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Ryberg, Morten W.; Andersen, Martin Marchman; Owsianiak, Mikoaj; Hauschild, Michael Zwicky

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Morten W Ryberg*, Martin Marchman Andersen, Mikołaj Owsianiak, Michael Z Hauschild

Quantitative Sustainability Assessment group, DTU Management Department of Technology, Management and Economics, Technical University of Denmark, Produktionstorvet, Building 424, 2800 Kgs. Lyngby, Denmark

*Corresponding author: Morten W Ryberg (moryb@dtu.dk)
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Quantitative Sustainability Assessment group, DTU Management Department of Technology, Management and Economics, Technical University of Denmark, Produktionsstorvet, Building 424, 2800 Kgs. Lyngby, Denmark

*Corresponding author: Morten W Ryberg (moryb@dtu.dk)

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Abstract

The safe operating space as defined by the Planetary Boundaries framework can be used as an environmental sustainability reference in absolute environmental sustainability assessments (AESAs). In AESAs, the safe operating space must be distributed among human activities so impacts associated with an activity can be related to its assigned share of the safe operating space to assess if the activity can be considered absolute sustainable. To ensure choices concerning sharing principles in AESA are deliberate, there is a need for understanding the distributive justice theory underlying the sharing principles. This study provides a framework for determining and communicating the distributive justice theories that underlie the choice of sharing principles in AESA. To comprehensively describe a sharing principle in relation to distributive justice theories, seven dimensions must be defined, i.e. target, currency, pattern, geographical scope, temporal scope, clauses, and constraints. We conducted a review of sharing principles used in AESAs in relation to contemporary distributive justice theories. 18 studies were identified with 34 sharing principles being applied. The most commonly applied sharing principle is equal per capita sharing of the safe operating space among countries or individuals. This was often combined with utilitarian principles for sharing among industrial units. Based on the review and analysis of the results, we provide recommendations on best practice for defining sharing principles in AESAs systematically based on distributive justice theories and recommendations for further research. The framework developed in this study provide a first step towards a systematic and informed selection of sharing principles used in AESAs.

Keywords

Absolute environmental sustainability assessment; Entitlement; Sharing principles; Distributive justice; Safe operating space
Introduction

Since its introduction in 2009, the Planetary Boundaries (PB) framework (Rockström et al., 2009; Steffen et al., 2015) has attracted attention from both academia, industry, and government (Clift et al., 2017; Galaz et al., 2012; Sim et al., 2016; WBCSD, 2010). The PB-framework defined a set of biophysical boundaries for key Earth Systems processes that human impacts should stay within to maximize the probability of staying in a Holocene-like state and, thereby, avoid potentially unacceptable Earth System changes (Rockström et al., 2009; Steffen et al., 2015). The PBs, thus, delimit a safe operating space for humanity to manoeuvre within and this has inspired an increased interest in integrating the PBs into product and technology oriented environmental assessment tools, such as Life-Cycle Assessment (LCA) (Bjørn et al., 2015). In traditional LCAs, impacts from an activity are normally related to an anthropogenic reference system. For instance, external normalization where impacts of the assessed activity are normalized against some measure of “background” impact of society (ISO, 2006; Laurent and Hauschild, 2015). Such assessments are referred to as relative environmental sustainability assessments. In contrast, the development of e.g. the PBs, has allowed use of absolute environmental boundaries as reference values that can be related to the impact of human activities quantified using LCA or related life-cycle based approaches. The benefit being that the outcome of the evaluation of an activity’s environmental performance will not depend on the performance of the anthropogenic reference system, but reflect its performance relative to absolute environmental boundaries. This is referred to as an absolute environmental sustainability assessment (AESA).

With regards to the PBs, normalization can be done relative to the full safe operating space as delimited by the PBs. However, direct normalization against the full safe operating space cannot reveal if an activity can be considered absolute sustainable (Bjørn et al., 2015; Ryberg et al., 2016). To be operational, the full safe operating space must be apportioned and assigned to the actor or activity that is being studied (i.e. downscaling), e.g. countries, companies, industry sectors, persons or products. The assigned share of the safe operating space (SoSOS) can be used as an absolute environmental sustainability reference (AESR) in an AESA of the assessed activity. To be absolute sustainable, the impacts associated with the assessed activity must not exceed the assigned SoSOS (Fang et al., 2015a). AESA and downscaling of the safe operating space is a method for making the ‘conceptual’ PB-framework operational and allow decision-makers in e.g. industries and governments to apply “PB-thinking” as part of their strategic planning (Biermann, 2012; Clift et al., 2017; Sim et al., 2016; Whiteman et al., 2013). The ability to assess if an activity is good enough relative to environmental boundaries, such as the PBs, allow for setting science-based relevant sustainability targets for an activity. Moreover, it allows for evaluating if new sustainability oriented initiatives and strategies are sufficiently ambitious for making the activity sustainable in an absolute sense, or if more ambitious actions are needed (Hauschild, 2015; Ryberg et al., 2018). However, we are left with questions of how to split the burden of collectively staying within the PBs. To know if e.g. a person or a company is absolute environmentally sustainable, we need to know that person’s or the company’s assigned SoSOS. How to determine a person’s or a company’s assigned SoSOS is not only normative, but essentially a question of distributive justice.

Previous studies have assessed the absolute sustainability of different systems at different scales of study (e.g. countries, sectors, companies and product) in relation to an assigned SoSOS (e.g. Nykvist et al. 2013; Sandin et
al. 2015; Ryberg et al. 2018 and Algunaibet et al. 2019). In particular, Sandin et al. (2015) and Ryberg et al. (2018) explicitly looked into the choice of sharing principles (also referred to as allocation principles or distributive principles in other literature). Both studies applied four different sharing principles and found that the choice of sharing principle strongly influenced conclusions about the activity being considered sustainable or not. Ryberg et al. (2018) evaluated the uncertainty of an AESA on laundry washing in EU and found that uncertainty from choice of sharing principle dwarfed uncertainty of the life-cycle inventory and of the location of the PBs in the known zone of uncertainty (Rockström et al., 2009; Steffen et al., 2015). Currently, there is no harmonization of the selection and application of sharing principles in AESA and comprehensive presentations of the normative values and ethics underlying the selection of sharing principles in previous AESAs are generally lacking. Because the choice of sharing principle has such large influence on the outcome of an AESA, there is a need for a more systematic and informed approach to the selection of sharing principle in AESA. The first step is to understand the values and ethics that underlie different sharing principles to allow practitioners to make informed and deliberate choices about which sharing principle to apply in an AESA.

Therefore, the purpose of this study is to provide AESA practitioners with a common framework for defining, documenting and communicating sharing principles based on prevailing theories of distributive justice. This is needed to ensure that sharing of the safe operating space in AESA is based on established theories of distribution and can be transparently documented in terms of which theory of distribution that has been selected. To enable such development, this article first presents the most prevailing theories of distributive justice in the fields of political philosophy and theory, and the dimensions these consist of. Distributive justice theories deal with the matter of how to distribute benefits and burdens in a “just” way among e.g. a group of individuals. This depend on ethical considerations about which rules to follow for performing such distribution and under which conditions and criteria the distribution is done. In this study, we include the following distributive justice theories: utilitarianism, prioritarianism, sufficientarianism, the difference principle, egalitarianism, luck egalitarianism, and libertarianism. A description of each theory and the dimensions each consist of is given in Section 2.1. Afterwards, a review of the application of sharing principles in previous AESA-studies using the PBs is conducted. The sharing principles in the retrieved studies are categorized into sharing principle categories based on their relation to the different distributive justice theories. The findings of the review and the categorization of sharing principles is discussed with regards to applicability of different sharing principle categories in different types of AESAs and the data requirements for their application. Based on the discussion of the findings, specific short- and long-term recommendations to AESA practitioners on the selection and application of sharing principles in LCA-based AESAs are provided.

2 Theory

2.1 Distributive justice theories in political philosophy and theory

The economic, political, and social frameworks of a society necessarily results in a distribution of benefits and burdens across members of that society. Essentially distributive justice concerns ideal just distribution of benefits and burdens. However, exactly how such ideal just distribution would look is not given. Thus, different
distributive theories have been put forward and are being discussed in political philosophy and theory. Indeed, 
when resources are scarce, distributive justice is prevalent. In much political philosophy and theory studying 
distributive justice, sustainability itself is considered a matter of distributive justice. Indeed, following the 
Brundtland Commission’s definition of sustainable development, this is quite obvious as sustainable 
development here is development that “… meets the needs of the present without compromising the ability of 
future generations to meet their needs.” (WCED, 1987). Sustainability, it may therefore be suggested, is 
especially a matter of what the current generation owes to future generations (Gosseries, 2008). When 
downscaling the PBs, the safe operating space represent a scarce resource that should be distributed among 
non-global actors, e.g. countries or persons. Given that the PBs are absolute boundaries for keeping the Earth 
system in a Holocene-like state, if one person exceeds’ her assigned SoSOS, she is, all else being equal, 
depriving others of their assigned share of the safe operating space (Vanderheiden, 2009) and, thus, not acting 
in an absolute sustainable manner.

To provide a common framework for selection of sharing principles in AESA, founded on the prevailing theories 
of distributive justice, we need to map the dimensions that distributive justice theories consist of. According to 
Meyer and Roser (2006) “the three most important questions for theories of distributive justice are: Distribute 
what, how, and among whom?” Along a similar line of thinking, Bjørn et al. (2016) introduced the need for 
identifying the different systems and activities (i.e. whom) that compete for an environmental space (i.e. what) 
and quantify their assigned SoSOS based on the value they contribute with relative to other systems and 
activities (i.e. how). We echo the what, how, and whom but suggest more comprehensively that for something 
to be a complete distributive justice theory, it needs ultimately to specify an answer to what currency it is that 
should follow a specific distribution pattern among which targets in what geographical scope, during which 
temporal scope and under which eventual constraints and clauses? (Lippert-Rasmussen, 2015). These seven 
dimensions are needed to characterize the specific differences between distributive justice theories (see Table 
1 for a short description of each dimension).

Table 1: Overview of the seven dimensions needed for comprehensively specifying distributive justice theories

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Currency</td>
<td>Answering what it is that ultimately should be distributed in some way (see Sen 1979; Dworkin 1981; Cohen 1989 for detailed discussion)</td>
</tr>
<tr>
<td>Pattern</td>
<td>The operational rule the distribution should follow, e.g. equality (see Hirose 2014 for detailed discussion)</td>
</tr>
<tr>
<td>Target</td>
<td>The target of distribution, being e.g. among individuals, among social groups, among countries. (see e.g. Lippert-Rasmussen 2015 for detailed descriptions)</td>
</tr>
<tr>
<td>Geographical scope</td>
<td>The geographical scope of the distribution, e.g. global, national, or regional (see e.g. Lippert-Rasmussen 2015 for detailed descriptions)</td>
</tr>
<tr>
<td>Temporal scope</td>
<td>The temporal scope of the distribution, e.g. infinite time, a person’s life-time, or shorter periods of time (see e.g. Lippert-Rasmussen 2015 for detailed descriptions)</td>
</tr>
<tr>
<td>Constraints</td>
<td>Some distributive principles are added a clause on the otherwise desired distribution. For instance, Luck egalitarianism is egalitarianism with luck as a clause, meaning that personal responsibility does justify deviation from the relevant equal distribution. (see e.g. Lippert-Rasmussen 2015)</td>
</tr>
<tr>
<td>Clauses</td>
<td>The all else being equal, or ceteris paribus, clause is added when a distributive principle is meant to be combined with another principle or other moral consideration. This is typically the case with egalitarianism, meaning that equality matters, but it is not all that matters. Utilitarianism, in contrast, is a single principle intended to answer all moral matters. Therefore, it is not followed by the ceteris paribus clause. (see e.g. Hausman 2018 for detailed descriptions and Section 2.1 for examples)</td>
</tr>
</tbody>
</table>
Table 2 provides an overview of the prevailing distributive justice theories (based on Roemer 1998; Meyer and Roser 2006; Lippert-Rasmussen 2015) that are discussed in contemporary political philosophy and theory.

Table 2 List of the identified distributive justice theories and information for each theory in relation to the seven dimensions that define a distributive justice theory.

<table>
<thead>
<tr>
<th>Distributive justice theory</th>
<th>Currency</th>
<th>Pattern</th>
<th>Target</th>
<th>Geographical Scope</th>
<th>Temporal Scope</th>
<th>Constraints</th>
<th>Clauses</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Utilitarianism</td>
<td>Welfare</td>
<td>Maximize</td>
<td>Everyone sensitive to welfare</td>
<td>No limit</td>
<td>Infinite</td>
<td>None</td>
<td>None</td>
<td>(Crisp, 2014; Scheffler, 1988)</td>
</tr>
<tr>
<td>Prioritarianism</td>
<td>Welfare</td>
<td>Prioritarian function. Increase for the worse off is weighted higher</td>
<td>Everyone sensitive to welfare</td>
<td>No limit</td>
<td>infinite</td>
<td>None</td>
<td>None</td>
<td>(Holtug, 2017)</td>
</tr>
<tr>
<td>Difference principle</td>
<td>Resources generally</td>
<td>Maximize resources of the worse off group (termed “Maximin”)</td>
<td>Socio-economic groups</td>
<td>No specification, can range from local to global scale</td>
<td>Life-spans</td>
<td>None</td>
<td>All else being equal</td>
<td>(Rawls, 1999)</td>
</tr>
<tr>
<td>Luck egalitarianism</td>
<td>Resources, welfare, capabilities</td>
<td>Equality</td>
<td>Individuals</td>
<td>No specification, can range from local to global scale</td>
<td>Over life-span, or smaller time fragments</td>
<td>Personal responsibility</td>
<td>All else being equal</td>
<td>(Lippert-Rasmussen, 2015)</td>
</tr>
<tr>
<td>Egalitarianism</td>
<td>Resources, welfare, capabilities</td>
<td>Equality</td>
<td>Individuals</td>
<td>No specification, can range from local to global scale</td>
<td>Over life-span, or smaller time fragments</td>
<td>None</td>
<td>All else being equal</td>
<td>(Temkin, 2003)</td>
</tr>
<tr>
<td>Sufficientarianism</td>
<td>Resources, welfare, capabilities</td>
<td>Absolute priority to those below a sufficiency level</td>
<td>Individual, or socioeconomi c groups</td>
<td>No specification, can range from local to global scale</td>
<td>Over life-span, or smaller time fragments</td>
<td>None or personal responsibility</td>
<td>None</td>
<td>(Nielsen, 2017)</td>
</tr>
<tr>
<td>Libertarianism</td>
<td>Basic rights</td>
<td>Equal</td>
<td>Individuals</td>
<td>No specification, can range from local to global scale</td>
<td>Life-span</td>
<td>None</td>
<td>None</td>
<td>(Nozick, 1974)</td>
</tr>
</tbody>
</table>

Utilitarianism holds that we should maximize the sum of welfare (Scheffler, 1988). Utilitarianism needs the content of welfare to be fully specified, and for it to be operational we need a time-limit (even though utilitarianism has none (Crisp, 2014)) and comprehensive knowledge (economic, psychological, etc.) on causes of welfare. Notably, as the goal is to maximize the sum of welfare, utilitarianism does not take into account potential increases in inequality (Meyer and Roser, 2006). Prioritarianism is similar to utilitarianism in that it holds that we should maximize the sum of prioritarian-weighted welfare, meaning that a benefit has greater moral value the worse the situation of the individual is to whom it accrues (Holtug, 2017). The target and geographical scope of prioritarianism is the same as for utilitarianism. This is in contrast to the difference principle for which John Rawls suggested that social and economic inequalities are to be arranged so that they...
are to be of the greatest benefit to the least-advantaged members of society. Thus, the target is to be understood as socio-economic groups and the scope is the society, rather than everyone, as in utilitarianism and prioritarianism (Rawls, 1999).

Egalitarianism and luck egalitarianism holds respectively that it is unjust for individuals to be worse off than others, and that it is unjust for individuals to be worse off than others due to no responsibility of their own (Andersen, 2014; Temkin, 2003). In luck egalitarianism, personal responsibility works as a constraint on an otherwise equal distribution. An all else being equal clause is typically added to both distributive justice theories to avoid levelling down implications. For instance, in a world populated by the blind and the seeing, without an all else being equal clause, an egalitarian would have to claim that there is something good about blinding the sighted, if full equality can only be achieved by blinding the seeing. However, any sensible egalitarian would consider both the intrusion into personal liberty and the loss of welfare from being blinded as far worse than the benefit of equality. Thus, all things considered, an egalitarian would not recommend blinding the seeing (Holtug, 1998). A key question in egalitarian distributive justice theories is the currency on which to base equality (Dworkin, 1981a). Here different currencies have been proposed such as resources, welfare, and capabilities (Cohen, 1989; Dworkin, 1981b; Sen, 1979). Sufficientarianism holds that equality is not what matters; what matters is that everyone has enough, and thus suggests a sufficiency level where people below the threshold have (absolute) priority compared to people above the threshold (Nielsen, 2017). Libertarianism, perhaps best defended by Robert Nozick (1974), questions the idea of a fixed distribution; if there is an initial just distribution, then any distribution following from that is just if it results from voluntary transactions. Yet, libertarianism holds that everyone should have equal basic rights (Nozick, 1974).

3 Methods

3.1 Review of sharing principles in PB-based AESAs

In accordance with this study’s purpose, LCA-based AESA studies were selected from the literature following the criteria that (i) the studies directly deal with the PBs or are based on the PBs as defined in the PB-framework (Rockström et al., 2009; Steffen et al., 2015); and (ii) the studies deal with assigning a share of the safe operating space or otherwise downscaling PBs to the scale of the studied activity. All sharing principles evaluated in this study were retrieved from Web of Science (WoS) Core Collection on December 20th, 2019. The time period of the review was set to between 2009 (i.e. year of first publication on Planetary Boundaries; Rockström et al., 2009) and 2019. All languages and all document types where included in the review.

To retrieve relevant studies a specific search query string was defined based on a list of key words for expressing Planetary Boundaries, Sharing, and AESA. Because the focus is on sharing of the safe operating space as delimited by the PBs, the key words “Safe operating space”, “Planetary Boundaries” and ”Planetary Boundary” was selected as part of the search query. The term “planetary boundary layer” was excluded from the search query string because this relates to the specific planetary boundary layer of the Earth. This is often referred to in e.g. meteorological studies, which are not relevant for AESAs and sharing of the safe operating space. It is evident from existing AESA studies that a common terminology is yet to be defined (Bjørn et al., 2020), thus many different terms are used to express the sharing of the safe operating space. Therefore, we
identified the following words being used in already known articles and reports that describe and deal with the aspect of sharing the safe operating space. Different tenses for each term were included to ensure that all relevant studies were identified. The following terms for “sharing” were included as part of the search query string: “allocation” (Bjørn et al., 2019; Lucas et al., 2020; Sabag Muñoz and Gladek, 2017); “sharing” (Ryberg et al., 2018); “downscaled” and “disaggregated” (Steffen et al., 2015); “scaling” (Häyhä et al., 2016). Finally, to ensure the focus on LCA-based AESAs, we included four different terms expressing AESAs and also terms that express LCA. The following terms were included as part of the search query string: “absolute sustainability”, “absolute environmental sustainability assessment”, “absolute sustainability assessment” and “AESA” (Bjørn et al., 2019; Ryberg et al., 2018); “life cycle assessment”; “life-cycle assessment”; “life cycle analysis”; “life-cycle analysis”; “LCA”.

This resulted in the search query string: \text{ALL}=\text{("planetary boundaries" OR "safe operating space" OR "planetary boundary" NOT "planetary boundary layer") AND ("share" OR "sharing" OR "shared" OR "scaling" OR "scale" OR "scaled" OR "downscaled" OR "downscaling" OR "downscale" OR "allocating" OR "allocated" OR "allocate" OR "disaggregate" OR "disaggregating" OR "disaggregated" OR "absolute sustainability" OR "absolute environmental sustainability assessment" OR "absolute sustainability assessment" OR "AESA" OR "life-cycle assessment" OR "life-cycle analysis" OR "life cycle analysis" OR "LCA"))}

The WoS search query resulted in 196 studies (see Supplementary Material (SM) 2 for full list). Hereafter, each study was checked for relevance using the following inclusion criteria:

- Life-cycle based (YES/NO)
- Dealing with sharing of safe operating space (YES/NO)
- Using Planetary Boundaries as indicators (YES/NO)
- Relating quantified life-cycle impacts to assigned share of safe operating space (YES/NO)

This resulted in a final list of 11 relevant studies. A bibliographic check of the reference lists in the 11 retrieved studies was performed to identify additional relevant studies and yielding seven additional studies. Thus, a total of 18 studies fulfilling the inclusion criteria were identified and listed in Table 3.
Categorization of sharing principles according to distributive justice theories

The sharing principles retrieved from the AESA review were categorized into sharing principle categories based on the distributive justice theories listed in Table 2. All sharing principles in the retrieved studies were reviewed with regards to the target of the sharing principle being human beings. This strict application of humans as the target for the sharing principles was needed to ensure consistency and comparability among the reviewed sharing principles. This was, in particular, needed for the study by Ryberg et al. (2018) that applied three sharing principles which were characterized as egalitarian, but where the target of the sharing principles was the industry. In the study by Ryberg et al. (2018), the assigned share was proportional to economic output of the industry or proportional to consumers’ revealed preferences for certain industries where the assigned SoSOS was distributed equally among industries based on the magnitude of their economic output. However, if humans were selected as target, and under the assumption that companies’ economic output is a proxy for added human welfare, these principles can be regarded as utilitarian because the company with the largest assigned share has the biggest contribution to economic output. Thus, in this study the sharing principles were categorized as utilitarian rather than egalitarian because the target was changes from industries to humans.

Categorization of each sharing principle with relation to distributive justice theories started from analysing the applied sharing principle in relation to the dimensions presented in Table 1 and Table 2, starting from selection of currency, then pattern and so forth. Using this method each sharing principle was categorized according to a distributive justice theory. Some sharing principles were based on a combination of distributive justice theories. For instance, first an egalitarian equal per capita downscaling to regional level followed by a utilitarian based sharing among companies in the region. Such combinations were identified during the analysis of each sharing principle and the combination of different distributive justice theories needed for defining a sharing
principle is reported in SM 1 Table S2 and Figure 1. Sharing principles that do not rely on the prevailing
distributive justice theories (as listed in Table 2) were also identified and are presented and discussed in the
results and discussion section, respectively.

4 Review findings

4.1 Application of sharing principle categories

In total, 18 studies were identified in the review and 34 sharing principles were applied in total. The retrieved
sharing principles were categorized according to the distributive justice theories described in Section 2.1 (Table
2). Out of the 18 studies, seven studies are related to assessment of products, companies or industrial sectors
with the remaining being country scale assessments (see Table 3).

Figure 2. Usage frequency of different sharing principles in the retrieved studies categorized in terms of distributive justice theories
and differentiated by the scale of the object of study.

Figure 2 shows the observed usage frequency of sharing principle categories differentiated by the scale of the
object of study. The most commonly applied sharing principle was equal per capita sharing of the safe
operating space, i.e. where the pattern followed is egalitarian and the currency is the safe operating space as a
resource expressed in a metric reflecting the particular impact category, e.g. expressed as ppm CO\textsubscript{2} or kg CO\textsubscript{2}-
eqs emitted per year for global warming (Figure 2). An equal per capita sharing was only applied as stand-alone
sharing principle in country scale assessments. The equal per capita sharing principle was also used in sector
and company scale assessments, but always in combination with other sharing principle categories, such as
utilitarian-based sharing principles to account for the value (i.e. utility) the sector or company delivers to people. Indeed, equal per capita sharing was often used to downscale the boundary to the relevant geographical scale of the industry or company after which utilitarian sharing principles were used within that geographical scale (see e.g. Ryberg et al. 2018; Algunaibet et al. 2019). One country scale assessment study applied sharing principles categorized as prioritarian (Lucas and Wilting, 2018) in which the assigned SoSOS was inversely proportional to countries’ “ability to pay” and capacity to cope with a reduced SoSOS. None of the sharing principles applied in the reviewed AESAs were based on distributive justice theories related to sufficentarianism, libertarianism, or the difference principle.

The results show that it is generally possible to categorize sharing principles according to distributive justice theories. This indicate that most sharing principles are, to some extent, based on distributive justice theories although the relative short list of distributive theories used and the similarity in selection of pattern, currency, etc. could indicate that new AESA studies tend to apply sharing principles applied in previous studies and, thus, not deliberately selecting sharing principles for the specific AESA study. The only type of sharing principles that could not be categorized based on prevailing distributive justice theories are based on what can be referred to as acquired rights principles (Banuri et al., 1996). Sharing principles applying acquired rights principles was observed in 13 out of 34 sharing principles. In acquired rights principles, the sharing of the safe operating space among activities is based on the activities’ current or historical acquired rights or property, such as occupied land area or contribution to environmental pressures (Banuri et al., 1996). For instance, the distribution of a CO$_2$ emission budget among countries could be based on the relative share of CO$_2$ emissions among countries in a specific reference year. Such approach was used for the Annex I countries for the Kyoto protocol where emission reduction targets were defined with respect to emissions levels in 1990 (Caney, 2009). Thus, a relatively large emitter of CO$_2$ in 1990 will be assigned a proportionally large share of the emission budget. Acquired rights based principles are discussed in relation to allocation of e.g. CO$_2$ emissions budgets, but are not discussed as part of distributive justice in political philosophical as distribution based on acquired rights is generally considered unjust (Caney, 2009; Meyer and Roser, 2006).

In total 12 of the 34 sharing principles were derived by combining different distributive justice patterns. The most common combination is egalitarianism and utilitarianism (used in seven studies; Figure 2). Here, the initial downscaling to a geographically specific area is done using an egalitarian resource-based equal per capita sharing principle, which is followed by utilitarian distribution among industries in the specific area based on their approximated utility to people. Another common combination is acquired rights and utilitarianism where historical contribution to environmental pressure is used for downscaling to a geographically specific area after which distribution within the region is based on utilitarianism. The need for applying a combination of distributive justice patterns for assigning a share of SoSOS appear to increase inversely with the scale of the object of study. A single stand-alone sharing principle is generally applied in country scale studies. A combination of two sharing principles is used in 12 out of 16 approaches for sharing the safe operating space in sector, company or product scale AESAs.

The most commonly assessed PBs are those related to biogeochemical flows, i.e. nitrogen and phosphorous, freshwater use, land-system change, and climate change which were all assessed in, at least, 10 out of 18
studies (Table 3). Change in biosphere integrity, stratospheric ozone depletion, ocean acidification, and atmospheric aerosol loading are only included in a few studies. We do not see a pattern in terms of application of specific impact categories for different scales of study. Likewise there is not a clear temporal pattern in the impact category coverage. It appears coverage of impact categories is dependent on the study’s goal and the availability of life-cycle impact assessment models for quantifying impacts for the different PBs (please see SM 1 Section S2 for discussion of the coverage of Planetary Boundaries in AESAs).

Table 3 List of studies identified in the review, the Planetary Boundaries covered in each study, the scale of the object of study (i.e. country, industry sector, company or product), and the sharing principle category or categories applied in the study. See Table S1 and Table S2 in SM1 for more details.

<table>
<thead>
<tr>
<th>Study</th>
<th>Planetary Boundaries covered</th>
<th>Scale of study</th>
<th>Sharing principle categories applied</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nykvist et al. (2013)</td>
<td>BI; OD; Pg; N; LC; FU</td>
<td>Country</td>
<td>Egalitarian</td>
</tr>
<tr>
<td>Hoff et al. (2014)</td>
<td>CC; BI; Pg; N; LC; FU</td>
<td>Country</td>
<td>Egalitarian</td>
</tr>
<tr>
<td>Dao et al. (2015)</td>
<td>CC; BI; OA; Pg; N; LC</td>
<td>Country</td>
<td>Egalitarian</td>
</tr>
<tr>
<td>Fang et al. (2015)</td>
<td>CC; LC; FU</td>
<td>Country</td>
<td>Egalitarian</td>
</tr>
<tr>
<td>Kahliluoto et al. (2015)</td>
<td>Pr; Pg; N</td>
<td>Country</td>
<td>Egalitarian</td>
</tr>
<tr>
<td>Sandin et al. (2015)</td>
<td>CC; BI; Pr; Pg; N; LC; FU</td>
<td>Industry Sector</td>
<td>Egalitarian &amp; Utilitarian; Acquired rights &amp; Utilitarian</td>
</tr>
<tr>
<td>Fanning and O’Neill (2016)</td>
<td>CC; Pg; N; FU</td>
<td>Country</td>
<td>Egalitarian; Acquired rights</td>
</tr>
<tr>
<td>Roos et al. (2016)</td>
<td>CC; Pg; N; LC; FU</td>
<td>Industry Sector</td>
<td>Egalitarian &amp; Utilitarian</td>
</tr>
<tr>
<td>Brejnerød et al. (2017)</td>
<td>CC; OD; N</td>
<td>Industry Sector</td>
<td>Egalitarian &amp; Utilitarian</td>
</tr>
<tr>
<td>Wolff et al. (2017)</td>
<td>BI</td>
<td>Company</td>
<td>Egalitarian &amp; Acquired rights</td>
</tr>
<tr>
<td>Hoff et al. (2017)</td>
<td>CC; Pg; N; LC; FU</td>
<td>Country</td>
<td>Egalitarian</td>
</tr>
<tr>
<td>Ryberg et al. (2018)</td>
<td>CC; OD; OA; Pr; Pg; N; LC; FU; AL</td>
<td>Industry Sector</td>
<td>Egalitarian (allocation-based) &amp; Utilitarian (outcome-based); Utilitarian (outcome-based)</td>
</tr>
<tr>
<td>Dao et al. (2018)</td>
<td>CC; BI; OA; Pg; N; LC</td>
<td>Country</td>
<td>Egalitarian</td>
</tr>
<tr>
<td>Lucas and Wilting (2018)</td>
<td>CC; BI; Pg; N; LC</td>
<td>Country</td>
<td>Acquired rights; Egalitarian</td>
</tr>
<tr>
<td>O’Neill et al. (2018)</td>
<td>CC; Pg; N; FU</td>
<td>Country</td>
<td>Egalitarian</td>
</tr>
<tr>
<td>Chandrakumar et al. (2019)</td>
<td>CC</td>
<td>Product</td>
<td>Acquired rights ; Acquired rights &amp; Utilitarian</td>
</tr>
<tr>
<td>Algunaibet al. (2019)</td>
<td>CC; OD; OA; Pg; N; LC; FU</td>
<td>Industry Sector</td>
<td>Egalitarian &amp; Utilitarian</td>
</tr>
<tr>
<td>Li et al. (2019)</td>
<td>Pr</td>
<td>Country</td>
<td>Acquired rights</td>
</tr>
</tbody>
</table>

4.2 Applicability of sharing principles at different scales of study

As evidenced from the usage frequency of sharing principles in the reviewed studies (Figure 2), egalitarian sharing principles are commonly applied for assessments of countries where the safe operating space is treated as a finite resource and equally distributed among countries based on population numbers. Egalitarian sharing can also be applied for assessments at person scale with equal sharing among people. While it is possible to apply different currencies for an egalitarian distribution, all retrieved studies use the safe operating space as the currency for equal distribution among people (see SM 1 Table S2 for overview). As indicated in Figure 2, the egalitarian sharing principles can be, and are often, used as single stand-alone sharing principles at country and person scale assessment. For assessment of sectors, companies or products, egalitarian sharing principles are often used as an initial sharing principle in combination with other sharing principles related to other sharing principle categories (see Figure 2 and Table S1 for details). Here, egalitarian sharing principles are used to scale down from global scale to the population of the relevant geographical scale or down to individual person scale.
Hereafter, the review shows that other sharing principles (e.g. based on utilitarianism) can be applied for further sharing of the safe operating space among companies or industries. Indeed, egalitarian sharing principles using the safe operating space as currency cannot be used directly for sharing at product, company or sector scale. This is because it is hard to justify using anything but human individuals as our ultimate target. To further assign shares among products, companies or sectors, an additional sharing must be applied that take into account the value that the products, companies or sectors have for its users, our ultimate target: individual humans.

Both utilitarian and prioritarian distributive justice theories use welfare as currency, thus, sharing principles based on utilitarianism and prioritarianism should rely on indicators that reflect the welfare for people (see Table 2). Utilitarian and prioritarian based sharing principles can be directly applied at person and country scale, where e.g. the share assigned to a person using a utilitarian sharing principle should be based on a formulation that maximizes the sum of utilities across all persons. Both utilitarian and prioritarian based sharing principles can be used as stand-alone sharing principles at company and sector scale if the distribution of the safe operating space among companies and sectors is such that it maximizes the utility (welfare or prioritarian weighted welfare) of people. Thus, for application in AESAs, the currency for distribution of the safe operating space should be based on the products’, companies’ or sectors’ contribution to utility and should be proportional to their contribution to total utility relative to other product, companies or sectors. For instance, using methods for measuring the marginal utility of income as shown by Layard et al. (2008) or the marginal utility change from consumption of different products and services. Other possible indicators of utility could be peoples’ preferences for specific products over others, contribution to economic value, contribution to happiness, or fulfilment of human needs relative to e.g. Maslow's pyramid of needs (Maslow, 1943). The choice of indicator to express utility is a challenge that is further discussed in Section 4.3. Sharing principles belonging to the Acquired rights sharing principle category can be applied to studies at all scales either as stand-alone or in combination with other sharing principles related to other sharing principle categories (see Figure and Table S1 for examples).

In general, the complexity of sharing the safe operating space is inversely proportional with the scale of the object of study. It is relatively simple to perform an equal per capita sharing of the safe operating space in a national scale assessment and communicate how this is done and the underlying choices. It is substantially more complex to assign a SoSOS to a product because this requires additional steps in the downscaling procedure. For instance, Chandrakumar et al. (2019) uses up to four steps for assigning a share of the safe operating space at the scale of individual agri-food products. Each step requires an additional choice of sharing principle and associated data for calculating the share. Thereby, increasing the associated uncertainty of the assessment due to value-based choices (Ryberg et al., 2016). Without a standard or consensus on how to consistently estimate the assigned SoSOS to products based on accepted values and approaches, a comparison of results among AESAs becomes very challenging as the difference in choice of sharing principle will likely lead to large discrepancies (as illustrated in Ryberg et al. (2018)). Hence, it is important to investigate the current relevance of AESAs and sharing of the safe operating space at different scales of study. As presented by Ryberg et al. (2016), it currently appears more practical to assign a SoSOS in large scale studies such as country,
company, or industrial sector scale, and avoid AESAs at product scale. The larger scale require fewer choices with regard to defining the sharing principle, thus keeping uncertainty due to value-based choices low. An additional benefit is that it gives central actors involved with the studied system room for making internal decisions and decide on specific trade-offs within the country, company or sector. For instance, a company might have different options for making the environmental improvements needed for staying within the assigned SoSOS. Which option they opt for should be up to the company based on its priorities and interests.

4.3 Selection of currency for distributing the safe operating space

A key aspect with regard to sharing of the safe operating space is the selection of currency. For instance, the egalitarian distribution of the safe operating space will likely differ substantially depending on the sharing being based on equality in the assigned SoSOS (as a resource) or equality in welfare among humans from a distribution of the safe operating space. From a decision-making perspective, it appears more relevant to base sharing on currencies that express an outcome (e.g. to increase welfare of people) rather than the means to reach the outcome, e.g. equal distribution of the safe operating space as a resource. Nevertheless, the review showed that all country scale AESAs, which apply an egalitarian sharing principle, use an equal per capita sharing of the safe operating space as a finite resource (Table S2). The lack of outcome-based sharing principles might be because of increased complexity and uncertainty when moving from a relatively simple distribution of the safe operating space as a resource, towards an outcome-based distribution. Indeed, outcome-based sharing principles require knowledge of the causal links between an assigned SoSOS and the currency in which the outcome is to be expressed. For instance, emissions of CO$_2$ can be measured with certainty but the welfare experienced by people as a result of an assigned CO$_2$ emission budget cannot be measured easily and must be estimated e.g., using surveys or models that can link the assigned CO$_2$ emission budget to welfare. Prediction of outcome-based indicators, such as personal welfare, are challenging. For instance, the correlation between monetary value, its distribution, and human welfare is a difficult and controversial matter (Easterlin et al., 2010). Methods for creating indicators of subjective welfare are available such as indicators of “happiness” (Diener, 2000) and application of these should be investigated. In the absence of more specific indicators of welfare, more readily available economic indicators could be (and are being) applied as proxies for welfare (e.g. Chandrakumar et al., 2019; Ryberg et al., 2018), with the limitation that proportionality between economic output and welfare is not always observed (Diener, 2000; Easterlin et al., 2010; Jebb et al., 2018).

Moreover, the debate in political philosophy and theory on how the right to emit e.g. greenhouse gases should be distributed initiates on the challenge of whether we should distribute the right to impact the climate isolated from other concerns of distributive justice (isolationism), or in light of such other concerns (Caney 2012). According to most theories of justice, the current global distribution of benefits and burdens is probably unjust. Should that not influence the distribution of rights to impact the environment? If so, it seems very complicated and fragile to first determine the principles of overall justice and then “deduce” a just distribution of rights to occupy the safe operating space. Indeed, equality in welfare should not only be based on the right to occupy the safe operating space, but should also take other concerns into consideration. In contrast to the outcome-based sharing principles, the sharing of the safe operating space as a resource is more straight
forward in its use as the size of the safe operating space is already known and can be distributed among people using either egalitarian or acquired rights based sharing principles.

5 Recommendations for definition of sharing principles in AESAs

Based on the identified theories of distributive justice and the review of sharing principles used in previous AESAs, we attempt to provide recommendations for a more harmonized and standardized approach for assigning a SoSOS. We consider this important as a first step towards standardizing application of AESAs, to increase comparability across AESAs, and to make choices about assigning SoSOS transparent and deliberate.

To be consistent and enhance transparency, the principle on which to assign the safe operating space should not only specify the overall distributive justice theory (e.g. utilitarianism or egalitarianism) or the particular pattern or currency used. It should specify all relevant dimensions of distributive justice and communicate them explicitly in an AESA. For instance, an egalitarian distributive justice theory might be applied, but the actual sharing principle will depend on the choice of currency, thus, it is important to state not only that the sharing principle is based on egalitarianism, but also that the currency is e.g. equal distribution of the safe operating space and not equal distribution of welfare or capabilities. Target, scope, and time are most often relevant dimensions too.

5.1 Selecting target for sharing the safe operating space

Regarding target, we should recall that even though the aim in AESA is to analyse the sustainability of different units, such as industrial sectors, companies, or products and services, we should not confuse such units with targets in the basic dimensional sense of distributive justice. This is so because obviously we do not owe anything to the products, the companies, the institutions, and the countries themselves. When we owe something to a country it is because we owe something to its inhabitants, when we owe something to a company it is because we owe something to its users. In accordance with Lippert-Rasmussen (2015) distribution among individual human beings should be our target, because it is individual human beings that we ultimately owe anything (WCED, 1987) and which are to operate within the safe operating space for humanity (Rockström et al., 2009). Therefore, even though we should analyse the absolute environmental sustainability of different industry related units, these units should ultimately be defined in terms of their linkage to individuals, such that the SoSOS assigned to industry related units depends on the number of individuals using the units and the units’ value to these individuals.

5.2 Selecting pattern and currency for sharing the safe operating space among humans

As stated above, the overall target should be individual human beings, however, regarding recommendations for patterns and currencies we distinguish between short-term and long-term recommendations for distributing the safe operating space among humans.

Short-term recommendations concern how the safe operating space can currently be shared in AESAs using a pragmatic approach that rely on existing available information. Thus, in the short-term, we recommend that the following patterns and currencies are applied in AESAs. We recommend using equal per capita sharing of
the safe operating space as a resource to distribute from global to national, regional, or individual scale. This is based on the following arguments. First, the complexity of estimating equality in e.g. welfare or capabilities, suggests that we must distribute the safe operating space in isolation from other concerns of justice. Indeed, it is highly controversial what more precisely a fully just world would look like. Thus, to be operational in a non-ideal world, we suggest to distribute shares of the safe operating space as a resource in isolation from other concerns of justice. If we accept isolationism, it seems hard to justify using other currencies than equal per capita sharing of the safe operating space. Any deviation from this currency and pattern would need a justification and such justification can, presumably, only stem from other concerns of justice – concerns we just accepted to isolate ourselves from. In terms of data needed for calculating equal per capita sharing of the safe operating space, only population numbers are needed to apply this approach. This approach is also the most common approach in the reviewed studies (see Figure 2), which indicate an overall acceptance among AESA researchers. A general acceptance of this approach would be beneficial as it would increase the comparability of different AESA studies.

**Long-term recommendations** concern what we should be aiming towards in terms of sharing principles in AESAs. Here, further research is needed to operationalize sharing based on outcome-based currency indicators such as welfare or capabilities rather than using the safe operating spaces as a resource as currency. As stated above, the question about a distribution of the safe operating space being just cannot be performed in isolation of other concerns of justice. These other concerns must be taken into account to evaluate if the overall distribution of all concerns is just. This will require substantially more complex models and data that is currently not available. Therefore, we recommend research on development of operational methods for sharing of the safe operating space among humans and industrial units, based on some recognized pattern of distribution, such as maximization of equalization, of welfare or capabilities among people. To do so, such models must include other concerns (e.g. economic and social distribution of burdens and benefits) and integrate these with the distribution of an environmental safe operating space to estimate a comprehensive just distribution of burdens and benefits.

The equal per capita sharing of the safe operating space as a resource was short-term recommended because it can be performed in isolation from other concerns of justice. If models are developed that convincingly link SoSOS to welfare or capabilities, then it is still an open matter whether the distribution of the safe operating space should be based on an egalitarian, utilitarian, prioritarian or sufficientarian pattern of distribution. This choice depends on normative ethics and should be decided as part of a political standardization process. Hence, we recommend working towards a consensus in the AESA community to standardize sharing in AESAs and ensure comparability among AESA studies. The long-term recommendations should, therefore, also be seen as a first step towards a consensus buildings process and as a starting point for future discussions on the approaches used for sharing. An alternative or complementary approach to a standardization could be to apply different sharing principles based on different theories of distributive justice to obtain a range of AESA results rather than a single result. Decisions on the basis of the AESA could, hereafter, be based on an evaluation of all results that can be considered absolute sustainable.

### 5.3 Selecting pattern and currency for sharing the safe operating space among industrial actors
The target of downscaling of the safe operating space is, in accordance with the basic dimensional sense of distributive justice, individual human beings (see Section 5.1). Thus, assignment of a SoSOS among industrial units in AESAs (e.g. industrial sectors, companies, or products and services) must be relative to this target. A two-step approach is, therefore, recommended for downscaling of the safe operating space to industrial units. First, a SoSOS must be assigned to all people following a recognized pattern and currency – in our short-term recommendation: equal per capita and shares of the safe operating space (Section 5.2). Hereafter, the share assigned to an industrial unit should be based on the utility that the industrial unit provides to the people using the industrial unit. Thus, the SoSOS assigned to the industrial unit will depend on the number of users (and their assigned SoSOS) and the utility the unit provides to its users.

As expressed in Section 4.3 determination of the utility to individuals is not simple and will have to be based on approximations of utility based on the availability of relevant data. A set of rules must hereafter be defined. Approaches for indicating the added utility of a product relative to other products or services could, for instance, be based on marginal utility studies or studies looking into the revealed consumption preferences of individuals (Section 4.3). In lieu of such methods, previous studies have primarily sought to approximate utility to individuals from assessed industrial units relative to other industrial units based on existing economic indicators such as gross value added (GVA) or final consumption expenditure (FCE) (Algunaibet et al., 2019; Ryberg et al., 2018). We recommend continuing this approach in the short term, but stress the need for research on development of better methods for approximating the added utility to people and the development of better data to support such method development.

5.4 Selecting other dimensions for sharing the safe operating space

For Geographical scope, we recommend to apply a geographical scope that is in line with the scope of the environmental impact. This implies a global geographical scope for global impacts such as climate change. As the scope of the PB-framework is global (although regional and local boundaries are part of the framework), a global scope is recommended for sharing of the safe operating space. For AESAs dealing with environmental impacts that are confined to a regional area, the scope for assigning a SoSOS can also be confined to the regional area. However, care should be taken because most product life cycles cover multiple regions (and often span globally). Indeed, what appears to be a confined regional area may turn out to be influenced by outside factors, and it is important to account for these factors when assigning a SoSOS. Because of the globalization of value chains and environmental impacts, we recommend that a global geographical scope is generally applied. This entails that the safe operating space is globally shared and that all humans have a right to the safe operating space, but also that all humans should, in principle, share the safe operating space independent of the geographical location. Thus, the safe operating space can be seen as a global common resource. This approach can be used for AESAs and for assessing the absolute sustainability of different activities, still we acknowledge that in practice, such global common is challenged by geopolitical concerns.

Hence, research on further spatial specification of the local and regional safe operating spaces and how to deal with these in AESAs to avoid treating regional resources as a global common is ongoing, but for the moment we suggest, for operationalization of AESAs, as a default to treat the safe operating space as a global common.
The temporal scope in theory of distributive justice is the question of what span of time it is that ought to include a certain distribution (pattern) of something (currency) to obtain between someone (target). Choice about temporal scope includes difficult questions of what one generation owes to the next, including all matters of discounting the future (and the past) (Lippert-Rasmussen, 2015). Utilitarianism, for instance, has an unlimited time-span. We ought to maximize the sum of welfare in all time. For practical reasons of course we need to set a limit. In egalitarianism the matter is subject of disagreement. Whereas, for persons living today, it might be unjust that one person is better off than another person in the currency that should be equalized. However, it might not be unjust if a person living today is better off than a person living 1000 years ago. Indeed, such very broad temporal time-span would imply, all else being equal, that the latter is unjust (Lippert-Rasmussen, 2015). When downscaling the PBs to the individual person level, this time dimension becomes apparent. If we follow our recommendations of equal per capita sharing of the safe operating space, then we need to determine the temporal scope of that equal per capita distribution. This is a complex question, but no matter the answer, it is worth little if we have no data to support answering it. The PBs are based on various models and estimated over a specific future time. Thus, for operationalization in AESA, we recommend that the temporal scope is based on the temporal scope of the models and estimates used for defining the safe operating space used in AESAs. This is the temporal scope that sets the global boundary, which must then be shared among people. For instance, if the boundary is defined as an emission budget from e.g. year 2000 to year 2100, as sometimes seen for climate change (e.g. Rogelj et al., 2018), then temporal scope should also be defined as year 2000 to year 2100. When downscaling to the individual level, the safe operating space of climate change, should, accordingly, be determined in one of two ways. Either we divide the available emission budget equally among all individuals that are expected to live between 2000 and 2100, or we first distribute the emission budget across the years from 2000 to 2100, and then divide by the number of individuals living in each of those years. Finally, with regards to the clauses and constraints dimensions, these are not specific for use in AESAs and will depend on the chosen pattern of distribution. Thus, we recommend following the clauses and constraints that are specific to the particular distributive justice theory.

5.5 Recommendations for selection and documentation of sharing principles in AESAs

Figure 3 provide an overview of the recommendations for selection of the seven dimensions required for comprehensively specifying and communicating a sharing principle. These recommendations for sharing of the safe operating space in AESAs are meant as a first step towards ensuring transparency around sharing principle choices and comparability among AESA studies. They should be seen as a first step towards a consensus buildings process and as a starting point for future discussions on the approaches used for sharing.
**Figure 3 Recommendations for selecting sharing principles in AESA with specification for the seven dimensions required for comprehensively specifying and communicating a sharing principle used in AESA**

<table>
<thead>
<tr>
<th>Recommendations for selecting sharing principles in AESA</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Target:</strong> Humans are recommended as the target for assigning SoSOS in AESAs. Assigned SoSOS to industrial units should be based on value to humans</td>
</tr>
<tr>
<td><strong>Currency and pattern:</strong></td>
</tr>
<tr>
<td><strong>Human beings or territories</strong></td>
</tr>
<tr>
<td><strong>Short term:</strong> Currency: safe operating space as a resource</td>
</tr>
<tr>
<td><strong>Pattern:</strong> Equal per capita distribution</td>
</tr>
<tr>
<td><strong>Long term</strong></td>
</tr>
<tr>
<td><strong>Currency:</strong> Welfare or capabilities</td>
</tr>
<tr>
<td><strong>Pattern:</strong> To be decided as part of a consensus process</td>
</tr>
<tr>
<td><strong>Industrial units</strong></td>
</tr>
<tr>
<td><strong>Downscale to users</strong></td>
</tr>
<tr>
<td><strong>Downscaling of safe operating space among humans affected by the studied industrial unit based on recommended approach for assigning SoSOS to human beings</strong></td>
</tr>
<tr>
<td><strong>Upscale to industrial units</strong></td>
</tr>
<tr>
<td><strong>Assign share of the industrial unit’s users’ assigned SoSOS based on the utility that the industrial unit provides</strong></td>
</tr>
</tbody>
</table>

To comprehensively describe a sharing principle in relation to distributive justice theories, all seven dimensions in Table 1 must be defined, i.e. **target, currency, pattern, geographical scope, temporal scope, clauses, and constraints**. To ensure transparency about the choice of sharing principle, it is recommended that AESAs document this by specifying all seven dimensions pertaining to the sharing principle. A sharing principle in AESA may be based on more than one distributive justice theory. In this case the AESA practitioner must describe all distributive justice theories that are related to the defined sharing principle. Examples on how such documentation can be done in a consistent manner are shown for two actual studies (Table 4). The first study (Nykvist et al., 2013) uses one downscaling step as part of the sharing principle to scale from global to national scale. The second study (Wolff et al., 2017) uses three downscaling steps to scale from global to company scale. For each downscaling step, the seven dimensions pertaining to a distributive justice theory should be specified and finally the actual equation and data used for the downscaling step should be presented. This allows for consistently documenting the sharing principle used for downscaling from global scale to the scale of study and it is possible to identify the different steps used to scale from e.g. global scale to national, individual, company or industry sector scale. Indeed, the use of such table for documenting the choice of sharing principle and the underlying distributive justice theory is not likely to require extensive additional work form the AESA practitioner, but it will greatly improve the transparency of the sharing principle selection. This method for comprehensively documenting the basis for the sharing principles is important because it allows future users of the AESA study to evaluate the selection of sharing principles in AESA and if the used sharing principles align with their own values and, thus, if the AESA results can be applied in the context in which they want to use.
them. If this is not the case, it is recommended to either redo the results using different sharing principles based on a different distributive justice theories, which fully align with their own values.

### Table 4

Two examples on how to document the sharing principle used for downscaling from global scale to the scale of study. The overall sharing principle is divided into specific downscaling steps. For each downscaling step, the seven dimensions pertaining to a distributon justice theory are specified. The actual calculation and data input needed for the downscaling step is presented in the last column.

<table>
<thead>
<tr>
<th>Study</th>
<th>From scale to scale</th>
<th>Distributive justice theory</th>
<th>Currency</th>
<th>Pattern</th>
<th>Target</th>
<th>Geographic al Scope</th>
<th>Temporal Scope</th>
<th>Constrains &amp; Clauses</th>
<th>Calculation applied for specific downscaling step</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1: Nykvist et al. (2013)</td>
<td>Global to national</td>
<td>Egalitarian</td>
<td>Safe operating space as a finite resource</td>
<td>Equal assignment of safe operating space among individuals</td>
<td>Nations</td>
<td>Global</td>
<td>Annual distribution based on population in given year</td>
<td>Not specified</td>
<td>$SOS \times \frac{Pop_{nation}}{Pop_{world}}$ where $SOS$ is safe operating space, $Pop_{nation}$ is population</td>
</tr>
<tr>
<td>#2: Wolff et al. (2017)</td>
<td>Global to individual</td>
<td>Egalitarian</td>
<td>Safe operating space for biosphere integrity</td>
<td>Equal assignment of safe operating space among individuals</td>
<td>Individual s</td>
<td>Global</td>
<td>Annual distribution based on current conditions</td>
<td>Not specified</td>
<td>$SOS \times \frac{Pop_{nation}}{Pop_{world}}$</td>
</tr>
<tr>
<td>Individu al to industry sector</td>
<td>Acquired rights</td>
<td>Safe operating space for biosphere integrity</td>
<td>Assigned share is proportional to contribution to total impact on biosphere integrity</td>
<td>Industry sector</td>
<td>European</td>
<td>Annual distribution based on current conditions</td>
<td>Not specified</td>
<td>$\frac{I_{industry}}{I_{total}}$ Where $I_{industry}$ is the impact of the industry sector and $I_{total}$ is the total impact from all sectors</td>
<td></td>
</tr>
<tr>
<td>Industry sector to company</td>
<td>Acquired rights</td>
<td>Safe operating space for biosphere integrity</td>
<td>Assigned share is proportional to company’s market share</td>
<td>Compani es</td>
<td>European</td>
<td>Annual distribution based on current conditions</td>
<td>Not specified</td>
<td>$\frac{PS_{company}}{PS_{industry}}$ Where $PS$ is the number of persons fully served</td>
<td></td>
</tr>
</tbody>
</table>

### 6 Conclusion

A review of AESA studies that have assigned a SoSOS to human activities was used to provide an overview the use of sharing principles in AESAs and drawing on 18 studies with, in total, application of 34 sharing principles. The 34 sharing principles were categorized according to distributive justice theories used in political philosophy. This was used for getting an understanding of the underlying theories of distributive justice that the selection of the 34 sharing principles was based on. It was found that, three types of sharing principle categories are generally applied in AESA, i.e. egalitarian, utilitarian, and acquired rights principles. Other distributive justice theories are seldom used as a basis for defining sharing principles in AESAs. Based on the review and analysis of the sharing principles and their underlying distributive justice theories, a set of recommendations for future practice in the field were developed. This entails the selection of sharing principles and the subsequent documentation of sharing principles in AESAs. Conclusively, this study provides the first comprehensive framework for determining and transparently communicating the distributive ethics that underlie the choice of sharing principle as expressed by the distributive justice theories. The proposed framework and the recommendations for choice and documentation of sharing principles are intended to guide AESA practitioners when assigning a SoSOS and persons using the results of the AESA. It helps ensuring
that selection of sharing principles is deliberate and done in accordance with the values of the AESA study commissioner and practitioner and it allows users of AESA studies to evaluate if they agree with the distributive justice theories underlying the selection of sharing principles in AESA.

Acknowledgements

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Supplementary Material

Supplementary Material 1. Provide a full overview of the reviewed studies and more details on the sharing principles applied in the reviewed studies. An extended discussion of the environmental impact categories covered by the reviewed AESA studies is provided.

Supplementary Material 2. Provides overview of all studies retrieved from the Web of Science search query. The inclusion criteria, the studies identified from the bibliographic check and the final list of identified studies.

References


Highlights

- Reviewed sharing principles for sharing the safe operating space in 18 AESA studies
- Sharing principles were categorized according to theories of distributive justice
- Provide recommendation for defining and documenting sharing principles in AESAs
- First step towards harmonized approach for sharing of the safe operating space
Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: