALCA definition provided in this thesis (see section 2.2). It is also discussed which type of question a method can answer and what kind of conclusions it enables.

5.2.1 Methods in relation to ALCA definition

In section 2.2 the concept ALCA was defined as: *A subset of absolute environmental sustainability assessment methods that implement a comparison of a system's life-cycle based impacts applying LCA against a carrying capacity-based benchmark, specifically allocated to that system, in order to identify whether the product-system is absolutely sustainable*.

Looking at this definition we can identify that an ALCA method needs to contain (or at least be compatible with) three elements:

1. The quantification of product-system's life-cycle based impacts

2. The determination of an absolute benchmark that is specifically allocated to the product-system
3. A comparison between element 1 and element 2.

Table 18 gives an overview of whether these three elements are present in the 5 methods identified in the review, and whether they can therefore be considered as actual ALCA methods. We can conclude that only ALCA-characterization$_{PB\text{-}metrics}$ is really an ALCA method because it includes (or is at least potentially compatible with) all three elements. The other methods either do not include an absolute sustainability comparison at all (ALCA-weighting), only include a comparison against a per-capita benchmark (ALCA-characterization$_{LCA\text{-}metrics}$ & ALCA-normalization), or only enable a future comparison between achieved percent-wise impact reduction and a percent-wise reduction target.

Table 18: Presence of ALCA elements in methods

	ALCA elements from definition:			
	Life-cycle based impact quantification	Benchmark System specific	Absolute sustainability comparison	ALCA?
ALCA-weighting	Yes (separate)	No	No	No
ALCA-reduction-targets	Yes (separate)	No (reduction percentage for future)	Semi (future reduction against target)	Semi
ALCA-normalization	Yes (separate)	No (per capita)	Semi (against per capita benchmark)	Semi
ALCA-characterization LCA-metrics	Yes (in method)	No (per capita)	Semi (against per capita benchmark)	Semi
ALCA-characterization PB-metrics	Yes (in method)	Yes (separate)	Yes	Yes

Hereafter follows a more detailed explanation about why the 5 methods can or can't be considered as actual ALCA methods.

ALCA-weighting

Question that can be answered: Which product-system out of multiple alternatives is comparatively most environmentally sustainable based on an aggregated single score?

This method implements an adjusted form of traditional weighting usable in comparative LCA, to determine the most sustainable products system out of multiple alternatives, by comparing aggregated single scores. The method does not define a benchmark (by allocating a SoSOS to a specific product system) and does not involve a comparison between impact and such a benchmark. Therefore, it does not have the potential to identify absolute sustainable product-systems and is thus not truly an ALCA method.

A difficulty when operationalizing this method, even in comparative LCA, is that ISO 14044 standards do not allow weighting in "LCA studies intended to be used in comparative assertions intended to be disclosed to the public" (ISO 2006), because of the subjective nature of this step. Although this method attempts to take away this subjectivity by basing the weighting factors on biophysical parameters, the conflict with the ISO guidelines is still problematic for wider adoption.

ALCA-reduction-targets

Question that can be answered: What is the required impact reduction of a product-system?

This method is not a variation of LCA but does entail a procedure to determine percent-wise reduction targets based on the SOS_{rem} within each ESP, in turn copied 1:1 to related LCA-ICs. By using the ALCA-reduction-targets methods, a practitioner can't identify whether a product is absolute sustainable in the present. There is no benchmark against which current impacts can be compared. Yet, impact reduction targets can be seen as a form of future benchmarks. They provide guidance on the amount of impact reduction that is needed in the future to become absolute sustainable at a global scale, assuming that all products-systems have to do their part in this attempt.

Assuming that all product-systems do their part, a specific product-system could be considered absolute sustainable if its impact reduction is sufficient. This means that it has to meet the impact reduction target that was demanded by the ALCA-reduction-targets method. Consequently, product-systems which exert impact in ESPs where no SOS_{rem} is left (PB value transgressed), can never be absolute sustainable.

ALCA normalization and ALCA-Characterization$_{LCAmetrics}$

Question that can be answered: How much of the per-capita SoSOS does a product-system occupy?

Both ALCA-normalization (Bjørn & Hauschild, 2015) and ALCA-Characterization$_{LCAmetrics}$ (Doka, 2016) ensure that they produce impacts that are normalized against per-capita SoSOS. The difference between these methods is that ALCA-Characterization$_{LCAmetrics}$ starts with the life cycle inventory and implements a characterization step through which the impacts are simultaneously normalized, whereas ALCA-normalization starts with (ILCD) characterization results and then implements normalization using normalization references.

They both have the limitation that there is no guidance on further allocation of per-capita SoSOS among competing product-systems. There is thus no benchmark defined that is specifically allocated to the product system. For this reason, the methods do not enable a conclusion about whether a specific product system is absolute sustainable, but rather its occupation of an individual's SoSOS. Because both methods express results as the occupation of per-capita allocated SoSOS, these methods are particularly suitable for analyzing sustainable lifestyles. They could answer the question of whether an individual's impact budget is transgressed by one or a set of products/services. Moreover, they enable a practitioner to identify which products and consumption types are most accountable for exceeding total individual SoSOS.

Further, it is a limitation that both methods restrict the practitioner to a per-capita analysis, making the methods unsuitable for assessments in where a per-capita benchmark is not relevant. For example, assessments where the system serves the demands of multiple individuals. In some cases, this issue can be solved by multiplying per-capita SoSOS by the equivalent amount of individuals that a system fulfills in their needs, such as housing (Brejnrod et al., 2017) or food consumption (Wolff et al., 2017).

ALCA-characterization$_{PB\text{-}metrics}$

Question that can be answered: Is a product-system absolute sustainable based on a comparison between its impact and a benchmark specifically allocated to that system?

The ALCA-characterization$_{PB\text{-}metrics}$ method enables a practitioner to assess the absolute sustainability of a specific product-system by making a direct comparison between impact generated and determined SoSOS, which are both expressed in the units of control variables. Unlike ALCA-normalization and ALCA- characterization$_{LCA\text{-}metrics}$ which allocate a SoSOS per-capita, ALCA-characterization$_{PB\text{-}metrics}$ allocates a SoSOS specifically towards the product-system. Guidance on how this allocation should be done is however not included in the method itself. Nevertheless, this method complies best with the definition of ALCA.

Another advantage of this method is that: by the expression impacts in PB metrics, results become more usable and meaningful for (non-)scientists and decision makers (e.g. business or political) that are already familiar with the PB-framework but not with LCA.

5.2.2 Final ALCA overview

Figure 17 visualizes a main framework of ALCA. Similar to the previously introduced Figure 2 (section 2.2), and in accordance with the ALCA definition, the absolute sustainability comparison is placed at the heart of Figure 17. Consequently, a method such as ALCA-weighting that is not at all related to such an absolute sustainability comparison was not included in the visualization. The visualization is only including the 4 methods that involve – or are compatible with a general absolute sustainability comparison; ALCA-Characterization$_{LCAmetrics}$, ALCA-Characterization$_{PBmetrics}$, ALCA-Normalization and ALCA-Reduction-Targets. The visualization gives a full overview of the concepts that are involved in ALCA. It provides insight in how the methods position themselves in relation to the different activities and decisions that a practitioner encounters when conducting an ALCA. Visual patterns and color-coding are used to indicate which combinations of elements lead to which (final) results. For example, the 'Remaining SOS' has a blue color. Since it is used to determine impact reduction targets in ALCA-Reduction targets, the benchmark type 'impact reduction target' also gets a blue color. Similarly, the impact assessment methods ILCD, ALCA-Characterization$_{LCA\text{-}metrics}$ and ALCA-Normalization have a striped pattern, to indicate that they all express impacts in LCA metrics (which also has a striped pattern). The same principles apply to the three types of absolute sustainability conclusions in the visualization.

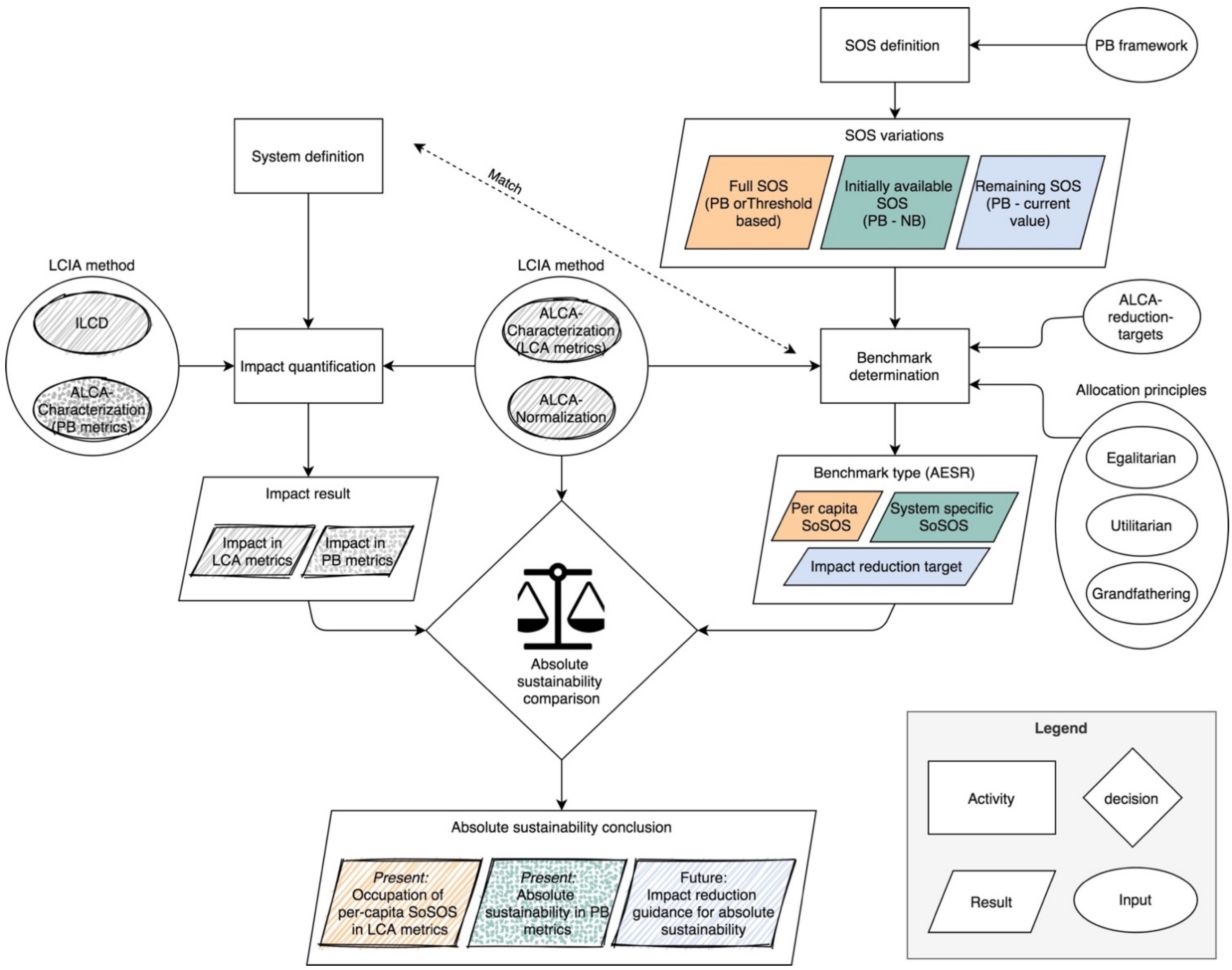

Figure 17: ALCA framework based on 4 ALCA methods

5.3 Allocation

The results showed that some methods, ALCA-Characterization$_{\text{LCA-metrics}}$ and ALCA-normalization, implicitly implement allocation of the SOS on a per-capita basis, using the egalitarian principle. Also in many applications of the ALCA-Characterization$_{\text{PB-metrics}}$ and ALCA-Reduction-targets, the first allocation step was conducted on a per-capita basis using the egalitarian principle. This raises the question: Why is there a tendency to allocate the SOS among individuals? This is likely because sustainability is inherently a human problem and is always related to anthropogenic activity. This makes an individual a logical starting point to make the comparison between generated impact and allocated SOS in order to define whether anthropogenic activities can be considered absolute sustainable.

Allocating SOS directly to product-systems using grandfathering or utilitarian allocation principles can lead to a disproportionally high SoSOS if that product-system has a large current impact or high economic value. Current impact and economic value are not necessarily good representations of what is most important for societies. They would rather support the further unequal division of wealth and resources because polluting or economically profitable product-systems receive much higher SoSOS than low-impact systems. This is probably why many ALCA applications do not directly allocate towards product-systems using grandfathering or utilitarian principles, but first allocate on a per-capita basis using the egalitarian allocation principle. After this first step, it is still possible to further allocate the per-capita SoSOS to a specific product system using grandfathering or utilitarian allocation principles. The egalitarian allocation principle is sometimes considered as most defendable from a morality perspective. The principle ensures that each individual is entitled to the same SoSOS, an environmental budget that can be seen as an environmental salary. The impact from all product-systems within an individual's consumption pattern have to fit in this per-capita SoSOS. Analyzing a product-system's occupation of this SoSOS gives a rough estimate of whether the product system is likely absolute sustainable or not.

There is a need to find common ground regarding the choice for allocation principles to determine SoSOS, not only for product-systems but for all anthropogenic entities (nations, individuals, companies, sectors, products etc). Otherwise, there is a risk that allocation principles are chosen based on what is most beneficial for claiming absolute sustainability in independent cases. This inherently makes the absolute sustainability conclusions less strong or could in the worst case even be labeled as a form of greenwashing. An example from our review is found in the ALCA-Characterization$_{\text{PB-metrics}}$ application from González-Garay et al. (2019). They argue that their product-system is absolutely sustainable because the quantified impact is lower than the allocated SoSOS, even though they conducted the allocation solely using the grandfathering principle and did not reflect on whether such allocation is just and supported by the ALCA community and larger society.

Another problem regarding the inconsistent use of allocation principles is that it hampers the conceptual viability of ALCA research. After all, there is a conceptual condition that the sum of SoSOS needs to equal the initial SOS on which they were based. This can't be the case if each practitioner is free to choose their own allocation approach, whether the approach is defended or not.

Given the fact that consensus on the use of certain allocation principles is still lacking, and the choice for an allocation principle is often the largest source of uncertainty in ALCA (Ryberg et al., 2018a; Sandin et al., 2015), Ryberg (2018a) suggests to always test multiple allocation principles in case studies. Doing so, researchers might prove that a certain system can be considered absolute sustainable independent of the allocation principle chosen, which dramatically strengthens the credibility of the assessment and conclusion.

The results (Table 14) pointed out that there are also many inconsistencies in terminology around allocation. For describing allocation based on the grandfathering allocation principle there were already four different terms observed: acquired rights, historical rights, status quo, grandfathering. Further, there is confusion created by classifying allocation based on economic value as utilitarian in some cases (Andersen et al., 2020) and egalitarian in others (Ryberg et al. 2018a). This might be explained by the absence of guidance on allocation within the ALCA-Characterization$_{\text{PB-metrics}}$ method. As explained in the results, we tried to take away the confusion that emerges due to inconsistent use of allocation principle terminology, by classifying the principles in three main categories with clear definitions: egalitarian, utilitarian, grandfathering. Nevertheless, it is important in any assessment to clarify on which indicator basis the allocation is actually conducted.

Also, there is a need to clarify if an allocation principle actually consists of multiple allocation steps, possibly also involving different allocation principles. If that is the case it should also be reflected in the terminology. For example, Andersen et al., (2020) clearly describe a combination: "sharing principle 2 = egalitarian + utilitarian", whereas Algunaibet et al. (2019) refers to egalitarian allocation while they actually apply a combination of egalitarian (equal per capita) and utilitarian (economic output measured in GVA) allocation in their assessment.

Finally, it should be noted that many allocation principles that are used in ALCA originate from climate science and distributive justice theory. A separate short literature review was done on allocation principles developed within these scientific domains (Appendix B). The terminology from these disciplines was however not used in this thesis because it deviated too much from the terminology that was used across the selected ALCA publications. Still, interesting lessons can be learned from these scientific domains. For example, next to the egalitarian allocation principle, other allocation principles are proposed that prioritize countries (and thus individuals) that have been disadvantaged in the past. Especially developing countries argue that applying egalitarian allocation (uniformly distributing SOS) is not equitable. For example, in the past decades especially developed countries generated large economic growth but caused the approximation or transgression of PB values along the way. Developing countries also want to achieve such socio-economic development but now have to comply with environmental targets which might restrict their development. Moreover, the effects of environmental problems are generally more severe in developing countries (Thomas et al., 2008). Therefore, there is also a moral ground for supporting allocation principles where the determination of a SoSOS is inversely proportional to cumulative emissions (the polluter pays) or based on wealth and capacity (ability to pay).

5.4 Flux-pulse problem

We identified that there is a conceptual inconsistency between LCA impacts and the PBs. LCA impacts represent total quantities of impact without a time dimension (pulses). Moreover, these impacts are exerted over many years. On the other hand, the PB framework proposes limits of annual impacts, fluxes having a time dimension. This makes it conceptually impossible to compare a SoSOS based on the PB framework and the impacts from a product-system in order to determine absolute sustainability.

Only in ALCA-Characterization$_{PB\text{-}metrics}$ there was an attempt to solve the flux-pulse problem by assuming a continuous fulfillment of the FU. In other words, they assumed a steady-state situation to convert the pulses into annual fluxes. With a continuous FU, the total impacts of all processes from one life cycle equal the total annual impacts from the same processes from overlapping life cycles, as shown in Figure 18. This means that they assume that past impacts from certain processes (e.g. the construction of a factory) are still exerted in the same quantity in the present (the same factory is build every year). That is not the case in reality where technology improves or is substituted.

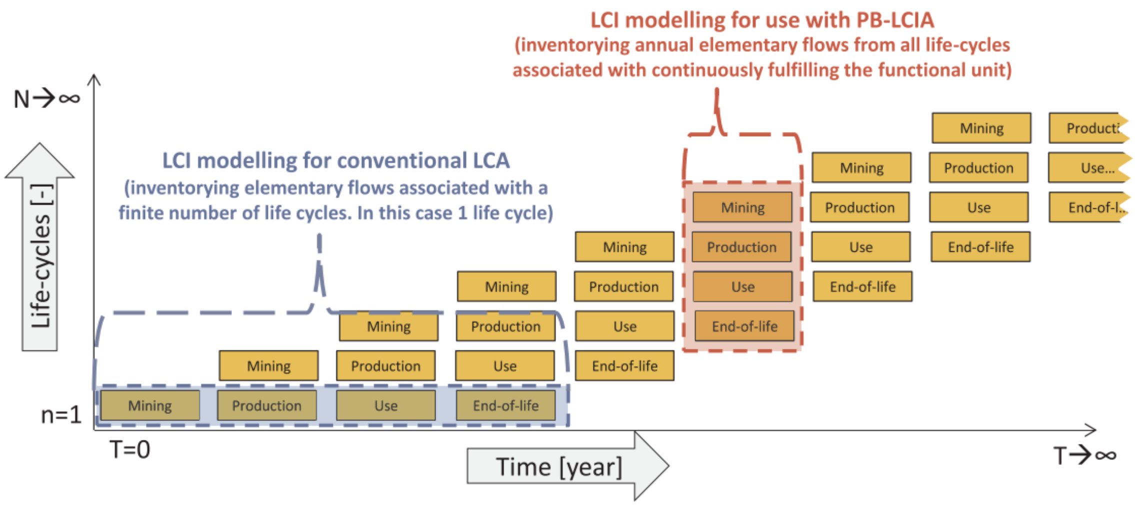

Figure 18: Flux pulse in conventional LCA and ALCA-Characterization$_{PB\text{-}metrics}$ (PB-LCIA), copied from (Ryberg et al., 2018b).

The results showed that only one method, ALCA-Characterization$_{PB\text{-}metrics}$ recognizes that the flux-pulse inconsistency is a problem and thus made the explicit assumption that the impacts are exerted in one and the same year. The other methods did not recognize the flux-pulse inconsistency and therefore made this assumption implicitly. We conclude that this is one of the major problems that impair absolute sustainability conclusions. Even with ALCA-Characterization$_{PB\text{-}metrics}$ an absolute sustainability claim is conceptually still debatable.

5.5 ALCA methods in relation to SDGs

Now that it has been identified which methods can actually be considered as ALCA methods and which questions can be answered, it is possible to describe the potential of each method for supporting product-level contributions to SDG targets. Table 19 lists the pros, cons and usability of each method in the context of the SDGs.

Table 19: Potentials of ALCA methods for supporting product-level SDG contributions

Method	*Pros*	*Cons*	*Usability for supporting product-level contributions to SDGs*
ALCA-weighting	X	- Applying PB-based weighting factors results in single scores, which cannot be related to individual SDG targets.	- Not usable
ALCA-normalization	- Compatible with ILCD characterization results - Compatible with (yet to be defined) linkages between LCA-ICs and SDG targets	- Practitioner is limited to a per-capita benchmark (expressed as a normalization reference). - Practitioner is restricted to the egalitarian allocation principle.	- Limited usability due to per-capita benchmark. - Need to identify linkages between LCA-ICs and SDG targets
ALCA-characterization LCA-metrics	- Compatible with (yet to be defined) linkages between LCA-ICs and SDG targets	- Practitioner is limited to a per-capita benchmark - Low coverage of LCA impact categories - Practitioner is restricted to the egalitarian allocation principle.	- Limited usability due to per capita benchmark. - Need to identify linkages between LCA-ICs and SDG targets
ALCA-characterization PB-metrics	- Uses system specific benchmark that facilitates the definition of absolute sustainability - Allows for multiple allocation principles	- PB metrics: need to identify linkages between ESPs and SDG targets	- Usable, Need to identify linkages between PB framework and SDG targets
ALCA-reduction-targets	- Compatible with (yet to be defined (linkages between LCA-ICs and SDG targets - Allows for multiple allocation principles	- Time frame in which impact reduction targets need to be achieved is subjective	- Usable for assessing incremental impact reductions

5.6 Research limitations and scientific recommendations

In this thesis, we proposed our own definition for ALCA. Yet, it is important for the scientific community to find common ground on how ALCA is defined because this would also determine which methods can be counted as ALCA methods. For example, we formulated the ALCA definition such, that there should be an implementation of a comparison between impact and a benchmark allocated to a product-system. Consequently, methods in which the benchmark was not allocated to a product system could not be considered as actual ALCA methods. An alternative definition of ALCA might not include the condition that a benchmark has to be specifically allocated to product-systems, nor that the goal should be to identify absolute sustainable product-systems specifically, but also other types of systems. Such a definition would likely embrace a broader range of methods and applications.

Within this thesis research, the compatibility between LCA-IC's, PB's and SDG targets is still unilluminated (Figure 19). This is also why this thesis can't yet answer for which specific SDG targets ALCA can be useful in quantifying product contributions. Nor is it identified where specific conversions across DPSIR pathways occur. Identifying and supporting linkages between the LCA-IC's, PB's and SDG and identifying required DPSIR conversions is a time-intensive undertaking. Some research has been done here by Dong & Hauschild (2017) and Chandrakumar & Mclaren (2018). Therefore, we recommend further research to focus on getting insights in linkages between LCA-IC's, PB's and SDG and combining these insights with the knowledge on ALCA methods that has been provided in this thesis. Such a combination would be the next step to find the potential of ALCA methods for supporting contributions from product-systems towards environmental SDG(-target)s.

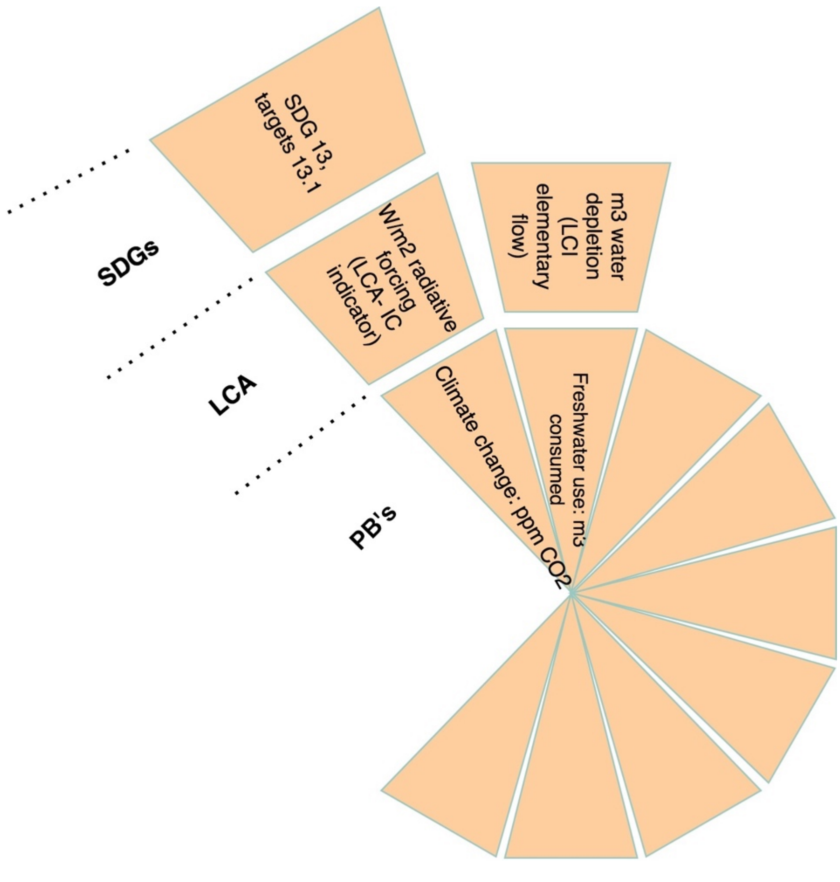

Figure 19: The need to identify the compatibility of PBs, LCA and SDGs

Also, in this thesis, there is no extensive guidance on choice for specific allocation principles, especially regarding ALCA-Characterization$_{\text{PB-metrics}}$ where a practitioner is free to choose the allocation approach. The number of applications included in this review was rather small to identify patterns in allocation approaches and make recommendations. Therefore, we recommend further research to provide guidance on the choice of allocation principles used for conducting allocation of SOS. This would likely require a larger review study in which more case studies are included.

Some authors suggest developing and testing more and new allocation principles, but we recommend that it is more important to first achieve consensus or standardization in the use of existing allocation principles. The scientific community should find common ground in allocation and its terminology, ideally in cooperation with other scientific disciplines and other actors in society (e.g. governments, NGOs and industries). A promising initiative here is the Science-Based Targets initiative (SBT, 2015). Consensus on allocation principles specifically important to avoid the aforementioned arbitrary allocation in individual case studies, leading to weaker absolute sustainability claims and inconsistency between the SOS and sum of SoSOS. Reaching consensus is also critically important because the choice of allocation principles was the highest source of uncertainty in ALCA (Ryberg et al., 2018a; Sandin et al., 2015). Consensus would strongly enhance the conclusion on whether a system is absolutely sustainable or not since the methodological choice for a certain allocation principle would then be supported by the scientific community instead of only the practitioner. Until such consensus or standardization is reached we suggest to follow the proposition by (Ryberg et al., 2018a) to test multiple allocation principles in the same assessment in order to conclude if the system is absolute sustainable independent of the allocation principle chosen. We add to this that practitioners should clearly clarify and support the allocation approach used, thereby also strengthening absolute sustainability claim. Describing the conducted allocation approach should entail the following aspects:

1. Is allocation conducted in different steps towards different subsequent anthropogenic entities? For example, first towards a sector and then towards a product.
2. For each allocation step, which allocation principle (and indicator basis) is used?
    a. For example: towards sectors with a grandfathering principle (current impact basis) and towards products with utilitarian principle (e.g. economic value basis)
3. Clarification of why the first two elements were conducted as such.

In the review approach, it is described that the AESA framework from Bjørn et al. (2019) as a foundation for deriving specific review criteria. Häyhä et al. (2016) developed a framework for allocating the PBs to national fair SoSOS. In this framework, allocation is divided in three dimensions: bio-physical, socio-economic and ethical. Especially the ethical dimension remains rather unilluminated in this thesis. Further research could analyze different allocation approaches in ALCA based on these three dimensions.

The PB framework only covers the natural environment AoP, which has a critical role in a possible disruption of the Holocene state of the Earth system (Rockström et al., 2009). Therefore, ALCA methods using the PB framework to determine benchmarks don't allow for sustainability conclusions on human health or resources. The SDGs are however covering many sustainability issues including social and economic. Therefore, we recommend further research on the potential of the Doughnut model (Raworth, n.d.) for quantifying contributions to SDGs. The doughnut model entails a framework in which the PBs are combined with 12 social dimensions (complemented with minimum social standards from the SDGs).

This research only includes the PB framework as an expression of CC. No other forms of CC were analyzed because the PB-framework is likely the most prominent. Neither was there an analysis at regional level. Some ESPs are heavily spatially dependent, such as freshwater use. Also, we identified several variations in the use of the PB framework across ALCA methods but did not go into detail on the benefits or drawbacks of each variation. We recommend further research on regional boundaries and the pros and cons of the variations in using the PB-framework within ALCA methods.

Lastly, we recommend further research around solving the flux-pulse problem within ALCA, or at least the extent to which it impacts certain absolute sustainability conclusions.

5.7 PRé Sustainability recommendations

The goal of PRé Sustainability is to determine whether product-systems contribute to certain SDG targets. For supporting contributions to environmental SDG targets, we envision two options:

Option 1: Using ALCA-Characterization$_{\text{PB-metrics}}$

1. Identify and support relations between ESPs and SDG targets.
2. Use ALCA-Characterization$_{\text{PB-metrics}}$ to quantify the impact of a product-system in PB metrics
3. Define SoSOS specifically for the product-system using multiple allocation principles.
4. Within each ESP, compare the impact against the multiple SoSOS determine with various allocation principles
5. If the impact is lower than the SoSOS under all/most allocation principles, product-system can be considered absolute sustainable in that ESP
6. If a product-system is absolute sustainable in an ESP, a contribution to a related SDG target can be claimed.

In the SDG project PRé Sustainability started by identifying and supporting linkages between LCA-ICs and SDG targets. Therefore, using ALCA-Characterization$_{\text{PB-metrics}}$ is not ideal, as it would be more convenient if an impact assessment can be used that expresses impacts in LCA metrics. Accordingly, we alternatively suggest the use of ALCA normalization. Although we concluded that this method is not truly an ALCA method and is not capable of identifying absolute sustainable product-systems, it does have the advantage that it is compatible with ILCD impact assessment (LCA metrics), enabling PRé to use the linkages towards SDG targets they have already identified. Additionally, we suggest that PRé could do an additional step (step 3 below) in order to define absolutely sustainable product-systems. They could estimate (or further allocate on the basis of an indicator, see section 4.3.3) what share of the normalization reference (per-capita SoSOS) can be assigned to the system under assessment.

Option 2: Using ALCA-normalization

1. Identify and support relations between ILCD impact categories and SDG targets
2. Use ILCD impact assessment methods to quantify the impact of a product-system in LCA metrics, leading to characterization results.
3. Use the normalization references (per-capita SoSOS) from ALCA-normalization to normalize the characterization results and thereby express the occupation of per-capita SoSOS.
4. Make an expert judgment on whether this occupation of per-capita SoSOS is sufficiently low to consider the system absolute sustainable in the impact category. Or, further allocate the per-capita SoSOS to the product-system using different allocation principles.
5. If a product-system is absolute sustainable in an impact category, a contribution to a related SDG target can be claimed.

6 Conclusion

In this final chapter, answers are formulated for each sub-question first, and thereafter the main research question will be answered. The research questions were:

- *Main RQ: To what extent is absolute life cycle assessment possible and does it enable a comparison of environmental impact against product-level benchmarks based on the PB-framework, to support the identification of absolute sustainable products contributing to the UN SDGs?*
- *SQ1: Which ALCA methods enable linking of planetary boundaries to LCIA midpoint indicators and which challenges can be expected when actually linking them?*
- *SQ2: What are the principles, normative foundations and practical differences of available methods for allocating planetary boundaries to product-level benchmarks allowing for comparisons with LCA characterization results?*

ALCA methods that enable linking of planetary boundaries to LCIA midpoint indicators (SQ1)

The literature reviewed showed that the ALCA field, as represented by the included publications, only consists of a few methods and multiple applications of those methods. Most methods were variations of the conventional LCA, by introducing adjustments at different steps in the framework. All of the methods used the PB framework (Steffen et al., 2015) as an expression of the earth's ecological CC. Within the methods that ensured the expression of results in LCA metrics (ALCA-normalization, ALCA-Characterization$_{\text{LCA-metrics}}$, ALCA-Reduction-Targets and ALCA-Weighting) it was necessary to link the PBs to LCA impact categories. While doing so, the problem arose that the indicators from the PB framework (control variables) were often positioned at a different point in the impact pathway than the LCA indicators. Therefore, conversions across the impact pathway were necessary, which required modelling. Due to the indicator mismatch problem, ALCA methods expressing results in LCA metrics generally showcase a low coverage of LCA impact categories. An exception is that the ALCA-Normalization method covered all of the ILCD impact categories. The aforementioned complications regarding linking PBs and LCA indicators were avoided in the ALCA-Characterization$_{\text{PB-metrics}}$ method since this method expresses results in the metrics of the PBs. This means that no conversions across impact pathways were required. Yet, modelling at the characterization level was necessary but the validity of such modelling was not in the scope of this thesis.

Allocating PBs to product-level benchmarks (SQ2)

The literature review showed that there are many different ways to allocate PBs to lower levels. Although many different terms were used for allocation principles across the publications, all allocation principles could be classified into three main categories: egalitarian allocation (allocating the SOS uniformly among individuals in a region), utilitarian allocation (allocating the SOS among competing systems based on an indicator that represents the utility of these systems, such as economic value), grandfathering allocation (allocating the SOS among competing systems based on their current contribution to total impact generated in a region).

Each of these allocation principles is based on a different normative foundation, and thereby also benefits certain systems or individuals over others. Intuitively, egalitarian allocation seems morally fair but doesn't account for the fact that, in the past decades, some countries have already achieved much more development at the expense of exerting higher environmental impacts than countries. Utilitarian allocation assigns a larger share of SOS to anthropogenic systems that perform well based on the utility indicator that is used (often economic), but that does not mean that these systems are also most important for the prosperity in society. Grandfathering allocation gives the advantage of higher shares of SOS to anthropogenic systems that are already responsible for the largest part of impacts in the present.

Some methods inherently applied a certain allocation principle: In the ALCA-Normalization method and the ALCA-Characterization$_{\text{LCA-metrics}}$ method a per-capita allocation with the egalitarian principle was applied in order to define a SoSOS for individuals, which in turn allowed them to express LCA impacts as the occupation of person-equivalent budgets. In other methods, ALCA-Characterization$_{\text{PB-metrics}}$ and ALCA-Reduction-Targets, a SoSOS was allocated specifically to a product-system. Practitioners of these methods are able to freely choose multiple allocation principles. In some methods there was no allocation of SOS applied at all ALCA-weighting.

Final conclusion (main RQ)

By conducting a systematic literature review we investigated the existence of ALCA methods that allow the identification of absolute sustainable product-systems by comparing life-cycle-based impact against an allocated SoSOS. It was found that only one method, ALCA-Characterization$_{\text{PB-metrics}}$, is truly an ALCA method that can identify absolute sustainability, because it is compatible with the determination of a SoSOS that is specifically allocated to a product-system. The other methods that were identified in the review are not truly ALCA methods for different reasons. Some methods only facilitate a comparison of impact against a per-capita SoSOS, representing the occupation of an individual's environmental budget by the system. These methods are rather usable for identifying sustainable consumption patterns. Some methods only enable the determination of impact reduction targets against which future impact reductions might be compared. Others do not involve any form of absolute sustainability comparison and are rather usable in comparative LCA. Even claims of absolute sustainability that are made using the ALCA-Characterization$_{\text{PB-metrics}}$ method are not fully conceptually consistent because a comparison is made between an annual SoSOS (derived from the PB framework) with LCA impacts that are exerted over many years. Therefore, we conclude that, despite many promising developments, a conceptually correct form of ALCA does not yet exist. In order to know whether ALCA methods can facilitate the support of contributions from product-systems towards environmental SDG targets, there is a need to identify linkages between LCA impact categories and SDG targets, or PBs and SDG targets, depending on the method used. Identifying such linkages and finding common ground on the choice for allocation principles are the main topics for further research.

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Appendix A: Systematic reviews of selected publications

A1 Algunaibet et al. (2019)

Title: Powering sustainable development within planetary boundaries

General summary and remarks

Energy system models (ESM) are currently focused on identifying electricity mixes that minimize the total cost while meeting a set of technical constraints (Algunaibet et al., 2019). Environmental impacts in ESMs can be quantified with LCA, but the integration of both fails to provide absolute bounds on the impact of an energy mixes and can therefore not indicate if it operates within the earth's ecological capacity (Child et al., 2018). Algunaibet et al. (2019) propose an approach that enables designing an absolute sustainable energy mix based on the PBs. They adjusted the emission reduction Cooperation Model (ERCOM) to include the PBs (ERCOM-PB). The overall approach is visualized in Figure A1.

It was found that the Business as Usual (BAU) energy mix to meet demand in 2030 transgresses 6 out of eight PBs considered, and that the least cost energy mix, in line with the 2 degrees Celsius target also transgresses five PBs. Both transgress the climate change PB. With the ERCOM-PB model, an electricity mix could be found that operates within 7 of the 8 PBs, only the stringent nitrogen PB could not be met. Such a mix would incur an additional cost of 40% compared to BAU.

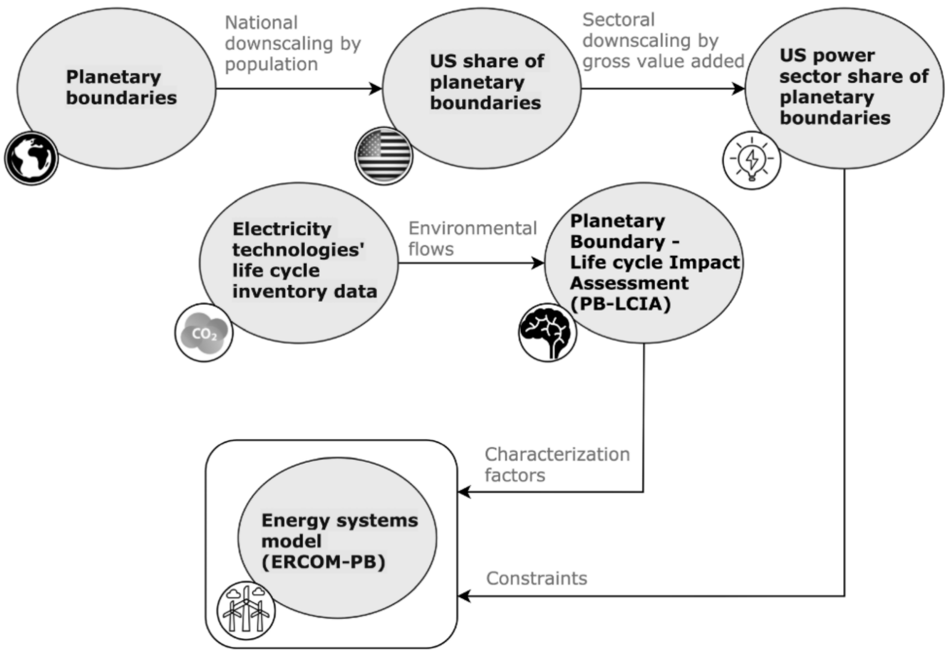


Figure A1: Approach (Algunaibet et al., 2019)

Review criteria

<u>LCA related criteria</u>

C0	**Method/application**
	Algunaibet et al. (2019) showcases an application of the PB-LCIA method from Ryberg et al. (2018).
C1	**Scale / object study**

	Scale: Sectoral Object: Energy mix of the USA They analyze three energy mix solutions, in other words scenarios, that meet the expected US electricity demand in 2030: 1. BAU solution that represents the US 2012 default developments 2. The Paris Agreement solution corresponds to the least cost solution that meets the 2 degrees Celsius target 3. A planetary boundary solution: the energy mix that would minimize the transgression of PBs at minimum cost (obtained with the PB compliancy constraints enforced in the ERCOM-PB model)
C2	**LCA adjustment**
	Life cycle inventory entries, $LCI_{i,j,l}$, connected to PBs were primarily retrieved from the ecoinvent LCA database. Then this was used in an adjusted LCA impact assessment method: PB-LCIA (Ryberg, Owsianiak, Richardson, et al., 2018), to eventually allow comparison against a share of safe operating space in the same unit. Published characterization factors (Ryberg, Owsianiak, Richardson, et al., 2018), $CF_{l,p}$, were applied to translate the life cycle inventories of electricity technologies into the environmental burdens, $EP_{i,j,p}$, linked to PBs: $$EP_{i,j,p} = \sum_{l} CF_{l,p} * LCI_{i,j,l} \quad \forall i,j,p$$
C3	**FU as flux/pulse**
	No clear definition of functional unit because it involves a complete sector and different combinations of energy mixes are analyzed. From the equations becomes clear that the environmental burden is calculated for the (projected) total electricity demand in the year 2030 in the US. Thus it is defined as a flux.
C4	**Absolute sustainability comparison**
	A comparison is made. First, the SoSOS for the US energy sector is determined by downscaling the PBs. Meanwhile, the environmental burden resulting from a specific energy mix is calculated (see criteria 2). Then both are compared in a model to find if a specific energy mix leads to transgression of the assigned SoSOS.
C5	**Results presentation**
	Presented as impact score in relation to the boundary, that is, the extent to which the included planetary boundaries are transgressed. This result presentation is possible due to the use of PB-LCIA, which translates impact in the units of the PBs.

PB related criteria

	Sustainability objective

C6 “The design of sustainable energy mixes based on the concept of Planetary Boundaries (PBs), a set of ecological limits that should never be transgressed by our planet to operate safely.”

C7 Planetary boundaries included?

8 out of 14 quantified PBs

7 out of 10 Earth System Processes (ESPs)

Some PBs still show data and methodological gaps that prevent their full use in practical application:

The biosphere PB and regional PBs on land-system change, freshwater use and biogeochemical phosphorus flows were omitted because of problems with the availability of corresponding inventory entries in life cycle repositories. The PB on atmospheric aerosol loading was omitted because it focuses on the Indian subcontinent and is therefore not applicable to the US. The novel entities PB was omitted due to unclear definition/quantification.

C8 Quantification of SOS

“The full safe operating space is a budget given by the difference between the PB and the natural background level, where the latter indicates the performance of each ESP before human intervention”. In this way it is neglected whether a PB has currently already been transgressed, meaning that no safe operating space is left.

Planetary boundary title	Unit	Planetary boundary[18]	Natural background level[18,27]	Full safe operating space	Assigned share of safe operating space to the US power sector ($aS_{USpower}$ = 0.062%)
Climate change (atmospheric CO_2 concentration)	ppm CO_2	350	278	72	0.045
Climate change (energy imbalance at top-of-atmosphere)	$W\ m^{-2}$	1	0	1	6.19×10^{-4}
Stratospheric ozone depletion[a]	DU	275	290	15	0.009
Ocean acidification[a]	Ω_{arag}	2.75	3.44	0.69	4.27×10^{-4}
Biogeochemical phosphorus flow (global)	Tg P $year^{-1}$	11	1.1	9.9	0.006
Biogeochemical nitrogen flow (global)	Tg N $year^{-1}$	62	0	62	0.038
Land-system change (global)[a]	%	75	100	25	0.015
Freshwater use (global)	$km^3\ year^{-1}$	4000	0	4000	2.476

[a] Planetary boundaries on stratospheric ozone depletion, ocean acidification and land-system change act as lower bounds[18] and hence when the full safe operating space is calculated, the absolute value should be considered.[27]

As a <u>stock</u>: climate change, stratospheric ozone depletion, ocean acidification, land system change

As a <u>flow</u>: biochemical flows (phosphorus and nitrogen), freshwater use.

Allocation related criteria

C9 Basis of allocation

The PBs are downscaled to a share that is an upper limit for the US power sector in the year 2030. Algunaibet et al. (2019) uses a cascading technique, that is, allocating on different basis in steps. First the PBs are allocated from global to the national level (US) on a capita basis. Then the PBs are allocated to the sectoral level (energy sector) based on its contribution to the national Gross Value Added (GVA). The allocation is thus made on a combination of biophysical and socio-economic grounds.

	$$aS^{USpower} = \frac{POP^{US}}{POP^{world}} * \frac{GVA^{USpower}}{GVA^{US}}$$ $aS^{USpower}$ = share of total safe operating space assigned to US power sector (PB-independent) POP^{US} = US population (2016) POP^{world} = world population (2016) $GVA^{USpower}$ = GVA for the US power sector (2016) GVA^{US} = GVA for the total US economy (2016) $$SoSOS_p = aS^{USpower} * SOS_p \quad \forall p$$ $SoSOS_p$ = US power sector absolute share of safe operating space for every PB p SOS_p = full safe operating space for every PB p We note that the 2016 population (POP^{US}) used to determine the $aS^{USpower}$ is not consistent with the year against which is compared in the assessment, 2030.
C10	**Allocation principle(s) used**
	Egalitarian for both steps, meaning that the assigned share that the US energy sector obtains is proportional with the population and GVA ratios as previously described.
C11	**Principle documentation**
	It is communicated that allocation is done with an egalitarian equity principle. Also the basis of allocation steps is communicated. However, the reason lacks clarification. There is no justification for the applied egalitarian equity principle. It is also not communicated why the PB is first allocated to the US on a capita basis, instead of directly using the ratio of the GVA provided by the US energy sector and the global GVA.
C12	**Compatibility allocation principles**
	The SoSOS are calculated independently and can be determined by using different equity principles or cascading techniques.

A2 Andersen et al. (2020)

Title: Assessment of absolute environmental sustainability in the built environment

General summary and remarks

The goal of the publication is to analyze the absolute sustainability of buildings. The building sector has a strong influence on total natural resource consumption and on release of emissions and waste to the environment. They assess if emissions and consumption of resources associated with environmentally optimized building designs are within the earth's carrying capacity.

Andersen et al. (2020) state: "To use LCA for analysis of whether Earth System processes are able to cope with the burdens of human activities, it is necessary to couple LCA with absolute measures. The results are referred to as Absolute Environmental Sustainability Assessments (AESAs).” However, we note that not all AESAs involve LCA. ALCA is just one form of AESA.

<u>The case study set up</u>

6 dwellings:

- 5 types of sustainable single family dwellings: miniCO2. These MiniCO2 houses are designed to each reduce one known source of CO2 emissions in buildings to an extreme degree.
- A sixth benchmark dwelling: reference house that reflects standard Danish building practice in 2015

6 Scenario’s:

- All modelled systems contain parameters that are likely to change in the future
- Five scenarios each representing a version of the future where one parameter is highlighted.
- A sixth best case scenario where all characteristics are changed

<u>Results:</u>

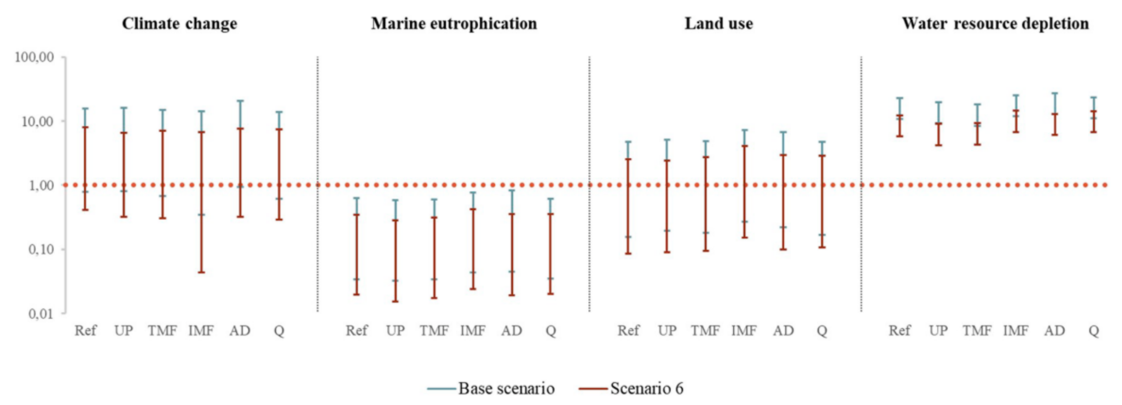
Some dwelling types are within the boundaries when applying CCnorm and a specific allocation principle, whereas none of the dwellings are within the absolute sustainability boundaries of absolute using PB-LCIA. The buildings’ energy use during operation was found to be an important determinant in the exceedance of SoSOS. This is also why houses of smaller sizes had better environmental performance, which is in line with findings from Brejnrod et al. (2017). This finding also understates the importance of the transition towards a sustainable energy grid.

Review criteria

<u>LCA related criteria:</u>

C0	**Method/application**
	Application of 2 methods: - CC based normalization (Bjørn & Hauschild, 2015) - PB-LCIA (Ryberg, Owsianiak, Richardson, et al., 2018)
C1	**Scale / object study**
	Scale: product (although the building sector is homogenous) Object: Dwellings (6 types) in Denmark
C2	**LCA adjustment**
	There are two AESA approaches used for quantifying impact. Both involve an adjusted form of LCA: - PB-LCIA - LCIA-method ILCD 2011 with carrying capacity based normalization
C3	**FU as flux/pulse**
	PB-LCIA method that characterizes elementary flows in the metrics of the PBs (Ryberg, Owsianiak, Richardson, et al., 2018). In contrast to conventional LCA, the resource use and

	emissions must be expressed on annual basis, in order to link to the PBs. In turn, the FU must also be defined as the annual provision of a function and the LCI must be modelled to express the annual "average" elementary flows associated with continuous annual fulfilment of the functional unit. Andersen et al. (2020) state: "The inventory must express elementary flows as continuous constant input per unit of time rather than an input integrated over time and thus the inventory is scaled to an annual basis in respect to the corresponding building service lives (either 120 or 150 years)." To comply with this requirement for PB-LCIA, the FU was defined as a an annual **flux**: "The FU of the compared systems was defined as to annually house one family in a stand-alone dwelling in Denmark."
C4	**Absolute sustainability comparison**
	In both AESA approaches a comparison is made: - The assigned share of safe operating space (SoSOS) is determined separately. - Then the characterized impacts are quantified and compared against this SoSOS (see C5).
C5	**Results presentation**
	They divide the characterized impact potential by the share of safe operating space, for each PB. If the result is smaller than or equal to 1, the dwelling can be considered withing its allocated share of safe operating space, and thus absolute sustainable: $$\frac{C_{IS}^{PB-LCIA}}{SP_i * SOS_{PB,i}} = \frac{C_{IS}^{PB-LCIA}}{SoSOS_i} \leq 1$$ $$\frac{C_{IS}}{SP_i * SOS_{CC,world,i}} = \frac{C_{IS}}{SoSOS_i} \leq 1$$ In which: - $C_{IS}^{PB-LCIA}$ is the characterized impact using the PB-LCIA method - $SOS_{PB,i}$ is the full safe operating space based on the PBs for a specific impact category i. - C_{IS} is the characterized impact using ILCD 2011. - $SOS_{CC,world,i}$ is the full safe operating space based on the annual carrying capacity for a specific impact category i. - SP_i is the sharing principle - $SoSOS_i$ is the share of safe operating space of a specific impact category i, allocated to the dwelling. Then numerical results are shown for each PB and dwelling type on a logarithmic scale. It shows whether the SoSOS (dotted line at 1,00) is exceeded or not. The bars represent the variation across different sharing principles.



PB related criteria

<table>
<tr><td>C6</td><td>Sustainability objective</td></tr>
<tr><td></td><td>Respect local, regional and global environmental boundaries in order to avoid destabilization of the Holocene state of global climate which is needed to support human society.</td></tr>
<tr><td>C7</td><td>Planetary boundaries included?</td></tr>
<tr><td></td><td>
<table>
<tr><th>Impact categories CC_{norm}</th><th>Impact categories PB-LCIA</th></tr>
<tr><td>Climate change (kg $CO_{2\ eq}$)</td><td>Climate change – energy imbalance (Wm^{-2})</td></tr>
<tr><td>Marine eutrophication (kg N eq)</td><td>Biogeochemical flows – N (Tg N)</td></tr>
<tr><td>Land use (kg C deficit)</td><td>Land system change – global (%)</td></tr>
<tr><td>Water resource depletion (m^3 water eq)</td><td>Freshwater use – global (km^3)</td></tr>
</table>
</td></tr>
<tr><td>C8</td><td>Quantification of SOS</td></tr>
<tr><td></td><td><u>For the SOS_{PB} (see criteria 5):</u>

The safe operating space (SOS) as defined by Ryberg, Owsianiak, Clavreul, et al. (2018) is adopted. This SOS is calculated by subtracting the natural background levels (Steffen et al., 2015) from the planetary boundaries (Rockström, J., Steffen, W., Noone, K., 2009).</td></tr>
</table>

Impact category	Unit	Planetary Boundary	Natural background level	Full safe operating space
Climate change - energy imbalance	Wm-2	1	0	1
Climate change - CO2 concentration	ppm CO2	350	278	72
Stratospheric ozone depletion	DU	275	290	15
Ocean acidification	mol	2.75	3.44	0.69
Biogeochemical flows - P, regional	Tg P yr-1	26.2	20	6.2
Biogeochemical flows - N, global	Tg N yr-1	62	0	62
Land-system change - Global	%	75	100	25
Land-system change - Boreal	%	85	100	15
Land-system change - Tropic	%	85	100	15
Land-system change - Temperate	%	50	100	50
Freshwater use - Global	km3 yr-1	4000	0	4000
Freshwater use - Basin dry	-	1	0	1
Freshwater use - Basin semidry	-	1	0	1
Freshwater use - Basin humid	-	1	0	1
Atmospheric aerosol loading	-	0	0.14	0.11

For the $SOS_{CC,world,I}$ (see criteria 5):

The set of normalisation factors proposed by Bjørn and Hauschild (2015) express a person's annual share of the carrying capacity, which are not compliant with ILCD 2011 Midpoint+ (ILCD 2011). Sala et al. (2016) has therefore translated them to be compliant with ILCD 2011 impact categories:

Impact category	Unit	ILCD compliant normalisation factor[a]
Climate change	kg CO2 eq	6.79E+12
Ozone depletion	kg CFC-11 eq	5.38E+08
Photochemical ozone formation	kg NMVOC eq	2.62E+10
Acidification	molc H+ eq	9.99E+11
Terrestrial eutrophication	molc N eq	6.12E+12
Freshwater eutrophication	kg P eq	5.79E+09
Marine eutrophication	kg N eq	2.00E+11
Freshwater ecotoxicity	CTUe	1.31E+14

	Land use	kg C deficit	1.37E+14
	Water resource depletion	m3 water eq	6.85E+11

Thus, the quantification of carrying capacity is different for both methods that were used:

- In the PB framework, a precautionary approach is used. This means that (if a planetary boundary is accompanied with an uncertainty interval) the lower limit is set as the carrying capacity that should be respected.
- In contrast, Bjørn & Hauschild (2015) set the carrying capacity as the average or median of the uncertainty intervals, in order to avoid bias during normalization of different impact categories.

Knowing about this difference, it was expected that larger SoSOS would be occupied by the dwellings when PB-LCIA was applied (this is also argued as a possible cause for the result that CCnorm finds more dwellings to be absolutely sustainable).

Allocation related criteria

C9

- **Basis of allocation**

There are 6 sharing principles (SP) based on different equity principle combinations. Using a combination of principles is in line with the finding from the review by (Ryberg, Owsianiak, Clavreul, et al., 2018), that it is more common to apply a combination of two sharing principles in a sector and company scale study, in contrast to country scale studies where the application of a single stand-alone principle is most common.

For these SPs the basis of allocation differs:

1. *SP_1 : egalitarian + utilitarian*

First allocates the PB on a **biophysical basis**: allocate to a per capita measure by dividing by the world population (Pop_{world}) and thus using an **egalitarian** principle.

Then follows second **socio-economic** allocation step that expresses the value of a household to a person, which is a **utilitarian** principle. This factor uses the final consumption expenditure (FCE) to households relative to the total FCE of a person. To further specify to the level of dwellings, the share of FCE to a dwelling (FCE_{dwe}) relative to the whole household (FCE_{HH}) is accounted for. N is the number of persons in a dwelling.

$$(1) \quad SP_1 = \frac{1}{Pop_{world}} \cdot \frac{\cancel{FCE_{HH}}}{FCE_{person}} \cdot \frac{FCE_{dwe}}{\cancel{FCE_{HH}}} \cdot N$$

2. *SP_2: egalitarian +utilitarian*

First allocates the PB on a **biophysical basis**: allocate to a per capita measure by dividing by the world population (Pop_{world}) and thus using an **egalitarian** principle.

Then a second **socio-economic** allocation step is applied that expresses the value of a household to a person, which is a **utilitarian** principle. This factor uses the annual hours spent in a household (H_{home}) relative to the total hours in a year (H_{year}), as time spent is a measure of what we value in life. To further specify to the level of dwellings, the share of FCE to a dwelling (FCE_{dwe}) relative to the whole household (FCE_{HH}) is accounted for. N is the number of persons in a dwelling.

$$(2) \quad SP_2 = \frac{1}{Pop_{world}} \cdot \frac{H_{home}}{H_{year}} \cdot \frac{FCE_{dwe}}{FCE_{HH}} \cdot N$$

3. *SP_3: egalitarian +acquired rights*

First allocates the PB on a **biophysical basis**: allocate to a per capita measure by dividing by the world population (Pop_{world}) and thus using an **egalitarian** principle.

Then follows second **biophysical** allocation step that expresses a dwelling's inherited right to emit based on the past impact, which is an **acquired rights** principle. This factor uses the energy consumption of an average household (E_{HH}) relative to the total energy consumption of a person (E_{person}). To further specify to the level of dwellings, the share of energy consumption for a dwelling (E_{dwe}) relative to the whole household (E_{HH}) is accounted for. N is the number of persons in a dwelling.

$$(3) \quad SP_3 = \frac{1}{Pop_{world}} \cdot \frac{\cancel{E_{HH}}}{E_{person}} \cdot \frac{E_{dwe}}{\cancel{E_{HH}}} \cdot N$$

4. *SP_4: acquired rights + acquired rights*

First allocates the PB on a **biophysical basis,** using an **acquired rights** principle: dividing the annual CO2 emissions from an average household ($CO2_{HH}$) by the total annual CO2 emissions worldwide ($CO2_{world}$).

Then to further specify to the level of dwellings, a second **biophysical** allocation step using an **acquired rights principle** is applied: the share of energy consumption for a dwelling (E_{dwe}) relative to the whole household (E_{HH}).

$$(4) \quad SP_4 = \frac{CO2_{HH}}{CO2_{world}} \cdot \frac{E_{dwe}}{E_{HH}}$$

5. *SP_5: acquired rights + utilitarian*

First allocates the PB on a **biophysical basis,** using an **acquired rights** principle: dividing the annual CO2 emissions from an average household ($CO2_{HH}$) by the total annual CO2 emissions worldwide ($CO2_{world}$).

Then to further specify to the level of dwellings, a second **socio-economic** allocation step using an **utilitarian principle** is applied: the share of FCE to a dwelling (FCE_{dwe}) relative to the whole household (FCE_{HH}).

$$(5) \quad SP_5 = \frac{CO2_{HH}}{CO2_{world}} \cdot \frac{FCE_{dwe}}{FCE_{HH}}$$

6. *SP_6: utilitarian*

Allocates the PB on a **socio-economic basis,** using an **utilitarian** principle:

the share of FCE to a dwelling (FCE_{dwe}) relative to the whole world (FCE_{world}).

$$(6) \quad SP_6 = \frac{FCE_{dwe}}{FCE_{world}} = \frac{FCE_{HH}}{FCE_{world}} \cdot \frac{FCE_{dwe}}{FCE_{HH}}$$

<u>Summarising table:</u>

Sharing principle	Equity principle 1	Basis of allocation	Equity principle 2	Basis of allocation

1	Egalitarian	Per capita (*biophysical*)	Utilitarian	Final Consumption Expenditure (*socio-economic*)
2	Egalitarian	Per capita (*biophysical*)	Utilitarian	Time spent (*socio-economic*)
3	Egalitarian	Per capita (*biophysical*)	Acquired rights	Energy consumption (*biophysical*)
4	Acquired rights	CO2 emissions (*biophysical*)	Acquired rights	Energy consumption (*biophysical*)
5	Acquired rights	CO2 emissions (*biophysical*)	Utilitarian	Final Consumption Expenditure (*socio-economic*)
6	Utilitarian	Final Consumption Expenditure (*socio-economic*)	-	-

C10 **Allocation principle(s) used**

See above

C11 **Principle documentation**

They provide ethical context and discussion in a separate section.

- They rightly acknowledge that the definition and use of different scaling principles is not only important to investigate uncertainty due to principle choice, but also enables discussion on the subjective ethical question: who can impact the environment and how much?
- The authors agree with (Brejnrod et al., 2017) that there is no objective way to assign the SOS to a building or any other service, as the sharing principle will be seen as more or less fair depending on the eyes of the beholder.
- For example it is mentioned that although egalitarian seems most equitable, not every individual needs the same SoSOS for housing because the needs for heating (and the subsequent emissions from energy use) are different across the world. We consider this notion especially relevant because the exceedance of the SoSOS may was found to be vastly dominated by the energy consumption for building operation, for most of the dwellings. In the future in might be possible to develop a sharing principle that includes a correction factor based on geographical location and different climates?
- It is important to communicate precisely what the SoSOS represents, as in this study there was a distinction between a household and dwelling. Assigning a SoSOS to the dwelling, meant leaving out all the activities taking place within the household, such as cooking, cleaning, and entertainment.
- Due to a growing world population the calculated shares become outdated, since dividing by a larger global population decreases the SoSOS available to an individual.
- The authors recommend transparency on the choice of sharing principles in AESA
- The authors recommend a standardized application of sharing principles to enable comparability across AESAs.

C12 **Compatibility allocation principles**

	Compatibility with other principles is possible and mentioned: "It should be noted that the sharing principles applied in this study only represent a selection of ways the safe operating space can be shared".

A3 Bjørn & Hauschild (2015)

Title: Introducing carrying capacity-based normalisation in LCA: framework and development of references at midpoint level

General summary and remarks

The purpose of this article is to provide a framework for developing normalisation references from carrying capacities for the use in LCA. The framework is then operationalized by developing European and global normalisation references compatible with characterization results for several midpoint impact categories.

Review criteria

LCA related criteria

C0	**Method/application**
	Method: carrying capacity-based normalisation
C1	**Scale / object study**
	Not applicable, no case study.
C2	**LCA adjustment**
	Adjusted LCA. Instead of regular normalization factors (in years), this method develops normalization factor (in person equivalents) based on carrying capacity: The normalisation references ($NR_{i,j}$) in 'per person year' for impact category i in region j were calculated by dividing the carrying capacities in indicator score per year ($CC_{i,j}$) by the population (P_j), according to the following formula: $$NR_{i,j} = \frac{CC_{i,j}}{P_j}$$ The 2010 global and European population was used but practitioners may choose a projected population for the median year of the time horizon considered in the analysis. All normalisation references can be seen in the table below, copied from (Bjørn & Hauschild, 2015)

Table 1 Developed global normalisation references based on carrying capacity (NR), comparison across scales and with traditional normalisation references (NR')

Impact category	NR_{global} (per person year)	$\frac{NR'_{Global}}{NR_{Global}}$	NR_{Europe} (per person year)	$\frac{NR'_{Europe}}{NR_{Europe}}$	$\frac{NR_{Global}}{NR_{Europe}}$	CF compatibility	Threshold
Climate change	985 kg CO_2-eq	**8.2**	985ton CO_2-eq	**9.4**	1	*GWP100 (CO_2-eq)* (Forster et al. 2007)	Temperature increase of 2 °C
	522 kg CO_2-eq	**15**	522 kg CO_2-eq	**18**			Radioactive forcing increase of 1 $W \times m^2$
Ozone depletion	0.078 kg CFC-11-eq	0.53	0.078 kg CFC-11-eq	0.28	1	*ODP* (Montzka and Fraser 1999)	7.5 % decrease in average ozone concentration
Photochemical ozone formation	3.8 kg NMVOC-eq	**15**	2.5 kg NMVOC-eq	**13**	1.6	*Tropospheric ozone concentration Increase* (Van Zelm et al. 2008)	Tropospheric ozone concentration of 3 ppm × hour AOT40
Terrestrial acidification	2.3×10^3 mole H^+ eq	0.34	1.4×10^3 mole H^+ eq	0.53	1.7	OT method of Posch et al. (2008)	Deposition of 1170 and 1100 mole H^+ eq $\times$ ha^{-1} $\times year^{-1}$ globally and for the EU
Terrestrial eutrophication	2.8×10^3 mole N eq	0.13	1.8×10^3 mole N eq	0.30	1.5	OT method of Posch et al. (2008)	Deposition of 1340 and 1390 mole N eq $\times ha^{-1} \times year^{-1}$ globally and for the EU
Freshwater eutrophication	0.84 kg P eq	0.74	0.46 kg P eq	**3.22**	1.8	*P concentration increase* (Struijs et al. 2009)	P concentration of 0.3 mg/L
Marine eutrophication	29 kg N eq	0.32	31 kg N eq	0.55	0.95	*N concentration increase* (Struijs et al. 2009)	N concentration of 1.75 mg/L
Freshwater ecotoxicity	1.9×10^4 [PAF] $\times m^3 \times$ day	0.036	1.0×10^4 [PAF] $\times m^3 \times$ day	0.85	1.8	*CTU* (Rosenbaum et al. 2008)	HC5(NOEC)
Land use, soil erosion	1.8 tons eroded soil	**4.9**	1.2 tons	**9.3**	1.6	Saad et al. (2013), land occupation CFs only	Tolerable soil erosion of 0.85 tons $\times ha^{-1} \times year^{-1}$)
Land use, biodiversity	1.5×10^4 $m^2 \times$ year	0.42	9.5×10^3 $m^2 \times$ year	0.79	1.6	LCI data, land occupation only	31 % conserved land area
Water depletion	306 m^3	**1.3**	490 m^3	0.52	0.63	LCI data classified as blue water consumption	Conservation of 57 % of river flows for aquatic ecosystems and 30 % for terrestrial ecosystems

Bold values indicate that NR′/NR fractions are above 1. Italics CF references mean compatibility with characterisation methods recommended by Hauschild et al. (2013)

C3	**FU as flux/pulse**
	Not applicable, no case study.
C4	**Absolute sustainability comparison**
	The carrying capacity is integrated in the result. The normalisation references can serve to communicate how large a share of the carrying capacity a given system or activity takes up in person equivalents (Bjørn & Hauschild, 2015). In this way, it does not tell which part of the carrying capacity is specifically allocated to the product of the analysis. Consequently, direct normalization against the full safe operating space cannot reveal whether an activity can be considered absolutely sustainable (Ryberg, 2018). Therefore, further disaggregation of the personal budgets would be possible based on average contributions of products to this personal budget. Even after such disaggregation, there is a normative component in how much of the budget can be occupied by the system of analysis. (Brejnrod et al., 2017) applied such further disaggregation of per-capita carrying capacity in a case study in housing.
C5	**Results presentation**
	The results reflect the carrying capacity occupation in person equivalents.

__PB related criteria__

C6	**Sustainability objective**
	"Ecological impacts and resource intensities of product life cycles should be reduced to a level at least in line with the Earth's estimated carrying capacity."
C7	**Planetary boundaries included?**

	See C2
C8	**Quantification of SOS**
	Definition: Carrying capacity defined as: “the maximum sustained environmental intervention a natural system can withstand without experiencing negative changes in structure or functioning that are difficult or impossible to revert.” *Quantification:* In contrast to the PBs, which are set at the lower limit of the uncertainty interval under the precautionary principle, Bjørn & Hauschild (2015) set the carrying capacity as the average or median of the uncertainty intervals, in order to avoid bias during normalization of different impact categories. We assume that this is done because PBs have divergent uncertainty intervals and not every PB has an uncertainty interval. *Point of expression:* The problem arises that not all impact categories nor thresholds are manifested at the same place in the impact pathway. This means that, to enable comparing a carrying capacity with LCA midpoint indicators, the conversion of a threshold to carrying capacity sometimes required translation across an impact pathway, for example using fate factors. Stocks/flows: The carrying capacities are expressed as flows since the units have a time element (e.g. kg CO2-eq/person*year) *Spatial considerations:* The authors mention that spatial extent of the impact categories should be taken into account for carrying capacity determination. Regional scale impact categories require carrying capacities of relevant local and regional areas corresponding to the spatial information of the LCI, whereas global scale impact categories require a single global carrying capacity. We argue that for global scale categories sharing becomes more relevant and difficult. After all, starting the allocation at a higher scale means more competing systems, more geopolitical dependencies, etc. Typical LCA studies can include hundreds of processes from different geographic locations, which would lead to practical complications if each of the emissions from those processes need to be compared to local allocated carrying capacities. Also, the supposed requirement for regional carrying capacities is not followed as far as would be desired for some impact categories. Carrying capacities at European level is the lowest level used in this article, while impact categories like freshwater use are ideally provided with carrying capacities at water shed level. *Temporal considerations:* In reality, carrying capacities change over time. Diurnal and seasonal cycles and weather events have an influence on the magnitude of carrying capacities. Also anthropogenic interventions can lead to temporary or permanent decrease of carrying capacity. However, including the dynamic nature of carrying capacities would require complex dynamic modeling

	and is not compatible with limited time information of typical LCIs. Therefore, carrying capacities are considered as static in the article. *Coverage of midpoint impact categories:* The authors only derived carrying capacities for midpoint impact categories linking to the natural environment area of protection, meaning that some impact categories from the human health and natural resource area of protection are not covered.

Allocation related criteria

C9	**Basis of allocation**
	The full global carrying capacity is shared uniformly on a per-capita basis (biophysical), using the egalitarian principle.
C10	**Allocation principle(s) used**
	The authors support the egalitarian principle under the argumentation that it may be possible to agree upon a moral rule that carrying capacities should be shared equally amongst people living within its geographical boundaries or an alternative rule that global carrying capacities should be shared equally within the global population. Such a rule does not restrict personal freedom regarding consumption patterns but rather puts a limit on the total amount of environmental pressure individuals are allowed to exert. There is however no reflection on whether sharing the carrying capacity 'equally' among the global population is also fair in ethical terms.
C11	**Principle documentation**
	The authors mention that the allocation of carrying capacity and therefore the sustainability criteria is inherently subjective because it involves sharing among systems that meet different human needs.
C12	**Compatibility allocation principles**
	The authors suggest that, supplementary to the concept of personal carrying capacity, sector specific reduction scenarios could be used as a basis to share carrying capacity among products within different sectors, but this is not further elaborated.

A4 Brejnrod et al. (2017)

Title: The absolute environmental performance of buildings

Review criteria

LCA related criteria

C0	**Method/application**

	This publication is an application of carrying capacity based normalization (Bjørn & Hauschild, 2015).
C1	**Scale / object study**
	Scale: Product Object: Buildings (or more precisely: the service of accommodation)
C2	**LCA adjustment**
	Adjusted. Carrying capacity based normalization (see review of Bjørn & Hauschild (2015)) The normalized impact of the building B, in impact category i ($I_{B,i}^{N}$) is calculated with the following formula: $$I_{B,i}^{N} = \frac{I_{B,i}}{CC_{BT,i}}$$ In which: $I_{B,i}$ = Total annual contribution to the impact potential from the building B, in the impact category i $CC_{BT,i}$ = annual carrying capacity allocated to the impact category i for the specific building type (BT)
C3	**FU as flux/pulse**
	The functional unit in this publication is defined as a pulse: “A typical Danish single-family dwelling with a net floor area of 128 m2 and an estimated service-life of 50 years.”
C4	**Absolute sustainability comparison**
	The carrying capacity is integrated in the results, as the result reflects the occupation of person-equivalent carrying capacity. However a comparison against a target value(acceptable impact as a share of the person-equivalent carrying capacity) is also made. In this way they overcome the limitation that normalization factors alone do not enable a conclusion on whether the system is absolute sustainable.
C5	**Results presentation**
	As percent-wise occupation of allocated CC for each impact category.

PB related criteria

C6	**Sustainability objective**
	Assessing a building's sustainability performance in an absolute context
C7	**Planetary boundaries included**
	See C8

C8	**Quantification of SOS**
	All quantified as an annual flow:

Impact category	*Global Normalisation Factor (annual person equivalents ($CC_{PE,i}$)*
Terrestrial Acidification (TA)	$2.3 * 10^3$ H^+ eq./yr
Terrestrial Eutrophication (TE)	$2.8 * 10^3$ N eq./yr
Water Depletion (WD)	306 m^3/yr
Land Use Soil Erosion (LUS)	1.8 ton eroded soil/yr
Land Use Biodiversity (LUB)	1.5 * 104 m^2 year/yr
Climate Change (CC, temp)	985 kg CO_2 eq./yr
Climate Change (CC, rad)	522 kg CO_2 eq./yr
Ozone Depletion (OD)	0.078 kg CFC-11 eq./yr
Freshwater Eutrophication (FE)	0.84 kg P eq./yr
Marine Eutrophication (EP)	29 kg N eq./yr
Photochemical Oxidant Formation (POF)	73 kg NMVOC eq./yr
Freshwater Ecotoxicity (FET)	1.9 * 104 [PAF]* m^3*day/yr

Allocation related criteria

C9 + C10	**Basis of allocation**
	Allocation principle(s) used

The allocation is conducted in 2 steps:

1. The earth system's carrying capacity is allocated on a per-capita basis (biophysical), resulting in a person-equivalent carrying capacity (or in other words personal budget).

This allocation step is done uniformly with the egalitarian principle (which means that every person gets the same share, as seen under C8).

2. A share of the person-equivalent carrying capacity is allocated to the building, using a utilitarian principle: Based on economic value (socio-economic)

The formula to calculate the impact category specific carrying capacity for a dwelling ($CC_{DWE,i}$), is formulated as:

$$CC_{DWE,i} = CC_{PE,i} * A_{HH,i} * AH_{HH,dwe,i} * R_{BT,ave}$$

In which:

$CC_{PE,i}$ = the person equivalent carrying capacity (See C8)

$A_{HH,i}$ = share of the person equivalent allocated to the household

$AH_{HH,dwe,i}$ = share of the household allocated to the dwelling service

$R_{BT,ave}$ = average number of residents in the specific building type (BT)

C11	**Principle documentation**
	The authors recognize that there is no single way to allocate carrying capacity to a product or service, and that it is always subjective in terms of cultural perspective.

	They also reflect on limitations of allocation principles: 3. The economic allocation is considered as possibly non-optimal because it assigns an equal share of carrying capacity to all impact categories although there might be variation in the impacts across the impact categories exerted by the products or services. 4. The allocation based on current impact disadvantages products or services that have already had reductions by assigning them smaller shares. 5. Temporal issues have not been considered: the per-capita egalitarian allocation has the limitation that it is dependent on the population size. Since the population is growing, using this principle will result in increasingly smaller person-equivalent carrying capacities in the future.
C12	**Compatibility allocation principles**
	The authors discuss that allocation step 2 can also be done based on current impact of buildings (bio-physical), constituting the grandfathering principle.

A5 Chandrakumar et al. (2019)

Title: A Benchmarking Approach to Operate Agri-food Systems within the 2°C Global Carbon Budget

General summary and remarks

The authors test the absolute environmental sustainability concept, focusing on climate change, on different New Zealand agri-food systems. The use the term absolute sustainability-based life cycle assessment (ASLCA).

The authors conducted a short literature review in which they give background information on the previous work on AESA. They also mention that the Science Based Targets initiative (SBT, 2015) worked out a method like the greenhouse gas emissions per unit of value-added (GVA) to guide companies to set GHG emissions reduction targets. It recommends a reduction of 5% per year for all economic sectors and their companies in order to achieve a 50% global GHG reduction in 2050. However, this method does not take heterogeneities in to account, a limitation that has been addressed in the sectoral decarbonizaiton approach, SDA, (Science Based Targets Initiative - SBTI, 2015) which provides sectoral and individual company carbon intensity pathways based on physical and economic indicators. Still, the SDA does only provide such pathways for homogenous sectors. Heterogeneous sectors such as agriculture also require absolute sustainability benchmarks, which is the scope within this publication.

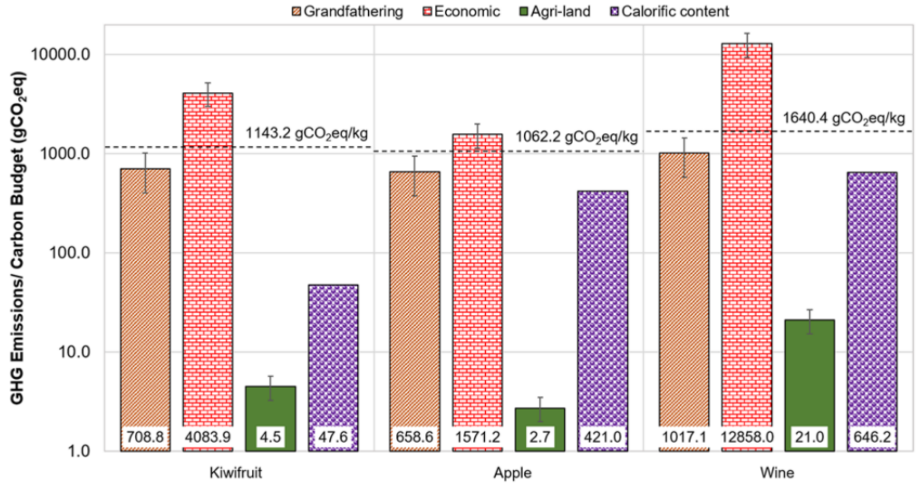
As they only focused on carbon budgets, they rightly acknowledge that further developments are needed to account for other environmental impacts for which the boundaries are better defined at regional or local levels.

Review criteria

LCA related criteria

C0	**Method/application**

	This method is an application of PBA'06 (Doka, 2016): "In this study, the 2°C target was used as the global boundary and an associated annual carbon budget was calculated (29.9 GtCO2eq) using the method ofDoka (2015, 2016)".
C1	**Scale / object study**
	Scale: product and sectoral Object: Several agri-food systems - Agri food sector NZ - Horticulture industries - Products
C2	**LCA adjustment**
	Standard LCA. Several previously conducted LCA studies for specific agricultural products (kiwi, apple, wine) have been identified and used.
C3	**FU as flux/pulse**
	The production of 1 kg of a certain agricultural product. Thus defined as a pulse, because not time dimension is included.
C4	**Absolute sustainability comparison**
	A comparison is made. The results from the LCA studies were compared against the allocated carrying capacities at three levels: - Products (LCA results for these products, specifically climate impacts, were directly usable) - Product-industries (when data was not available, the LCA results were assumed to be representative for the whole industry and therefore scaled up according to the production volumes) - Sector in the country, New Zealand (climate impacts of the NZ agri-food sector were estimated by combining datasets from different sources)
C5	**Results presentation**
	Bar charts, with: - normal or logarithmic scales depending on the differences of the results. - Bars representing the carbon budgets per kg determined with the different sharing principles - A dotted line representing the impact per kg from the LCA studies For example for the horticulture products:



<u>**PB related criteria**</u>

C6	**Sustainability objective**
	''To investigate how current and future agri-food systems can operate and develop within absolute environmental boundaries including the ones proposed for climate change."
C7	**Planetary boundaries included**
	The publication only elaborates on climate change, supported by the argument that this impact category provides sufficient data to enable calculations.
C8	**Quantification of SOS**
	The authors mention the two global PBs on climate change by (Steffen et al., 2015): 1. A global average of carbon dioxide concentration of 350 parts per million [ppm] CO2 or GHG concentration of 400 ppm car- bon dioxide equivalent [CO2eq] 2. A radiative forcing of 1 Watts per square meter [Wm−2]) However these reflect a limit of global temperature increase of 1.5 C. Since 2C is the internationally ratified target in the Paris Agreement and embraced by many players in industry, a 450 ppm CO2 eq (Clift et al., 2017) was adopted in this publication. An annual global carbon budget (CB_{Glo}) related to the 2C target was calculated by dividing the radiative forcing value (2.6W/m-2 here) by the absolute global warming potential of CO2 eq (8.69E-14 (W*yr)/(m2*kg GWP_{100yr} CO2eq, as determined by (Doka, 2016): CB_{Glo} = 29.9 (GtCO2eq/yr)

<u>**Allocation related criteria**</u>

C9 + C10	**Basis of allocation**
	Allocation principle(s) used
	1. <u>First, for the global agri-food sector, bio**physical** allocation was applied based on CO2 emissions, thus using the **grandfathering principle**:</u>

A share of the global annual budget was allocated based on current contribution, in CO_2 emitted, of global agri-food sector to global climate change.

After some adjustments and assumptions, the authors found:

$CB_{Glo,\ Ag\ Fd} = 0{,}23\ (23\%) * CB_{Glo} = 7.1$ $GtCO_2$ eq annualy.

In which:

$CB_{Glo,\ Ag\ Fd}$ = annual carbon budget for the global agri-food sector

2. Second $CB_{Glo,\ Ag\ Fd}$ could be allocated:
- among the countries producing agri-food products (NZ versus other countries)
- among the agri-food industries (products) of that country
- Finally, to obtain budget in CO_2/kg product, the budget for a an industry was divided by the total production volume in kg.

This second allocation procedure was conducted based on 4 different sharing principles:

Equity Principle	*Allocation basis* *(biophysical = B, Socio-economic = SE)*	*Reasoning provided*
Grandfathering principle	current contribution to CO_2 emissions (B)	-
Economic value (utilitarian)	GDP contribution (SE)	Economic value can be considered a proxy for societal value creation
Agri-land (utilitarian)	land occupation (B)	Agri-food systems require agricultural land
Calorific content (utilitarian)	contribution to global calorie production (B)	Calories can be a proxy to represent the fact that the primary purpose of agri-food production is to feed people

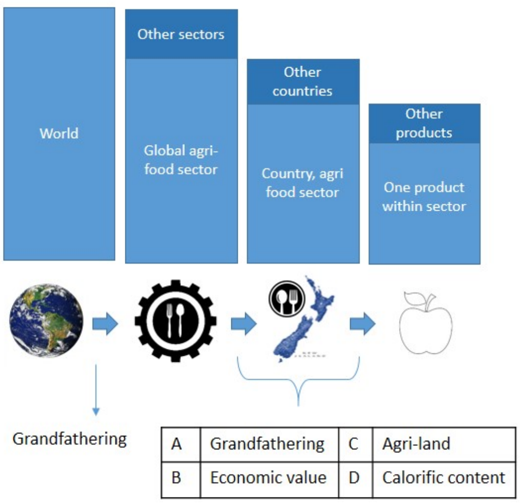


	Figure A2: allocation principles used
C11	**Principle documentation**
	The authors reflect on the implications of each sharing principle. They acknowledge that all four principles effectively reward certain sectors, countries or producers over others, in the form of higher carbon budget shares.
C12	**Compatibility allocation principles**
	Possible but not discussed.

A6 Doka, G. (2016)

Title: Combining life cycle inventory results with planetary boundaries: The Planetary Boundary Allowance impact assessment method Update PBA'06

Review criteria

<u>LCA related criteria</u>

C0	**Method/application**
	Method: Planetary Boundary Allowance impact assessment method (PBA'06)
C1	**Scale / object study**
	Not applicable, no case study included.
C2	**LCA adjustment**
	Doka (2016) developed an adjusted form of LCA: - The LCI results are characterized in to planetary boundary allowance (PBA) scores. Characterisation factors are developed and expressed as a fraction of the per-capita allowance for each of the eight planetary boundaries. The inventory multiplied with the characterization factors gives the occupation of one person's annual allowance of the boundary in question, by the studied system, where a value of 1 PBA always represents the total per-capita annual allowance. In this way, the method is similar to the normalisation from (Bjørn & Hauschild, 2015) but just applied to a different stage in the LCA framework. - Doka mentions that it is in principle desirable to have a geographical distinction of characterization factors, but if LCI data is not regionalized either (in many cases) than regionalized characterization factors would not add an increase in result precision. Therefore the PBA-06 is not regionalized and only provides generic global characterization factors. - There is optional weighting involved, when the determination of single scores trough aggregation is applied (see C5).

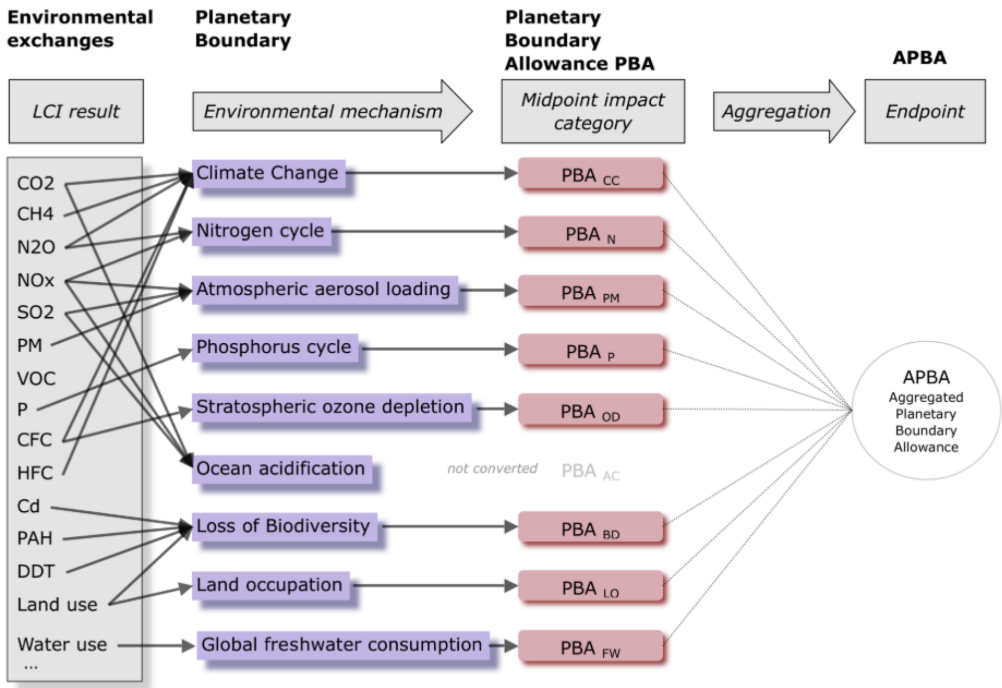


Figure A3: Visualized PBA'06, copied from (Doka, 2016).

C3 **FU as flux/pulse**

Not applicable, no case study.

However, there is no mention either of flux/pulse mismatch between PB and LCA indicators.

C4 **Absolute sustainability comparison**

The carrying capacity is integrated in the results and there is no allocation of this full personal PBA to the specific system. The result only reflects on the extent to which the personal PBA is occupied by a specific system.

Thus, similar to (Bjørn & Hauschild, 2015), a comparison is only made in the sense that the number is compared to the full PBA (1) awarded to each person.

C5 **Results presentation**

The results can be presented as a fraction of PBA in each separate impact category.

Alternatively, the results can be aggregated in to a APBA (aggregated planetary boundary allowance) single score for overall environmental damage. Such single scores are not recommended for sustainability checks, but only for comparative LCA purposes, due to several considerations:

- Adding up unaggregated PBA scores can result in a number above 1, which has no significance anymore.
- By adding up all unaggregated PBA scores it is assumed that all PBs are equally important (weighting).
- Compensations between burdens on PBs would be possible of full aggregation is applied, but this is not always desirable. Instead of only looking at a single score, it is important to also analyse the scores in PBs to identify whether exceedance takes place.

PB related criteria

C6	**Sustainability objective**
	"Check if the life cycle burdens of a particular lifestyle or personal consumption pattern fits into the available planetary capacities."
C7	**Planetary boundaries included**
	8 PBs are operationalized:

Planetary System Damage	Boundaries set in Steffen et al. 2015	Operationalisation in PBA'06 for Life Cycle Inventory data	Per-Capita Allowance in PBA'06
Climate Change	• ≤ 305 ppm CO_2 in atmosphere and • ≤ 1 W/m^2 warming power surplus	Warming power surplus converted to GWP for various greenhouse gas emissions	1150.75 kg CO_2-Eq per capita and year
Loss of biodiversity	• ≤ 10 extinctions per million species.yr (E/MSY) and • ≤ 1 E/MSY aspirational target and • ≥ 90% Biodiversity Intacness Index BII (new)	10% Biodiversity Intacness Index BII loss converted to relative reversible species loss from various emissions	0.0000195 species.yr per capita and year
Nitrogen cycle	• ≤ 62 Mt N /yr fixation	Nitrogen-containing emissions to air, water, soil	6.2 kg N emitted per capita and year
Phosphorus cycle	• ≤ 11 Mt P /yr emitted to ocean and • ≤ 6.2 Mt P mined + applied to erodible soils	Emissions of phosphorus and PO_4 to oceans directly, and indirect effects via characterisation approach for non-marine emissions	1.1 kg P emitted per capita and year
Stratospheric ozone depletion	• ≥ 276 Dobson Units stratospheric ozone concentration	14 Dobson Unit loss converted to ODP-weighted emissions of various ozone-depleting gasses	0.04094 kg ODP-Eq per capita and year
Ocean acidification	≤ 20% reduction aragonite saturation	not operationalised	–
Global freshwater use	• ≤ 4000 km3 / yr blue water use • Maximal monthly withdrawal in basin per flow-regime	Evaporative blue water consumption from water emissions to air	400'000 litre water per capita and year
Land occupation	• ≥ 75% original forest cover (global average) • Regional distinctions	Non-forest land occupations counted as forest loss	8510 m^2 non-forest land occupation per capita and year
Atmospheric aerosol loading	• ≤ 0.25 Atmospheric Optical Depth AOD on Indian Subcontinent • ≤ 10% warming Aerosols in total AOD	AOD converted to particle formation of air emissions (climate effect, not human health related)	Various particle generating emissions (SO_2, NH_3, NO_2, NMVOC, PM) derived from $2.22 \cdot 10^{-12}$ AOD.yr per capita and year
Chemical pollution	Undefined, renamed to "Introduction of novel entities" (includes GMO, nanomaterials, unknown effects)	not operationalised	–

C8	**Quantification of SOS**
	Eight different planetary boundaries are converted into per-capita–limits, using a projected human population of 10 thousand million (because using current population would require continuous adjustments). Thus the carrying capacity is quantified as a stock in individual PBs, for every individual human.

Allocation related criteria

C9	**Basis of allocation**
	The carrying capacity is allocated to individual humans. The allocation is therefore conducted on a per capita (biophysical) basis. The socio-economic dimension is not involved.
C10	**Allocation principle(s) used**
	Only egalitarian, because the full planetary carrying capacity is shared among all humans. By dividing by 10 billion, the egalitarian approach is even taken further because it also takes in to account future generations.
C11	**Principle documentation**
	The use of the egalitarian principle is not communicated or reflected on. This is a rather big limitation because the method does intend to use the per-capita allowance values to identify sustainable lifestyles or consumption patterns. This will lead to highly varying results considering different average per-capita impacts across different regions and countries.
C12	**Compatibility allocation principles**
	Would be possible but not discussed.

A7 González-Garay et al. (2019)

Title: Plant-to-planet analysis of CO2-based methanol processes

General summary and remarks

Review criteria

General steps:

C0	**Method/application**
	This publication is an application of the PB-LCIA method (Ryberg, Owsianiak, Richardson, et al., 2018).
C1	**Scale / object study**
	Scale: product (homogenous, or could possibly even be considered as a sectoral activity) Object: CO2 based methanol synthesis.
C2	**LCA adjustment**

	The method by Ryberg was applied to quantify the absolute sustainability level of methanol synthesis in terms of the PBs.
C3	**FU as flux/pulse**
	"The functional unit corresponds to one kilogram of methanol product". The functional unit is thus defined as a pulse, since no time dimension was included.
C4	**Absolute sustainability comparison**
	A comparison is made, but in the form of a division (impact over the allocated share of safe operating space) resulting in a dimensionless value. (see C5)
C5	**Results presentation**
	The results are expressed as a level of transgression in a PB i (TT_i) expressed by the following formula: $$TT_i = \frac{IMPT_i}{SHARE_i} \forall i$$ In which: $IMPT_i$ = impact from the system in accordance with the functional unit $SHARE_i$ = share of safe operating space (see C9) Sustainability determination: - If TT_i < 1 the technology can be considered absolute sustainable. - The authors argue that in case of TT_i > 1, a technology can still be appealing under the condition that the PB is still within the safe operating space and/or the contribution of the system to the specific PB is low. - The authors suggest that quotas in some earth systems could be traded among main contributors (e.g. agricultural actors need more space in the nitrogen/phosphorus PB compared to actors in the energy sector), in order to ease the compliance with absolute sustainability objectives.

<u>PB related criteria</u>

C6	**Sustainability objective**
	Quantify the extent to which green methanol can contribute to operating safely within the Earth's capacity.
C7	**Planetary boundaries included?**
	Eight (out of fourteen) PBs linked to six (out of nine) Earth systems: 1. energy imbalance (climate change) 2. atmospheric CO2 concentration (climate change) 3. Nitrogen cycle: global industrial and intentional biological fixation of nitrogen

	4. Phosphorus cycle: global phosphorus flows from freshwater systems into the ocean 5. stratospheric ozone concentration (depletion) 6. Ocean acidification 7. Land system change: area of forested land as a percentage of original forest cover 8. Freshwater use: maximum amount of consumptive blue water use
C8	**Quantification of SOS**
	The share of safe operating space in a PB is expressed with the following formula: $$SOS_i = [BOUND_i - NB_i] \; \forall i$$ In which: SOS_i = Safe operating space in a PB i $BOUND_i$ = boundary value for the PB i NB_i = natural background level for PB i

<u>Allocation related criteria</u>

C9	**Basis of allocation**
	A share of the safe operating space is assigned to methanol production based on a status quo principle (grandfathering principle), which allocates on the basis of current contribution towards total level of impact (biophysical, e.g. CO2 emissions). The percent wise share of safe operating space allocated to methane production ($PSHARE_i$) can be obtained with the formula: $$PSHARE_i = \frac{IMPBAU_i}{IMPTOT_i} \; \forall i$$ The actual share of safe operating space allocated to methanol production ($SHARE_i$) can be obtained with the formula: $$SHARE_i = PSHARE_i * SOS_i \; \forall i$$ Variables in the formulas: $IMPBAU_i$ = impact on PB i exerted by the total production of methanol via fossil based business as usual process $IMPTOT_i$ = current total level of impact in PB I subtracting the natural background level SOS_i = Safe operating space in a PB i
C10	**Allocation principle(s) used**
	Only the grandfathering principle.
C11	**Principle documentation**
	The use of the principle is announced but not further supported, discussed or nuanced.

	Yet, the language is rather enthusiastic regarding that the activity can be within its assigned SOS: "CO2-based methanol would contribute to operating safely within critical ecological limits of the Earth linked to carbon emissions, currently transgressed by the conventional process." This might not be valid under the application of other sharing principles.
C12	**Compatibility allocation principles**
	Possible but not discussed.

A8 Ritzen et al. (2019)

Title: Sustainable Energy Technologies and Assessments Carrying capacity based environmental impact assessment of Building Integrated Photovoltaics

General summary and remarks

The goal of this publication is to determine whether building integrated photovoltaics can operate within environmental carrying capacity.

This publication seems to present LCA impact results within one category as a carrying capacity. In this way the authors mix up the generated impact by the system with the biophysical carrying capacity allocated to this system, leading to confusing.

Furthermore, the publication only includes land use in the scope, thereby taking away the possibility to make trade-offs between different impact categories.

Review criteria

LCA related criteria

C0	**Method/application**
	Application, case specific method
C1	**Scale / object study**
	Scale: Product Object: building integrated photovoltaics (BIPV)
C2	**LCA adjustment**
	The authors do not follow the LCA framework correctly, which is already clear from the description of the stages: " 1. Goal and scope definition; during the first stage the goal of the LCA is described and the system boundaries are determined. 2. Inventory analysis; in the second stage, the main product variables are specified that influence the environmental impact.

	3. Impact assessment equations; in the third stage, the Life Cycle Inventory (LCI) phases included in this study are specified and the environmental impact equations are formulated. 4. Application: in the fourth stage, the environmental impact equations are applied on the different BIPV configurations " Standard LCI. Then in the LCIA, the embodied energy, and eventually embodied land use (EL) is calculated using the following equations in the impact assessment: <u>Embodied Energy EE:</u> $EE_{tot} = EE_{ext} + EE_{man} + EE_{constr} + EE_{reuse} + EE_{recyc} + EE_{circ}$ <u>Embodied Land use:</u> $EL_{tot} = EL_{ext} + EL_{man} + EL_{constr} + EL_{reuse} + EL_{recyc} + EL_{circ} + EL_{EE}$ $EL_{EE} = EE_{tot} * f$ $f = E_{gen}$ /array size *In which:* - *EE = Embodied Energy* - *EL = Embodied Land* - *E_{gen} = produced energy by the BIPV installation over its lifespan* *Subscores:* - *Tot = total* - *Ext = raw material extraction* - *Man = manufaturing* - *Constr = on site construction* - *Reuse = reuse* - *Recyc = recycling* - *Circ = circulation* - *EE = embodied energy*
C3	**FU as flux/pulse**
	Not defined. Assumed functional unit: The use of 1m2 BIPV in one year. Would correspond to a flux.
C4	**Absolute sustainability comparison**
	"With current maximum recycling rates and selected circulation route, the BIPV configuration with lowest environmental impact is the bamboo ventilated Amorf-Si variant with 3.67E+03m2·a impact. With a lifetime of 30 years, this would result in an environmental impact of 123 m2 per 1m2 BIPV rooftop."

	"The three selected BIPV configurations are indicative to demonstrate the application of the equations and show that their environmental impact exceeds carrying capacity." The embodied impact of the full life cycle is thus compared against 1m2 of operational BIPV, which is rather strange because this will always result in exceedance considering that the conversion of solar energy to usable energy on 1m2 of land will never be 100%.
C5	**Results presentation**
	As Embodied land per 1 m2 of different BIPV configurations including (current) maximum recycling percentages.

PB related criteria

C6	**Sustainability objective**
	- Avoid that resource consumption exceeds resource production - Avoid that land area demand exceeds land area availability.
C7	**Planetary boundaries included?**
	Including land use, but not using the planetary boundaries or another type of boundary.
C8	**Quantification of SOS**
	The authors write: - "The carrying capacity is defined as the ability of a system to (re) generate the resources consumed within the system itself." - "Carrying capacity based environmental impact covering direct and indirect land use is expressed in Embodied Land (EL), which is the time and land (m2·a) necessary to convert solar energy in operating energy, biotic resources, and Embodied Energy (EE) consumed in all life cycle stages." Actually, this EL is not the carrying capacity but rather the carrying capacity occupation; the impact for which the product system is responsible. The (assigned) environmental carrying capacity is thus not quantified in this publication.

Allocation related criteria

C9	**Basis of allocation**
	Although probably unintended, the authors assume by using this approach that the use of 1m2 BIPV in one year should also stay within 1m2 land use in the same year (See C4). Thus, they allocate on a biophysical basis (land occupation).
C10	**Allocation principle(s) used**
	Not communicated
C11	**Compatibility allocation principles**
	Not communicated

C12	**Compatibility allocation principles**	
	Could be explored, not further elaborated.	

A9 Ryberg, Owsianiak, Clavreul et al (2018)

Title: How to bring absolute sustainability into decision-making: An industry case study using a Planetary Boundary-based methodology

General summary and remarks

This publication tests the PB-LCIA method on a hypothetical laundry washing case study in the European Union. They applied four different sharing principles within the determination of the fair share of operating space and found that the choice for a principle was the biggest influencer of the results.

The authors reflect on previous ALCA work:

- Instead of using the PBs, the method from (Bjørn & Hauschild, 2015) on carrying capacity based normalization references, uses the average of the lower and upper value of the uncertainty zone, which was assumed to reflect the carrying capacity of the specific Earth System process.
- The previously conducted ALCA studies (Bjørn & Hauschild, 2015; Brejnrod et al., 2017; Sandin et al., 2015; Tuomisto et al., 2012; Wolff et al., 2017) had in common that the metrics of the PBs were matched with the existing impact categories in LCA. However, this involves a general mismatch because the indicators of existing impact categories are sometimes not at the same place on the impact pathway as the PB control variables. This mismatch was solved by developing an LCIA method in which the characterization factors express the impact scores in the units of the PB control variable (Ryberg, Owsianiak, Richardson, et al., 2018).

Review criteria

General steps:

C0	**Method/application**
	This publication is an application of the PB-LCIA method (Ryberg, Owsianiak, Richardson, et al., 2018).
C1	**Scale / object study**
	Scale: Product level Object: Laundry washing in the EU The case study is hypothetical because it extrapolates the data from only one model (to the EU level, for the sake of simplicity. The goal of the study is rather to test the usability of the PB-LCIA method (Ryberg, Owsianiak, Richardson, et al., 2018), apply different sharing principles, and analyze sensitivity.

	However, by making the drastic simplification to base the assessment of all the laundry in the EU on just one 'product-model' (see also the FU in C3), the study is representing a larger scale: the entire laundry sector at EU level.
C2	**LCA adjustment**
	Adjusted. They applied PB-LCIA. For details on this method, see the specific review of (Ryberg, Owsianiak, Richardson, et al., 2018) in appendix A10. The authors also recognize the importance to express the LCI elementary flows as mass per year: 1. Express results in metrics of the PBs, which are also annual 2. Including a time perspective to the LCIA ensures a transparent and freely selectable choice to assigning a SoSOS to the activity. In contrast (Bjørn & Hauschild, 2015; Doka, 2016) used mass to express the LCI, and therefore had to compare against annual personal shares. This restricted them to the equal per capita principle instead of multiple principles.
C3	**FU as flux/pulse**
	The functional unit was defined as a flux: "doing 34.3 billion washes per year of 4.5 kg of normally soiled dry fabric at medium water hardness with a model liquid detergent".
C4	**Absolute sustainability comparison**
	A comparison is made. The LCIA results are compared against the assigned SoSOS. If the results are below the assigned SoSOS, the activity can be considered absolute sustainable and not responsible for current/future PB exceedance. There is good reflecting on how to interpret the outcome depending on whether the PB is already transgressed or not: - For boundaries not yet transgressed, if all activities would have less impact than their assigned SoSOS, future PB transgression will be avoided. We note this this will only be the case if there is consistency in the application of sharing principles that determine this SoSOS. - For boundaries already transgressed, if all activities would have less impact than their assigned SoSOS, it is possible to maintain or reduce impact levels close to natural background levels, although this could take decades or hundreds of years. A condition is that the boundary transgression is still within the uncertainty zone and hasn't yet caused disruptions.
C5	**Results presentation**
	The results are presented as $occSoSOS_{PB,SP}$, which is a dimensionless indicator representing the occupation of the SoSOS: $$occSoSOS_{PB,SP} = \frac{IS_{PB}}{SoSOS_{PB,SP}}$$

- If $occSoSOS_{PB,SP_i}$ < 1 the technology can be considered absolute sustainable.
- If $occSoSOS_{PB,SP}$ > 1, a technology can be considered absolute unsustainable.

The values are then presented in a figure, in which

- The sharing principles are the columns on the x-axis (#1 and #8 represent scenarios used in the study)
- The y-as is a numerical value in logarithmic scale.
- The black dotted line at 1 is the $SoSOS_{PB,SP}$
- The black dots above or under 1 are the $occSoSOS_{PB,SP}$
- The strips around the dots are the 95% confidence interval of impact scores
- The red strips represent the uncertainty of the specific PB

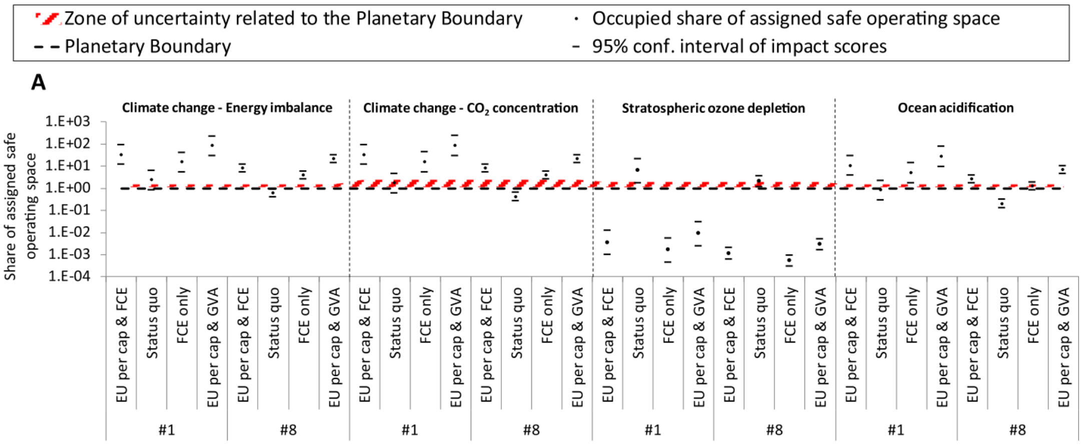


Figure A4: result presentation

Note that the copied figure A4 in this document only shows 4 of the PBs, see the publication for the others.

PB related boundaries

C6	**Sustainability objective**
	This publication deals with the various sustainability objectives (from a company perspective) rather specifically: - Facilitate business growth in the context of environmental limits - Mitigate reputational/regulatory/resource risks due to transgressing such limits - Improve competitiveness by minimizing costs of doing business
C7	**Planetary boundaries included?**
	- The publication includes the same PBs as in the PB-LCIA method (see figure C8). This means that it covers climate change, stratospheric ozone depletion, ocean acidification, biogeochemical flows (P and N), land system change (spatially differentiated, freshwater use (spatially and temporal differentiated, and atmospheric aerosol loading.

- The authors underline that it is important to treat every impact category separately because the assigned SoSOS shouldn't be transgressed in any impact category.

C8 Quantification of SOS

- The safe operating space available for human all activities was quantified as the value of the PB subtracted by the 'natural background level (see figure).
- Using this definition consistently is important to also ensure consistency in sharing the safe operating space among activities.

Impact category	Unit	Planetary Boundary (Steffen et al., 2015)	Natural background level (Steffen et al., 2015 and references therein)	Full safe operating space
Climate change - energy imbalance	Wm^{-2}	1	0	1
Climate change - CO_2 concentration	ppm CO_2	350	278	72
Stratospheric ozone depletion	DU	275	290	15
Ocean acidification	mol	2.75	3.44	0.69
Biogeochemical flows – P, regional	Tg P yr^{-1}	26.2	20	6.2
Biogeochemical flows – N, global	Tg N yr^{-1}	62	0	62
Land-system change – global	%	75	100	25
Land-system change – boreal	%	85	100	15
Land-system change – tropic	%	85	100	15
Land-system change – temperate	%	50	100	50
Freshwater use – global	km^3 yr^{-1}	4000	0	4000
Freshwater use - basin dry	–	1	0	1
Freshwater use - basin semidry	–	1	0	1
Freshwater use - basin humid	–	1	0	1
Atmospheric aerosol loading	–	0.25	0.14	0.11

Alternatively, the safe operating space might be defined as remaining safe operating space, by the PB minus the current value of the control variable). However, this involves fundamental flaws:

- It can discourage sustainable transition by 'removing' the full SOS in some categories or even suggesting negative values. In that case all activities with a positive impact score are unsustainable, regardless of whether they have less impact than existing technologies.
- The remaining SOS is not relevant for the assessment of whether an activity is within its SoSOS.
- By using the remaining SOS one applies a grandfathering (status quo) principle by pre-assigning the currently occupied share of SOS to current activities. New and possibly more sustainable technologies are then excluded from this share of SOS.

Allocation related criteria

C9 Basis of allocation

+ Allocation principle(s) used

C10

The general equation to calculate the share of safe operating space ($SoSOS_{PB,SP}$) according to sharing principle SP is:

$$SoSOS_{PB,SP} = SOS_{PB} * aS_{PB,SP}$$

In which:

- SOS_{PB} = the full safe operating space of the PB
- $aS_{PB,SP}$ = the percentwise share assigned to the activity according to the chosen principle.

The authors use four principles: three egalitarian and one non-egalitarian. There are two principles with a different economic indicator to test whether this would lead to the approximately same SoSOS.

Equity Principle	*Allocation basis* *(biophysical = B, Socio-economic = SE)*	*Reasoning provided*
1.Status quo (grandfathering)	Current impact relative to global current impact(B)	The laundry service is entitled to the same share of impact that it already occupies
2.FCE only (egalitarian)	FCE: Final Consumption Expenditure (SE)	FCE can be considered a proxy for citizen preferences (expenditure on laundry versus other activities)
3.EU per-cap & FCE (egalitarian)	First per capita (B) Second per FCE: Final Consumption Expenditure (SE)	economic value can be considered a proxy for contribution to human wellbeing, i.e. increased economic value leading to increased wellbeing
4.EU per-cap & GVA (egalitarian)	First per capita (B) Second per GVA: Gross Value Added (SE)	Economic value can be considered a proxy for contribution to human wellbeing, i.e. increased economic value leading to increased wellbeing

The specific equations that were used for each sharing principle can be found in the original publication (Ryberg, Owsianiak, Clavreul, et al., 2018).

C11 **Principle documentation**

It is acknowledged that the use of any sharing principle somehow favors specific activities over others, and that transparency is therefore important

- Grandfathering favors established activities with high impact by assigning them a higher share
- Sharing based on economic indicators favors activities that generate high economic output
- The authors recommend to develop and test more principles
- The SoSOS changes over time due to changes in the indicators they are based on (e.g. population and economic output). A future recommendation for this problem is to couple external dynamic models to the assessment to ensure that the SoSOS is always up to date.

	In absence of a general agreement on the choice of sharing principles, the authors suggest a **solution**: To quantify the uncertainty related to the choice of sharing principle by applying Monte Carlo simulation. A condition for claiming the absolute sustainability of an activity could be that a minimum of four sharing principles were used an that 95% of the iterations didn't transgress the SoSOS.
C12	**Compatibility allocation principles**
	The authors suggest that a sharing principle could also be based upon the technological feasibility for operating within the SoSOS. For example, (Krabbe et al., 2015) defined sector specific targets based on their impact reduction potential regarding GHG emissions. Yet, such a principle has not been brought to practice in this study.

A10 Ryberg, Owsianiak, Richardson et al. (2018)

Title: Development of a life-cycle impact assessment methodology linked to the Planetary Boundaries framework

General summary and remarks

Previous work is recognized, in which the conversion of the metrics in the PB-framework to existing impact categories in LCA took place (Bjørn & Hauschild, 2015; Sandin et al., 2015). The limitation in such an approach is a mismatch between the position of LCA indicators and PB control variables in the impact pathways (cause effect chains that describe how emissions, pollutants or resource use result in impacts).

The authors also reflect on (Doka, 2016) and comments that this method uses indicator which are expressed as annual person-equivalent budgets. In this way the method does not include the determination of a share of personal budget that an activity is allowed to occupy.

The authors suggest that a PB-LCIA method supports the quantifying and evaluating of progress regarding SDG 12 (on sustainable consumption and production), although no further explanation is given for this suggestion.

Review criteria

<u>LCA related criteria</u>

C0	**Method/application**
	Method: Planetary Boundary Life Cycle Impact Assessment (PB-LCIA)
C1	**Scale / object study**
	N.A. Method introduction
C2	**LCA adjustment**
	Adjusted LCA. Characterisation factors that express impact at midpoint in the metrics of the control variables from the PB framework.

This introduces some new aspects compared to conventional LCA:

- Goal definition: to assess the sustainability of the occupation of safe operating space by a system, and how to improve it.
- Scope and LCI: the goal requires that all processes needed to fulfill the FU are actually modelled in order to get an holistic representation of SOS occupation. (not a necessity in comparative LCA).
- LCI elementary flows have to be expressed as constant annual inputs and FU has to be defined accordingly (see C3)

C3 **FU as flux/pulse**

The authors devote a lot of explanation to the pulse/flux problem.

“The presented PB-LCIA method requires that the LCI provides flows as constant inputs [mass /time] instead of pulses [mass]. To accommodate for this, the functional unit (FU) in the LCA, on which the assessment is based, must be defined with a continuous constant time duration, i.e. as annual fulfilment of the function in the FU in order for the LCI to express the elementary flows that will occur annually in order to continuously fulfil the FU”

For example: traveling 25.000 km per year

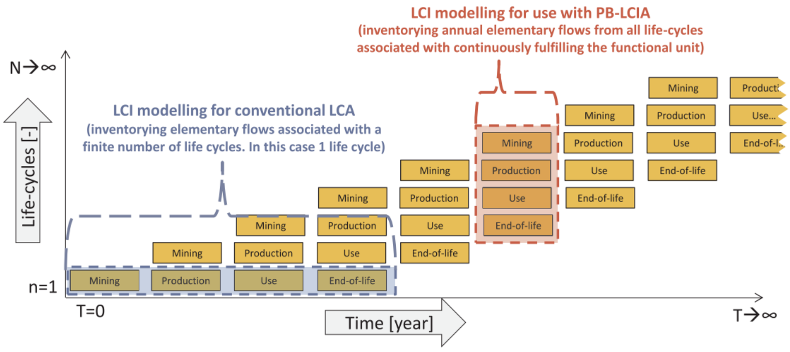


Figure A5: Flux pulse in conventional LCA and PB-LCIA, copied from (Ryberg, Owsianiak, Richardson, et al., 2018).

The figure shows that conventional LCA is about all elementary flows originating from a finite set of life cycles (left to right). On the other hand PB-LCIA is about all elementary flows originating from overlapping life cycles (top to bottom) which are all necessary to fulfill the FU continuously.

Note that functions will be fulfilled differently in the future, leading to different impact profiles, but this is not taken into account in the PB-LCA. It works with the assumption that the function will be provided continuously.

Even though the LCI expresses elementary flows as constant annual inputs, there are specific cases where emissions and resource uses actually occur only once. This can be problematic because it can result in and exceedance of the Earth system’s recovery time and therefore also the potential transgression of PBs (as the emissions are present in the environment for a long time). For example, deforestation and land transformation for agriculture leads to a single pulse of CO2, which may be problematic regarding the climate change PBs because of the long atmospheric residence time of CO2.

C4	**Absolute sustainability comparison**
	A comparison can be made, between the PB-LCIA results and the assigned share of SOS. But the publication itself does not include a comparison because the share of SOS for a system is not discussed.
C5	**Results presentation**
	After the application of CFs proposed in this publication, LCA results are expressed in the units of the control variables.

PB related criteria

C6	**Sustainability objective**
	Quantify the environmental performance of products and technologies in relation to Planetary Boundaries.
C7	**Planetary boundaries included?**
	Characterization factors were developed for all PBs from Steffen et al. (2015) except for the 'biosphere integrity' for which characterization models were considered immature, and except for 'introduction of novel entities' that does not yet have a defined PB.

Planetary boundary	Value	Comment
Climate change: energy imbalance	1W/m2	This boundary includes all GHGs, aerosols and other factors affecting radiative forcing.
Climate change: Atmospheric CO2 concentration	350ppm	This boundary does not include other GHG than CO2. Still it can be considered as a decent proxy for radiative forcing because currently the warming effect of non CO2 GHGs roughly balances out with cooling effect from aerosols
Stratospheric ozone depletion	275 DU	Representing a 5% reduction compared to a pre-industrial level of 290 DU
Ocean acidification	2.75 Ohm arag	
Biochemical flows: global P flow from freshwater to ocean	11 Tg P/yr	
Biochemical flows: Regional P flow from fertilizer to erodible soils	26,2 Tg P/yr	

	Biochemical flows: global, biological fixation of N	Tg N/yr	
	Land system change: global area of forest land	75%	Compared to original forest cover
	Area of forested land	Trop:85% Temp:50% Bor:85%	Compared to potential forest (Trop = Tropical, Temp = Temperate, Bor = Boreal)
	Freshwater use: Global, blue water consumption	4000 Km3/yr	
	Freshwater use: regional, blue water withdrawal	LFM:25% MFM:30% HFM: 55%	As % of mean montly flow (MMF) *Temporal variation*: (LFM = Low-flow month, MFM = Medium flow month, HFM = High flow month) *Spatial variation*: CFs specific for different aridity archetypes (arid, semi-arid, humid)
	Atmospheric aerosol loading: regional	0.25 AOD	AOD = aerosol optical depth. As a seasonal average over a region with South Asian Monsoon used as case study.

Impacts at different spatial (global vs local) and temporal (seasons) resolutions can be assessed by using spatial and temporally differentiated CFs. The aggregation of these impacts in a single global score is however not possible because it would result in the loss of specific details during averaging across spatial and temporal scales.

Consequently it is suggested separately assess impact scores at different spatial and temporal scales. For example in freshwater use, evaluate the global average level, the impact at aridity archetype level and possible even river basin level.

C8	**Quantification of SOS**
	As flows: Biochemical flows N & P Freshwater use As stocks: Climate change (energy imbalance and CO2 concentration), Stratospheric ozone depletion, Ocean acidification, Land system change: global area of forest land , Area of forested land, Atmospheric aerosol loading: regional

<u>Allocation related criteria</u>

C9	**Basis of allocation**

	The PB-LCIA method only offers a characterization step that enables a practitioner to express impacts in the control variables of the PB framework. The determination of the 'fair share of operating space' is a separate activity and is not treated in this publication.
C10	**Allocation principle(s) used**
	N.A.
C11	**Principle documentation**
	The authors do however advise to determine this share in numerous ways and therewith test the robustness of the sustainability conclusion.
C12	**Compatibility allocation principles**
	N.A.

A11 Sandin et al. (2015)

Title: Using the planetary boundaries framework for setting impact-reduction targets in LCA contexts

General summary and remarks

This approach assumes that each product is absolute unsustainable and needs to realize impact reductions in line with calculated impact reduction targets (percentages) based on the planetary boundaries and the status quo of control variables (transgression of the PB or not). These targets are adjusted to be more or less stringent with additional factors. The value of these adjustment factors rely on value based judgment.

Review criteria

LCA related criteria

C0	**Method/application**
	Method (PB based impact reduction targets) and also an application of the method
C1	**Scale / object study**
	Scale: sector Object: clothing The paper proposes a procedure to use global goals based on the planetary boundary framework for setting impact reduction targets at the scale of products. However, they are actually derived for the clothing sector, and are assumed to be applicable to each product within the sector. See criteria 9.
C2	**LCA adjustment**
	Not described in this paper. Yet, standard LCA which is conducted separately from the procedure described in the paper.

	"The application of the procedure is, however, independent of the results of the specific LCA, and details of the LCA (system modelling, inventory data, etc.). The outcome of applying the procedure in the LCA context holds also for other similar contexts where the studied product or service reflects Swedish consumption, where the supply chain is global in nature, where 2050 is a reasonable time horizon, and where it can be reasonably assumed that the per capita demand for the functional unit is constant over time."
C3	**FU as flux/pulse**
	The functional unit was defined as a flux: "The service provided by one day's use of each studied garment, i.e. the study covered five different functional units, one for each garment." The authors aim to understand whether interventions can reduce impact per functional unit (within each impact category) sufficiently to meet global environmental challenges as expressed by the PBs.
C4	**Absolute sustainability comparison**
	This approach in fact assumes that each product is absolute unsustainable because some boundaries have been transgressed, and therefore all products need to realize impact reductions according to the PB framework and additional equity factors. Thus, no comparison between current impact and a reference. An absolute sustainability comparison can however be made in the future: The impact reduction targets can be used to calculate future impact allowance.
C5	**Results presentation**
	Three possibilities are mentioned (only 1 and 3 are presented in the paper) - Percentages as impact reduction targets - Future impact allowance: An impact reduction target of 90% translates to a 10% future impact allowance. An actual impact allowance value can thus be obtained by multiplying the current impact value with the impact reduction target percentage. - Increase in environmental efficiency

PB related criteria

C6	**Sustainability objective**
	Respect the nine biophysical planetary boundaries to avoid risks of abrupt, non-linear environmental change causing functional collapses in ecosystems. The time frame to meet the boundaries is set at 2050.
C7	**Planetary boundaries included?**
	Only included the PBs that were quantified by Steffen et al. (2015) and were feasible to use for setting global impact reduction targets which relate to commonly used impact categories in LCA:

PB	Control variable(s) for quantifying the PB	Related impact categories	Global target for impact reduction until 2050 implied by the PB
Climate change	(i) Atmospheric carbon dioxide concentration (ii) Energy imbalance at top-of-atmosphere	Climate change	100 %
Interferences with the nitrogen cycle (part of the biogeochemical flows PB)	Annual rate of industrial and intentional biological fixation of nitrogen	Eutrophication, marine eutrophication, terrestrial eutrophication, terrestrial acidification	59 %
Interferences with the phosphorus cycle (part of the biogeochemical flows PB)	(i) Annual rate of phosphorus flowing into oceans (ii) Annual rate of phosphorus flow from fertilisers to erodible (agricultural) soils	Eutrophication, freshwater eutrophication	56 %
Freshwater use	Annual consumptive blue water use (global control variable; control variables are also suggested at the level of biomes)	Freshwater consumption	−54 %
Land-system change	Area of forested land as percentage of original forest cover (global control variable; control variables are also suggested at the level of basins)	Land transformation (in particular transformation of forest land)	100 %
Changes in biosphere integrity	(i) Species extinction rate (as a control variable for genetic diversity) (ii) Biodiversity Intactness Index (as a control variable for functional diversity)	Land occupation (midpoint), land transformation (midpoint), biodiversity loss (endpoint)	99 %

They exclude the boundaries that are quantified as an absolute state and are thus not suitable for setting impact reduction targets: Stratospheric ozone depletion, aerosol loading.

C8 **Quantification of SOS**

Climate change: stock, global

Biochemical flows N & P: flow, global

Freshwater: flow, global

Land-system change: stock, global

Changes in biosphere integrity: flow, global

<u>Stocks/flows:</u>

It is rather straightforward to interpret the PBs in terms of impact reduction targets when the control variables are expressed as rate of intervention (flow), but more difficult for PBs expressed as absolute state (stock). In the paper, the PBs with absolute state control variables are only included is a full stop of impact is required (100% impact reduction). Defining impact reduction target from other absolute state control variables is suggested as further research.

The authors mention that in order to improve the PB framework, it is needed to discuss the appropriateness of illustrating PBs in the same figure if control variables of both rates of interventions (flows) and absolute states (stocks) are used. Moreover, for the purpose of operationalizing the PB framework into efforts for reducing environmental impacts, control variables expressed as rates of interventions are preferable.

<u>Global/local expression of PBs</u>

Since all assessed PBs are at a global level, the procedure is deemed particularly feasible

for assessments of consumption sectors that involve many globally distribute supply chains. For other cases, the authors mention that it would be better to use characterization methods that involve location-dependent factors, such as for land and water use.

<u>Allocation related criteria</u>

C9	**Basis of allocation**

The procedure for deriving top-down product-level impact reduction targets consists of four sequential steps:

1. For the impact categories studied in the product assessment, identify the quantified planetary boundaries
2. Interpret these planetary boundaries to set the allowed annual global impact and therefrom set annual global impact reduction targets (until a certain point in time dependent on the study)
3. First translate the global target towards a target for the particular global market segment
4. Then translate the market segment target to a specific target for the studied product

Interestingly, this procedure is the other way around compared to AESA framework (Bjørn, Richardson, et al., 2019). There, the selection of data and calculation of environmental pressure caused by product system depends on which carrying capacities have been defined.

The four-step procedure is mathematically described as:

$$RT_{i,j,k} = 100 - (100 - RT_i) \times A_{Step3,j} \times A_{step\ 4,k}$$

- $RT_{i,j,k}$ is the impact-reduction target (in %) for (characterized) impact result in impact category i, related to functional unit k belonging to global market segment j. This is the final result of the procedure.
- RT_i (the result of step 2) is the required percentage of global impact reduction in impact category i based on planetary boundary knowledge.
- $A_{Step3,j}$ is the allocation factor of step 3, i.e. the share of the globally allowed annual impact allocated to global market segment j at the chosen point in time, versus its current share of current global annual impact.
- $A_{step\ 4,k}$, is the allocation factor of step 4, i.e. a factor reflecting the allowed impact for functional unit k versus the allowed impact of global market segment j.

C10	**Allocation principle(s) used**

For the impact categories that have an impact reduction target of 100%, the allocation is not applicable. After all, if there is no room for impact left, it does not matter how you share it.

For the other impact categories, now follows an overview of how $A_{Step3,j}$ and $A_{step\ 4,k}$ are determined based on ethical principles.

<u>Principles step 3 (translate the global target towards a target for the particular global market segment):</u>

The authors mention that the determination of market segment's share of allowed global impact compared to its current share is dependent on whether it is considered as essential human need. This is an ethical and value based dilemma, for which three approaches are developed:

Three approaches by (Sandin et al., 2015)	Ethical reasoning provided	Value of $A_{Step3,j}$

The clothing market segment is assumed to have the right to cause the **same share** as impact.	All segments have the same obligation to reduce impact and the clothing segment can be considered as an average sector in terms of fulfilling essential needs.	1
The clothing market segment is assumed to have **half the share** of current impact	The impact of the clothing segment is currently larger than needed for fulfilling human needs.	0.5
The clothing market segment is assumed to have **half the share** of current impact.	The clothing segment can fulfills essential human needs because it protects from sunlight and provides warmth.	2

We note that:

- The ethical reasons provided are conflicting with each other and it is not clear who should decide this.
- The adjustments of the shares of impact are rather normative, but this is still an unavoidable aspect of such impact allocation. Yet, these numbers seem even more arbitrary than allocating based on a specific indicator.

<u>Principles step 4 (translate the market segment target to a specific target for the studied product):</u>

If the assumption is made that there the future per capita need for daily clothing use is equal to the present need, then the question is about sharing the allowed impact of the global clothing segment (in 2050) between Swedish citizens and the global population. Based on previous literature, such as Grasso, (2012), four ethical principles for sharing this allowed impact are deemed usable in the procedure:

Principle	Explanation	Equation:
Equal per capita (egalitarian)	The allowed impact of global clothing segment is split equally over all citizens globally.	$A_{step4,k} = \frac{P_{GloCur}}{P_{GloFut}} \times \frac{I_{glo}}{I_{reg}}$
Grandfathering segments	The regional market segment has the right the emit the same share as the corresponding global segment.	$A_{step4,k} = \frac{P_{RegCur}}{P_{RegFut}}$
Grandfathering population	The future citizens of a region (Sweden) inherit the right to emit the same share of emissions that its current citizens have compared to the rest of the world.	$A_{step4,k} = \frac{P_{GloCur}}{P_{GloFut}} \times \frac{P_{RegCur}}{P_{RegFut}}$
Cumulative emissions per capita (historical debt = egalitarian)	The emissions per capita are considered on a cumulative basis; The future citizens of a region are allowed to cause less impact per capita than the global average because the current citizens cause more impact per capita than the global average.	$A_{step4,k} = \frac{P_{GloCur}}{P_{GloFut}} \times \frac{P_{RegCur}}{P_{RegFut}} \times \left(\frac{I_{Glo}}{I_{Reg}}\right)^2$

	A proxy if used: if current regional share is X times global average, then the future share is 1/X times global average. We note that: - The allocation is only done to the level of the full Swedish clothing sector, and the impact reduction targets are therefore assumed to be applicable to all products within this sector. This is later also mentioned indirectly: “The results of this paper could be useful for the Swedish clothing sector when formulating targets and/or strategies for impact reduction (at a product, firm or sector level)”.
C11	**Principle documentation**
	The principles are well communicated.
C12	**Compatibility allocation principles**
	It is also mentioned that step 3 (determination of $A_{Step3,j}$) can also be subjected to ethical principles similar to those used in step 4. For example a possibility is to determine the value of $A_{Step3,j}$ based on historical rights of global market segments. However, due to the lack of data this was not realized. Instead the authors used the three normative principles as described under C10.

A12 Swiader et al. (2018)

Title: Application of ecological footprint accounting as a part of an integrated assessment of environmental carrying capacity: A case study of the footprint of food of a large city

Review criteria

LCA related criteria

C0	**Method/application**
	Application, case specific method
C1	**Scale / object study**
	Scale: city Object: Environmental impact of food consumption in Wroclaw, Poland
C2	**LCA adjustment**
	The publication includes a bottom up approach to quantify the environmental footprint of food consumption in Wroclaw, using standard LCA. Ecological footprint (EF) is defined as: “human demand on nature (such as consumed resources, occupied space, and emitted pollutants) that compete for biologically productive space.” The LCA quantified the carbon footprint of food (CF_f). First the exerted amount of CO2 eq from food consumption by an average inhabitant of Wroclaw was determined. This CO2eq was

	converted to equivalent area needed to sequestrate the GHG emissions, using the global CO2 sequestration index. Thus, the CF_f can be calculated with the equation: $CF_F = \sum(I_N \times A_{Fn} \times I_{CO2eq})/1000 \times Is_{CO2}$ In which: CF_F = the Carbon Footprint of food (gha) I_N = the total number of inhabitants A_{Fn} = the annual weighted average amount of given consumed food in kg per inhabitant (kg) I_{CO2eq} = the amount of CO2eq emitted during whole life duration of given n-product (at all levels from production by consumption to final disposal) (kgCO2eq/kg or L of product Is_{CO2} = the global carbon dioxide sequestration rate (gha/tCO2).
C3	**FU as flux/pulse**
	Not communicated. Assumed: The consumption of food for the city Wroclaw within one year. Corresponds to a flux.
C4	**Absolute sustainability comparison**
	A comparison is made between the values of environmental footprint of food (EF_F) and the biocapacity benchmark (BC), See C8. The difference between both would indicate whether or not the environmental carrying capacity is exceeded. The results showed that the EF exceeded the BC 10-fold, but this is not surprising because the EF of a city is generally always bigger that the area it occupies itself (on which the biocapacity is based). Therefore the comparison is a bit meaningless.
C5	**Results presentation**
	Both EF and BC are expressed in global hectares (gha).

PB related criteria

C6	**Sustainability objective**
	Assess the boundaries to growth for the future development of cities by the inclusion of the assessment of the environmental carrying capacity (ECC) into spatial management
C7	**Planetary boundaries included?**
	Only land use
C8	**Quantification of SOS**
	Environmental carrying capacity expressed as biocapacity (BC): Actual annual bioproductive ability of an area (an ecological benchmark) to provide the human needs. The biocapacity can be calculated with the following equation:

	BC = ∑(An × YFn × EQFn) In which: BC = the biocapacity (gha) An = the area of given land use type (ha) YFn = the yield factor for given land use type (ha) EQFn = the equivalence factor for given land type (ha) The biocapacity is in this way based on the amount of land and land use types within the city and it's municipalities.

Allocation related criteria

C9	**Basis of allocation**
	The amount of land that is allocated to the city is equal to the area that the city occupies. This is also the main limitation, because this usefulness of this measure as a sustainability benchmark is questionable (see C4).
C10	**Allocation principle(s) used**
	Not applicable
C11	**Principle documentation**
	Not applicable
C12	**Compatibility of method with other allocation principles?**
	Not applicable

A13 Tuomisto et al. (2012)

Title: Exploring a safe operating approach to weighting in life cycle impact assessment - a case study of organic, conventional and integrated farming systems

General summary and remarks

Introduction of weighting factors for usage in LCA, based on a distance-to-target approach using the safe operating spaces from the planetary boundary framework and the current status of these boundaries.

This weighting approach is only valuable if single scores are desired. The method provides single scores based on weighted results, to compare overall performance of products on planetary boundaries. This would make the method potentially useful for supporting overall performance on an environmental SDG that aligns with (some of) the planetary boundaries included in the analysis, but it is not suitable if the goal is to report about performance on most SDG targets or indicators, as they are about a specific impacts.

Review criteria

LCA related criteria

<table>
<tr><td>C0</td><td>Method/application</td></tr>
<tr><td></td><td>Method: PB-based weighting factors

And application</td></tr>
<tr><td>C1</td><td>Scale / object study</td></tr>
<tr><td></td><td>Scale: Company level

Object: Farming alternatives</td></tr>
<tr><td>C2</td><td>LCA adjustment</td></tr>
<tr><td></td><td>Standard characterization, normalisation. Adjusted weighting.</td></tr>
<tr><td>C3</td><td>FU as flux/pulse</td></tr>
<tr><td></td><td>The FU is not explicitly mentioned but was extracted from the text:

“Each farm was assumed to utilize 100 ha land and produce food crop output of 460 tonnes (t) potatoes, 88 t winter wheat, 60 t field beans and 66 t spring barley.”

It is assumed that the food crops outputs reflect a full production year, which would make the FU a flux.</td></tr>
<tr><td>C4</td><td>Absolute sustainability comparison</td></tr>
<tr><td></td><td>Integrated in the results. One of the steps from the LCA framework, weighting, is adjusted around the planetary boundary framework. This leads to PB based weighting factors:

<table>
<tr><th>ESP (Rockström et a., 2009)</th><th>Unit</th><th>PB</th><th>Current value

(2012)</th><th>Weighting factor</th></tr>
<tr><td>Climate change 1</td><td>Parts per million</td><td>350</td><td>387</td><td>1,11</td></tr>
<tr><td>Climate change 2</td><td>Watts per m2</td><td>1</td><td>1.6</td><td>1.6</td></tr>
<tr><td>Climate change average</td><td>-</td><td></td><td></td><td>1.31</td></tr>
<tr><td>Biodiversity loss</td><td>Number of species per million species years</td><td>10</td><td>100</td><td>10</td></tr>
<tr><td>Nitrogen cycle</td><td>Million tonnes N per yr</td><td>35</td><td>121</td><td>3.46</td></tr>
</table>
</td></tr>
</table>

	Phosphorus cycle	Million tonnes P per yr	11	9	0.82
	Ozone depletion	Dobson units	276	283	1.02
	Ocean acidification	Saturation state of aragonite in surface sea water	2.75	2.9	1.05
	Global freshwater use	Km3 water consumed per yr	4000	2600	0.65
	Land use	% crop land	15	11.7	0.78

The (normalized) results in the impact categories are multiplied with the PB based weighting factors, according to the following formula:

$$W = \sum_i \propto_i D_i / N_i$$

In which:

W is the weighted score for all aggregated impact categories

α_i is the weighting factor for each individual impact category

D_i is the impact result before weighting in each individual impact category

N_i is the normalization value for each individual impact category

C5	**Results presentation**
	Single scores

PB related criteria

C6	**Sustainability objective**
	To meet the challenge of maintaining the stable state of the planet.
C7	**Planetary boundaries included?**
	In this method, only the global boundaries (see C8) are used to obtain one single weighting factor for each boundary. The weighting becomes more challenging when spatially differentiated boundaries would be used to granulate the results, such as desired for boundaries such as freshwater use.
C8	**Quantification of SOS**
	Climate change: 350 ppm CO2 (stock), 1 W/m2 (flow)

	Biodiversity loss: annual extinctions/million species (flow) Nitrogen cycle: million tonnes N per yr (flow) Phosphorus cycle: million tonnes P per yr (flow) Ozone depletion: Dobson units (stock) Ocean acidification: saturation state of aragonite in surface sea water (stock) Freshwater use (global): km3 of annual water consumption (flow) Land use: % of crop land (stock) - If a PB was accompanied with an uncertainty range (biodiversity loss, phosphorus cycle, global freshwater use), then the lower value was used, in line with the precautionary principle. - The GHG emissions, nutrient balances, land use and biodiversity impacts of these farming systems were quantified in the case study. There is no comment on why the other impacts are left out. - The method does not account for interdependencies among boundaries. Also, the assumption is made that staying within safe limits of each impact category is equally important, which is consistent with the planetary boundary framework (Tuomisto et al., 2012). Further, the mismatch between planetary boundaries and LCA-IC's is not resolved; i.e. the weighting factors for nutrients loss are separately calculated for nitrogen use and phosphorus use, instead of deriving one weighting factor for the eutrophication impact category. - Especially the biodiversity weighting factor is problematic because the biodiversity impacts in the LCA were expressed as vascular plant species richness whereas the biodiversity weighting factor was based on extinction of all species. This makes them incompatible. Both indicators also have their own flaws.

Allocation related criteria

C9	**Basis of allocation**
	This method provides no guidance on the allocation of remaining operating space based on the PBs. The authors state: "the method does not represent the way in which priorities might be given for the competing demands for ways in which the available capacity might be used. This needs to be allocated between countries and between projects and initiatives within countries, which would create different weighting factors for different regions or countries.''. Because the assignment of a share of safe operating space to a specific system is not dealt with, this method is not truly a AESA method if the framework from Bjørn et al. (2018) is followed.
C10	**Allocation principle(s) used**
	N.A.
C11	**Principle documentation**
	N.A.
C12	**Compatibility allocation principles**

	N.A.

A14 Wolff et al. (2017)

Title: Detecting unsustainable pressures exerted on biodiversity by a company. Application to the food portfolio of a retailer

General summary and remarks

Biodiversity has an integrative character and is driven by many local (such as habitat loss) and global pressures (such as climate change) due to anthropogenic activity. This hampers the attribution of biodiversity loss to individual entities such as a company or person. An AESA generally intends to compare the environmental impact (footprint) of an entity) against it assigned share of carrying capacity (in other words: its environmental budget).The goal in this publication is to propose and test an adaptation of the AESA approach to the biodiversity impacts of a company and its supply chain.

Review criteria

LCA related criteria

C0	**Method/application**
	Application of CC-based normalization (Bjørn & Hauschild, 2015)
C1	**Scale / object study**
	Scale: Company Object: Food portfolio of a retailer including more than 50.000 food references over 880 categories of human and pet food products.
C2	**LCA adjustment**
	Standard LCA, quantified impact on midpoints (ILCD prioritized) and endpoints (ReCiPe2016). All midpoints or endpoint cover or are related to biodiversity impact.
C3	**FU as flux/pulse**
	The functional unit was clearly defined, and formulated as a flux: “To produce from cradle-to-farm-gate the food Portfolio of products (PoP) that was delivered by CASINO France over a 1-year time interval”
C4	**Absolute sustainability comparison**
	A comparison is made. The impact is considered unsustainable if: $f_i > b_i$ In which: b_i = environmental budget assigned to a company

	f_i = footprint exerted by the company entity in impact category i
C5	**Results presentation**

A graph showing the assessed impact categories (colums) and the corresponding:

- exerted impact result including the uncertainty (as a percentage of full ecological budget)
- a consumers full ecological budget (red dotted line at 100%)
- The assigned ecological budget to the company, based on different sources (colored stripes)

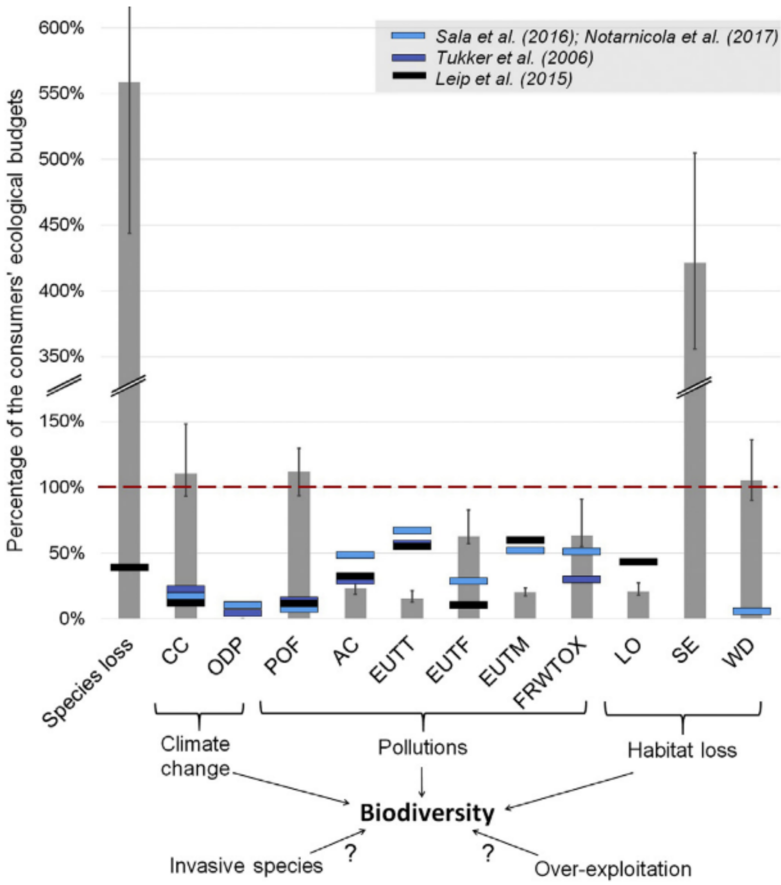


Figure A6: result presentation

PB related criteria

C6	**Sustainability objective**
	More general: Maintain the Earth in Holocene-like conditions. More specifically; consider whether the ecological impacts of a company are compatible with biodiversity conservation objectives.
C7	**Planetary boundaries included?**

+	**Quantification of SOS**
C8	The authors used the definition of carrying capacity by Bjørn & Hauschild (2015): "the maximum sustained environmental interference a natural system can with- stand without experiencing native changes in structure or functioning that are difficult or impossible to revert"

Level of analysis	LCA impact category	Ecological carrying capacities		
		Individual ecological budget (CC/pop in pers.year)	**Stock / flow**	**Threshold used (original sources in publication)**
Endpoints:				
Impact, biodiversity loss	Species loss	1.95 E-5 species.year	flow	PB BII at 90%
Midpoints:				
Climate change	Climate change	985 kg CO2 eq	Stock	Planetary boundary, temperature increase of 2C
	Ozone depletion	0.078 kg CFC-11 eq	Stock	Planetary boundary, 7.5% (±2.5%) decrease in average ozone concentration
Pollution	Photochemical ozone formation	3.8 kg (*global*) or 2.5 kg (*Europe*) NMVOC eq	Stock	Accumulated ozone exposure, 3 ppm h AOT40, long-term policy target from the european air quality directive
	Terrestrial acidification	145 mol (*global*) or 89 mol (*Europe*) H+ eq	Stock	Average critical load of 1170 mol H+ eq/ha/year globally and 1100 mol H+ eq/ha/year at the european scale
	Terrestrial eutrophication	887 mol (*global*) or 577 mol (*Europe*) N eq	Stock	Average critical load of 1340 mol N eq/ha/year globally and 1390 mol N eq/ha/year at the european scale
	Freshwater eutrophication	0.84 kg (*global*) or 0.46 kg (*Europe*) P eq	Stock	Freshwater phosphorus concentration threshold of 0.3 mg/l integrated at the global and european scale
	Marine Eutrophication	29 kg (*global*) or 31 kg (*Europe*) N eq	Stock	Coastal waters nitrogen concentration threshold of 1.75 mg/L (±0.75 mg/L) integrated by the global and european coastal volumes
	Freshwater ecotoxicity	1.87E4 (*global*) or 1.03 (*Europe*) [PAF].m3.day	Flow	HC5(NOEC), used in the EU Water Framework Directive to define environmental quality standards

Soil erosion	1.8 (*global*) or 1.2 tonne eroded soil(*Europe*)	Stock	Tolerable average soil erosion of 0.85 t/ha/year (±0.55 t/ha/year)
Land use	1.99E4 kg (*global*) or 8.12E3 kg (*Europe*) C deficit	Stock	Based on soil erosion threshold
Land occupation	1.5E4 (*global*) or 9.5E3 (*Europe*) m2 year	Flow	Protection of 31% of terrestrial areas (managed with conservation of nature as a primary objective), median of estimates
Water depletion	99.3 m3 (*global*) or 159 m3 (*Europe*) water eq	Stock	Conservation of 87% of accessible blue water resources worldwide

Allocation related criteria

C9 + C10

Basis of allocation

Allocation principle(s) used

The authors agree with (Clift et al., 2017) that a normative basis is required for the allocation of environmental operating space for at least three classes of users:

- Governments
- Producers (industry)
- Individuals

The following formula was used to determine the environmental budget for a company:

$$b_i = \alpha_i \beta_i \frac{CC_i}{pop}$$

In which:

b_i = environmental budget assigned to a company

α_i = relative contribution of the sector to the impact category i

β_i = consumer base of the company in person.year eq

CC_i = carrying capacity of the ecosystems for the impact category I over one year

pop = population size

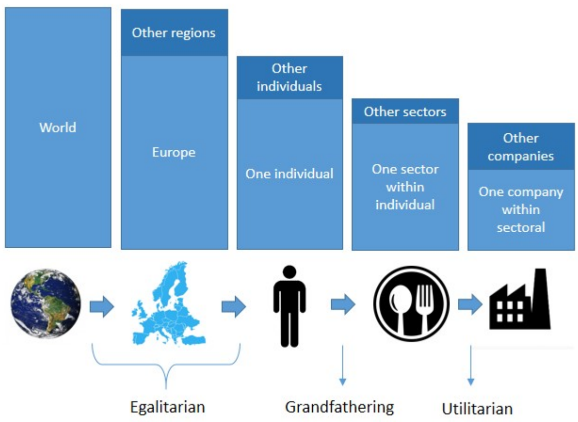
There are three ‘rules’ and equity principles used to β_i downscale carrying capacities to the company level:

Rules (ethical principle):	A: assignment between sectors based on (grandfathering principle)	B: assignment between companies is based on their market share	C: all humans in a given region have the same budgets (egalitarian)

		(utilitarian principle)	
Budget (bi) components:	α_i is the relative contribution to impact i of the sector of the entity under study	β_i is the consumer base of the company in person.year eq	CCi/pop is the carrying capacity allocated to each person.
Application to case:	Agriculture's contribution to total European impacts for each impact category	Equivalent number of persons fully fed by the company	See C7+8

This assessment does not go to the product level, but to the entire product portfolio of a company.

The ecological budget for the company is actually expressed as a part of a person’s budget:



The assignment of carrying capacity involves all three dimensions (biophysical component that shares the CC among individuals, socio-economic component that shares the CC among sectors and companies. The ethical dimension involves the different equity principles that determine how the CC is shared within the other dimensions.

C11	**Principle documentation**
	It is recognized that sharing principles have an intrinsic political/normative dimension. The (dis)advantages of the grandfathering principle are discussed: It favors sectors with worst impacts and does not take a sector’s progress-potentials in to account. Scenarios show that the agri-food sector has substantial impact reduction potentials, although probably not enough to become absolute sustainable according to the authors.
C12	**Compatibility allocation principles**
	The only mentioned variation for sharing carrying capacity applicable to their approach: Allocate based on sector’s respective pressures reduction potential.

Appendix B: Sharing principle classification from climate science and distributive justice

The issue with operationalizing ecological boundaries from higher geographical scales (such as the planetary boundaries) to smaller geographical scales (e.g. nation, sector or product-level), is that there are multiple principles in which the corresponding emission budgets can be shared among the competing systems. Such sharing principles/scaling principles have primarily been developed within the distributive justice theory and climate change science. In this appendix, multiple sharing principles will be explained in the context of climate change.

Sharing principles in distributive justice and climate change literature

Grasso (2012) has provided the main families of distribution patterns, corresponding principle and criteria for sharing the climate change emission budget (657 Gt CO_2 from 2010-2050 for having a 75% chance of limiting warming in 2100 to 2°C above pre-industrial levels)[4] between countries and thereafter regions and groupings of countries.

Grasso (2012) argue that the distribution of emission budgets is primarily related to the way in which benefits and burdens are shared in society, and they state that therefore three general questions first need to be answered:

1. Who (what) are the subjects of justice?

Given the fact that countries (not citizens) participate in climate negotiations, Grasso (2012) argued that it is relevant to consider countries as the subject of justice, and investigate the options to determine individual emission rights of those countries. Countries are in that case thus perceived as representations of their members' identity and cultural norms and values. However, it is very well possible to consider other subjects of justice, also in environmental contexts other than climate change. In a different analysis, non-geographical units such as individual citizens, products and sectors can also be chosen.

2. What kinds of benefits and burdens are to be justly shared?

Here, the right to emit CO2-eq is to be shared justly since GHG emissions are an unavoidable by-product of human activities which increase the well-being of people.

3. What is (are) the pattern(s) and/or principle(s) of distribution?

This question entails two aspects; the trajectory of emission reduction and the way in which the emission rights are distributed. Grasso (2012) focusses on the second aspect and takes an emission budget of 657 Gt CO2 from 2010-2050 as a starting point.

The path of distributing the emission budgets is further scrutinized in to three levels:

1. Two main patterns or groups of principles are distinguished;
    a. Broadly egalitarian principles, anchored within distributive justice theory as they are based on a general tendency to achieve equality in the sense that they improves the lives of people who disadvantaged in society (Arneson, 2010). Broadly egalitarian can be subdivided in three subcategories (egalitarian, prioritarian, sufficientarian).

[4] Other more recent values could be used. This budget was calculated by Grasso (2012)and accompanied with the disclaimer that it is only an indicative number. Calculation: The 1000 Gt CO2 budget (Meinshausen et al., 2009), for the period 2000-2050, yielding 75% probability of limiting warming to 2 C in 2100, was subtracted by the emissions from the 2000-2009 period, leading to a 657 Gt CO2 budget for 2010-2050.

b. Non-broadly egalitarian principles, not based on an underlying equality goal.

2. Each pattern is divided in to several principles of distribution that morally justify and specify how emission budgets are to be shared.
3. The principles are accompanied with distribution criteria that specify the type of reference bases and data needed to operationalize distribution principles. Reference bases are the quantities with no ethical contents that are used (e.g. population, Gross Domestic Product, emissions). To some extent there might also be debate about the details of the criteria. For instance, instead of Gross Value Added (GDP) the Gross Value Added (GVA) could be used, which is the value created before taxes added and subsidies are subtracted.

The patterns, principles and criteria are listed and provided with an explanation in Table B1.

Table B1, paths for sharing the emission budget between (from Grasso. (2012), adapted with explanation):

General pattern	Principle	Explanation	Criteria in (Grasso, 2012)
Broadly Egalitarian I (Egalitarian)	Equal per capita	Each country has the right on a share of the global emission budget that is proportional to their share in global population.	EPC: proportionality to countries' 2006 population
	Equal burdens	Each country should reduce its emissions by a share of the burden of overall abatement that is equal to the burden of other countries (Moellendorf, 2009). This can be done by integrating a factor that equalizes marginal cost of reducing emissions so that the foregone opportunities are equal.	EB: proportionality to countries' 2006 GDP corrected by a factor equalizing marginal abatement costs
	Equal Access	Geographical differences are accounted for in the sense that not every country has the same amount of agricultural land (and fertilizer use), renewables, heating or cooling demands, etc.	EA: proportionality to countries' 2006 population corrected by an energy services factor (heating/cooling needs).
Broadly Egalitarian II (Prioritarian) *Prioritarianism focuses on the absolute situation: the lower a subject's level of the currency of justice, the more the subject has to be benefited (giving it priority in accessing equal standards)*	Historical Responsibility	The 'polluter pays' idea. Countries that emitted less CO2 than others are prioritized by granting them an amount of emissions inversely proportional to their cumulative emissions. This can practically be done by using a parameter of responsibility (e.g. cumulative emissions)	HR-EPC: proportionality to countries' 2006 population corrected by the historical responsibility factor (CO2 1990–06 cumulative emissions)
			HR-GF: proportionality to countries' 2006 emissions corrected by the historical responsibility factor (CO2 1990–06 cumulative emissions)
	Ability to Pay / Beneficiary Pays	Advantaged countries with greater wealth (GDP) and capacities should bear a proportionally larger part of mitigation costs.	ATP-BP: proportionality to countries' 2006 GDP corrected by the wealth factor (country's GDP as a share of world GDP)
Broadly Egalitarian III (Sufficientarian)	Survival/luxury emissions	This principle identifies a minimum level of emissions (moral threshold)	S/L: proportionality to countries' 2006

Sufficientarianism advocates that very subject must have a sufficient, yet not equal, share of the specific currency of justice, i.e.		that a country needs to fulfill basic activities for having a decent life (survival). Emissions above this level are considered as a result of increased affluence (luxury). So, in this principle, for countries below the moral threshold the limits on emissions are removed, allowing them to perform the activities necessary decent life of citizens.	population only for countries above the threshold of subsistence. (the lowest 90 out of 185 countries in terms of cumulative emissions are exempted).
Non-broadly egalitarian	Grandfathering	Distributing the emission budget among countries proportional to their respective past shares of emissions at a given date.	GF: proportionality to countries' 2006 emissions

Ethics of the principles

The difficulty in reaching consensus on which principle should be applied lies in the fact that one's preference for a certain principle is heavily dependent on one's values and cultural and socio-economic background. For each principle there are different ethical arguments to claim that it is superior to others. Therefore, this section covers a discussion on the ethical arguments for the sharing principles.

Some researchers defend the historical responsibility principle because ignoring it would favor people who lived in the past in high-emission wealthy countries and discriminate people that now live in the developing world (Neumayer, 2000). However, the historical responsibility principle might be resisted because the term responsibility is a slippery or confusing term which raises large conceptual and practical difficulties in the climate change mitigation context (Grasso, 2012).

Grandfathering is most applied in practice (i.e. in policy context) because of its intuitive and practical nature, but it is also hard to defend on a moral basis (Caney, 2009): "*no moral and political philosopher (to my knowledge) defends grandfathering, presumably because it is unjust*." In fact, grandfathering proposes to continue based on the existing distribution of emissions which only originates from the chronological development of countries but disregards moral entitlement, making the whole principle implausible (Jamieson, 2005). On the contrary, grandfathering is sometimes favored because it is considered as the most reliable principle for ensuring the protection against climate threats (priority argument) as it better engages and involves major emitters in the emission reduction process (Caney, 2009).

The equal per capita principle is widely advocated by most southern policy makers and activists because it favors the developing world and is ethically justified in authoritative papers (Jamieson, 2005; Singer, 2016). Interestingly, the survival/luxury emissions principle proved to be more favorable to developing countries in the analysis of (Grasso, 2012). However, the survival/luxury emissions principle exempts developing countries to cut emissions and thereby takes away their incentive to invest in cleaner technologies. In that sense, the principle does not favor them as much because they risk being left behind in future non-fossil development (Grasso, 2012). Accordingly, Baer et al. (2008) suggests that such countries should pursue no-regret mitigation policies and should be financially compensated. An argument in Furthermore, it should be noted that the moral threshold (or sufficiency line) used in the survival/luxury principle is rather normative.

The equalization of the marginal costs of emission reduction in the equal burdens principle is questionable because it does not account for other aspects of justice such as wellbeing or capability

(Grasso, 2012). The equal access principle is rather unexplored and is potentially promising if more necessary data on geographical differences would be available (Grasso, 2012).