A Novel Methodology for the Sustainability Impact Assessment of New Technologies

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Abstract

The introduction of new technologies can have profound impact on society and nature. Therefore, a need exists for a method that can provide a balanced assessment of new technologies that takes into account all different impacts. Within the EU-funded PROSUITE project, the aim is to develop a methodology for the sustainability assessment of existing and emerging technologies. Here, existing approaches of sustainability assessment are reviewed. All of them have their merits, but none of them is applicable in a generic way to all aspects of sustainability for a technology. Using concepts developed initially for environmental life cycle assessment, we propose an approach consisting of the following major impact categories: 1) impact on human health; 2) impact on social well-being; 3) impact on prosperity; 4) impact on natural environment; 5) impact on exhaustible resources. All primary impacts can be grouped under these categories. For several of these categories still quite some analysis of mechanisms in the cause-effect chain is necessary and there will be substantial remaining uncertainties for the others. For a complete assessment, the five major impact categories need to be integrated. Several approaches are available for this purpose, such as multicriteria analysis with or without weighted aggregation.

1 Introduction

New technologies have always been the engine of progress and change. Many have drastically changed our lives in the last decades and have therefore been controversial in terms of the net benefit they bring to society. A general awareness has grown that there is a need to carefully assess the expected impact of the introduction of new technologies. The PROSUITE project is a European initiative with the aim to develop and apply a coherent methodology, covering all impacts of new technologies, including social, economic and environmental impacts (PROSUITE, 2009). We will indicate all these impacts collectively as sustainability impacts. The project also intends to develop a corresponding set of operational open-source software tools for the sustainability assessment of future full scale implementation of technologies.

Many initiatives with the aim to assess sustainability of products or services have been developed or are under development. We will discuss some of these approaches:
1. Environmental life cycle assessment
2. Approaches that combine different methods
3. Product-specific methods for full sustainability assessment
4. Full sustainability assessment methods

1.1 Environmental life cycle assessment

In the field of environmental management, life cycle assessment (LCA) is a core methodology. It is a well-established methodology for assessing the environmental performance of products, services and technologies. The methodology has been standardized by the International Standards Organization (ISO 2004, 2006a, b). In terms of sustainability assessment, the methodology has its limitations, as it is generally accepted that sustainability not only covers environmental aspects, but also social and economic aspects. An important element of the methodology is that it uses a life cycle approach, and thus providing an overview of the indirect impacts of the application of products, services or technologies. Also, a rigorous treatment of the impact through the cause-effect chain is followed in the impact assessment, elements that will be helpful in developing our own methodology.

1.2 Approaches that combine different methods

Several projects have already worked on expanding the existing methods for environmental life cycle assessment to cover sustainability in a broader sense. Examples are the Calcas project (Italian National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA), 2009), the PROSA project (Griesshammer et al., 2007), the COMPASS project (Kuhndt and Liedtke, 1999), UNEP/SETAC's life cycle sustainability assessment methodology (Valdivia et al, 2012), and the Sustainability Assessment of Technologies (United Nations Environment Program (UNEP), 2012). These projects all are a combination of existing methods for each the environmental, economic and social dimensions of sustainability. For instance, Calcas describes what combination of methods can be used at different levels of analysis (product, meso and economy-wide). UNEP/SETAC's report on life cycle sustainability assessment illustrates how life cycle costing, social life cycle analysis and environmental life cycle analysis can be combined. None of these approaches have had the ambition to create one integrated method for sustainability assessment, and none of them aim at a full quantitative impact analysis along the cause-effect chain. It should be noted that in several of these cases, the project had completely different aims, e.g. (United Nations Environment Program (UNEP), 2012) is rather focused on creating adequate procedures for sustainability assessment. Such approaches may well be complementary to the approach that we will set out further on in this article.

1.3 Product-specific methods for full sustainability assessment

Several sustainability assessment methods have been developed for well-defined product categories. For instance, for transportation biofuels, several assessment methodologies have been developed as it was widely felt that both social and environmental aspects should be included to cover the key impacts (see e.g. German and Schoneveld, 2011). Sustainability assessment methods have been developed for e.g. electricity supply technologies (Roth et al, 2009) or transportation biofuels and for palm oil (Guariguata et al., 2011). Such assessment methods comprise a wide variety of aspects, such as greenhouse gas emissions, human and labour rights, local food security, and land rights. These approaches, however, are specific for the bio-based products under consideration and are not simply applicable to other products or technologies. A different approach is taken by the Sustainability Consortium. The Sustainability Consortium has developed a framework for the identification of sustainability-related aspects throughout the supply chain of products (Arizona State University and University of Arkansas, 2011). The approach is to identify for each product category hot spots in the supply chain of products in that category. These hot spots are then used to develop an LCA method tailored to that particular product category. So, this framework does not provide a generic methodology, but rather is a generic approach to generate product-specific methodologies for sustainability assessment.

1.4 Full sustainability assessment methods

A methodology that aims at providing an integrated sustainability assessment of many products are the ‘GoodGuide ratings’ (Goodguide Inc., 2012). This method assigns a score (between 1 and 10) for a products performance on each of the categories health, environment and society. It then takes the average of the three scores (without weighting). The analysis of a products performance comprises many categories. For example, for the environmental and social assessment, GoodGuide ratings take into account management issues, transparency, health and safety policies, controversies, product recalls as well as information about labeling and marketing practices. Furthermore, community relationships, stakeholder engagement initiatives and public policy positions are tracked. For the assessment of the health category, GoodGuide ratings take into account direct health effects of a product category, information on production and regulation of products (e.g. use of toxic ingredients) and whether products are sustainably managed. In only limited cases a direct quantitative score is used, most scores are based on qualitative assessments. Although the assessment method covers many impact categories, and the indicators used are definitely impact-related, there is no direct relation between indicators and impacts.

The same can be said of most indicators for corporate sustainability. The most well-known are the Dow Jones Sustainability Indexes (Dow Jones Indexes, 2013) representing a family of indices evaluating the sustainability performance of the largest 2500 companies listed on the Dow Jones and assesses issues such as corporate governance, risk management, branding, carbon intensity, supply chain standards and labor practices. Other examples of ratings for corporate sustainability are the ‘Global 100 Most Sustainable Corporations’ that lists the hundred most sustainable companies throughout the world. Like in the case of the GoodGuide ratings, the indicators have some sort of relation with sustainability impacts, but the relation is generally not straightforward. Various impact-related indicators are aggregated, without a clear background how different input variables relate to the ultimate scores.

Other approaches just focus on a limited number of interventions, like the ‘Carbon Disclosure Project Leadership Index’ which encourages companies to measure and disclose their greenhouse gas emissions, climate change risk and water strategies.

1.5 The need for a new methodology

Summarizing the existing methodologies mentioned we can conclude that they either do not cover all dimensions of sustainability, or they do not cover all dimensions of sustainability, they do not cover them in a comparable manner, or do not include a rigorous treatment of cause-effect relations towards impacts. Nevertheless all of these approaches have their merits, but none of them is applicable in a generic way to all aspects of sustainability for a technology. This means there is a need for a sustainability assessment method that:

- covers all dimensions of sustainability in a comprehensive way;
- is applicable to a wide range of technologies including emerging technologies, enhancing consistency in the assessment over a wide range of technologies which is helpful for policy decisions across technologies;
- pursues a well-founded and reproducible assessment along the cause-effect chain to ultimate scores, assessing tradeoffs between different phases in the life cycle and different impacts in an overarching and comprehensive way. This avoids suboptimal solutions;
- works with quantifiable indicators avoiding subjective or ad-hoc judgments as much as possible, providing the basis for the preparation of an operational software tool.

The PROSUITE project is a European initiative with the aim to develop and apply a coherent methodology for assessment of the sustainability of products, services or technologies (PROspective SUstaInability Assessment of TEchnologies (PROSUITE), 2009). In the current study this methodology is presented, covering all impacts of technologies, including social, economic and environmental impacts. The framework is aimed to support decisions concerning new and existing products, services and technologies, allowing for conducting retrospective as well as prospective assessments. Decision makers within companies, governments and society as a whole are the target audience.

We will start with a brief recap of key elements of the sustainability concept and give an overview of sustainability assessment methodologies that have been applied in the past. We will then turn to an area where thinking along the cause-effect chain is already advanced: environmental life cycle impact analysis. On the basis of this analysis, we will come up with a proposal to build a novel sustainability assessment methodology, based on five pillars. Finally we discuss the strengths and weaknesses of the proposed methodology and outline the needs for further development.

2 Key elements of sustainability

In this section, we discuss the main sustainability concepts emerging from the literature on definitions of sustainability.

The World Commission on Environment and Development (WCED), also known as the Brundtland Commission, has addressed sustainable development in its report ‘Our Common Future’ (WCED, 1987). The definition of sustainable development in the report is often cited and well known: *“Sustainable development is development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs”*. This definition shows two key elements, i.e. the concept of ‘needs’, in particular the essential needs of the world’s poor, to which overriding priority should be given and the idea of ‘limitations’ imposed by the state of technology and social organization on the environment’s ability to meet present and future needs.

It should be noted that in all sustainability assessment methods discussed above, the second part of the WCED definition is taken into account. Impact of activities for future generations, like resource depletion and environmental degradation, are covered by virtually all methods. That is much less the case for the first part, the needs of the present generation, which can be satisfied by (global) economic development. In the approach proposed here, we aim to provide a balanced treatment of both aspects.

The link of sustainability to the (natural) environment is quite obvious, since it concerns the world we live in and the primary source of biotic and abiotic resources. A study by the Projektgruppe Ökologische Wirtschaft (P.Ö.W., 1987) first emphasized the importance of also including economic and social aspects in sustainability assessments. At the first UN Conference on Environment and Development, in Agenda 21, the nations agreed upon a further elaboration (UNCED, 1992):

- Environmental sustainability aims at preserving the natural environment we live in. Human activities shall not exceed the carrying capacity of important ecosystems. Environmental sustainability also aims at preserving biodiversity. It requires care for the safety and health of humans, animals and plants.
- Economic sustainability aims at realizing an economic development that meets the needs of current and future generations and that respects the aspiration for equal distribution of capital. It also requires attention for the competitive power of industry and the security of supply. Attention should be paid to technological innovation but also to the vulnerability and flexibility of economic and technological systems. In addition, attention should be paid to the efficiency of deployment of resources.
- Social sustainability focuses on the social well-being of people. It aims at enhancing social cohesion and developing cultural identity. Furthermore, resources have to be equally accessible for different populations in order to guarantee social justice. Also safety and health of present and future generations should be guaranteed and this makes demands for the use of technologies.

At this moment it is widely accepted that sustainability should be defined along the three pillars social-environmental-economic. In the corporate world the three pillars are often referred to as people-planet-profit or the 'triple bottom line' (Elkington, 1994).

After having recognized that sustainability has several dimensions or 'pillars' it is important to consider how to deal with the trade-off between the various dimensions. For this trade-off, the distinction between 'weak sustainability' and 'strong sustainability' is relevant. These concepts were introduced by Costanza and Daly (1992) and are extensively described by Neumayer (2003). Weak sustainability is based on the belief that what matters for future generations is only the total aggregate stock of 'man-made' and 'natural' capital (and possibly other forms of capital as well) but not natural capital as such. According to weak sustainability it does not matter whether the current generation uses up natural capital, such as non-renewable resources or pollutes the environment, as long as enough machineries, roads, ports, etc. are built in compensation. Since, according to this definition, man-made capital can replace natural capital, this approach is also referred to as the 'substitutability paradigm'. The opposite of weak sustainability is strong sustainability. The essence of strong sustainability is that natural capital is fundamentally non-substitutable through other forms of capital. It is therefore referred to as the 'non-substitutability paradigm'. There are different interpretations of strong sustainability in the literature; one interpretation is that natural capital should be preserved in value terms. For example, coal mining should be compensated with investments in the development of renewable energy sources in order to keep the aggregate value of the total natural resource stock constant. In a second interpretation, those forms of natural capital that are regarded as non-substitutable should be preserved in physical terms. Practically, this means: a) use renewable resources such that their stock does not deteriorate, i.e. harvest at maximum the maximum sustainable yield, and b) use the environment as a sink for pollution only to the extent that its natural absorptive capacity does not deteriorate over time.

An important lesson from the weak vs. strong sustainability debate is that there is no single perspective on sustainability, and hence there is no single sustainability indicator that is valid for everyone; a sustainability assessment methodology must have the possibility for dealing in different ways with the various pillars.

A related, but different approach is proposed by Renn et al. (2009) that they call the 'normative-functional concept of sustainability'. The term 'normative' refers to a concept that is based on a goal-oriented vision of a desirable future. Basically it refers to a set of rules that incorporates what is a desirable state of being and what ought to happen in order to reach this state. The term 'functional' on the other hand concerns the idea that phenomena and institutions have particular functions within a societal or ecological system and can therefore be evaluated according to their performance with respect to functional goals. In other words, they can be evaluated on the degree to which they contribute to reaching the desired state of being set by the normative concept(s). Renn et al. (2009) identify three normative principles that cover most of the normative suggestions found in the literature: i) to guarantee the continuity of ecological systems, ii) to act in accordance with inter- and intragenerational justice and iii) to ensure an optimal level of quality of life. In order to reach these normative requirements, Renn et al. (2009) defined a broad set of functional indicators that can be quantified in order to determine the contribution of a development to sustainability.

3 Experiences of environmental life cycle impact assessment

As already noted in the introduction, the rigorous treatment of impact assessment along the cause-effect chain in environmental life cycle impact assessment (LCIA) can provide a useful structure for the development of a broader sustainability assessment methodology.

In the field of environmental management, life cycle assessment (LCA) is a core methodology. First concepts were developed already in the early seventies, though it went by different names such as Resource and Environmental Profile Analysis (REPA, see for example Cross et al., 1974), Energy Analysis (Boustead and Hancock, 1979) or Product Ecobalance (e.g. Rubik and Baumgartner, 1992). First comprehensive methodologies for LCA were developed by Müller-Wenk (1978, 1980) ("Ökobilanzen") and later by Steen (1990) with his first 'Environmental Priority Strategies (EPS)' method. In 1994, the International Standards Organisation (ISO) started developing standards for LCA and the first standards appeared in 1997. Since then, the LCA methodology has been specified in a series of ISO standards: 1) ISO 14001 (ISO, 2004), 2) ISO 14040 (ISO, 2006a) and 3) ISO 14044 (ISO, 2006b). Report 1 is an introduction to environmental management systems, report 2 defines the principles of the method, while report 3 explains the phases of the procedure (it replaces the old ISO standards 14041, 14042 and 14043).

In life cycle impact assessment, environmental impacts are calculated, starting from interventions in the environment. Interventions can be extractions of primary materials (biotic and abiotic) or emissions to soil, water or air. The interventions result from human operations in the life cycle of the product or service that is assessed in the LCA. The interventions are also referred to as 'elementary flows' between the product system and the environment, and they are derived from the inventory data compiled in the inventory analysis of the LCA. In order to calculate an environmental impact, the elementary flows are multiplied with so-called characterisation factors. These characterisation factors are based on scientific analysis; they convert the elementary flow to a unit that is used to quantify an environmental impact. For instance, it converts the emission of greenhouse gases (like methane and N_2O) to emissions expressed in CO_2-equivalents (eq.) that is used to measure the impact on climate change; e.g. the emission of 1 kg of methane emission to air is equivalent to 21 kg CO_2-eq. In a similar way, acidification is expressed in terms of kg SO_2-eq, and human toxicity in kg 1,4-dichlorobenzene-eq.

When all elementary flows in the life cycle have been converted/characterized into the metrics of (one or more) environmental impacts, they can be summed up for each of the impacts giving the resulting environmental impacts of the technology/service that is assessed (European Commission, 2010). These environmental impacts are generally referred to as ‘mid-point’ indicators[1].

But the midpoints as contributions to environmental problems, do not yet measure impacts, e.g. on humans and ecosystems. Therefore, a next step is needed, to get from midpoints to ‘endpoints’: the actual impacts. The ILCD handbook defines endpoints as impacts on the areas of protection ‘human health’, ‘natural environment’ and ‘natural resources’ (European Commission, 2010a).

Figure 1 shows an overview of the cause-effect chain with midpoints and endpoints. Note that one type of interventions can contribute to more than one midpoint, e.g. NO_x emissions contribute to both acidification, eutrophication, photochemical oxidant formation, human toxicity and ecotoxicity. Also, one midpoint can contribute to more than one endpoint, e.g. climate change impacts both human health and the natural environment (ecosystem quality).

A strong point of the LCIA methodology is that it is strictly based on the scientific analysis of cause-effect relations along the cause-effect chain. It must be noted that not all these cause-effect relations are already well established. The European Commission has issued a report in the ILCD series that contains recommendations on state of the art methodologies for characterizing environmental interventions at mid- and endpoint level of environmental impact assessment after having consulted a large number of European and non-European stakeholders and experts (European Commission, 2011).

[1] Discussion is ongoing on how to choose the midpoint indicators and, especially, where in the pathway of cause (‘intervention’), effect (‘environmental impact’) or eventually damage to the environment. Ideally, the midpoint should be located at that point of the impact pathway where the paths of the individual contributors converge, i.e. the first point of the impact pathway beyond which there is no distinction in the impact mechanism between the different contributing substances or physical interventions. For climate change, the radiative forcing indicator (used for the calculation of the global warming potential) respects this principle. However, some other impact categories are more heterogeneous, in particular the toxicity categories. Here, the midpoint indicators are chosen as closer to the areas of protection, which are also referred to as ‘endpoint’ indicators. Midpoint indicators are also referred to as a ‘problem-oriented approach’ because it is driven by environmental problems, while endpoint indicators are referred to as a ‘damage-oriented approach’ because it refers to damage within the areas of protection (Guinée et al, 2001a).

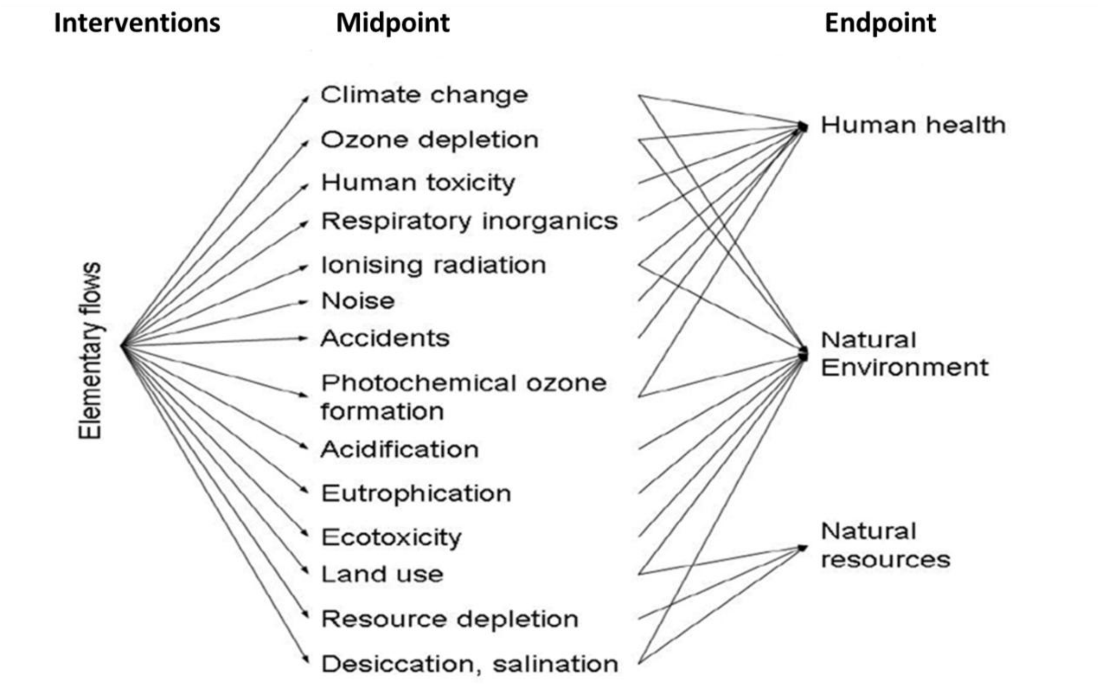

Figure 1: From interventions (elementary flows) to midpoints and endpoints in environmental life cycle impact assessments (European Commission, 2010a).

4 Proposal for a new sustainability framework

In this section the proposed methodological framework for sustainability assessment is described, providing the basic structure underlying the sustainability assessment of a product, service or technology. The basis for the methodology is a life cycle approach.

The specific material and product flows within the life cycle of the technology are analyzed within the methodological framework. It provides a basis for the calculation of the underlying impacts (midpoints), which then count to overall impact categories (endpoint indicators). First the reasoning for the choice of indicators is presented, followed by a description of the operationalization of each indicator and the overall methodology for integration.

4.1 Proposed impact categories

Building on the consistent and science-based approach developed for life cycle impact assessment, a logical step would be to expand the system of environmental impact assessment with two additional systems, on economic and social impact assessment. However, although the breakdown into the social, environmental and economic dimensions of sustainability is now very common and widely used, there are problems with these three pillars.

The most important one is that there are overlaps, even to the extent that some impacts could largely include some of the others. Health and income could for instance be included in the social pillar when having a broad interpretation of social well-being, since both factors have a large influence on the quality of life of people. When adopting an external costs approach all impacts could on the other hand (in theory) be converted to economic impacts when assigning monetary value to the damages to environment and human health. It is also illogical that health impacts caused by environmental interventions are generally considered to be part of the environmental pillar, whereas occupational health impacts are normally considered to be part of the social pillar (like for instance Benoît et al, 2009). Therefore, when using the three-pillar concept in an impact assessment, some distinctions would become quite artificial.

Impact categories should satisfy the MECE-principle: they should be mutually exclusive and collectively exhaustive[2]: indicators should be chosen such that there is no overlap between the indicators and that they together represent all potential sustainability impacts. There should be enough different impact categories to allow for strong sustainability assessment: taking into account non-substitutability between various impacts should be possible. This should at least reflect intergenerational non-substitutability (cf. WCED definition), but also within generations. Also, the impact categories should be selected in such a way that determination of the impacts up to the level of impact categories should to a large extent be possible based on scientific information, i.e. the impact of value-choices is limited. The overall sustainability assessment across the impact categories can then include value-based choices, e.g. a weak or strong approach to sustainability or different weighting of the seriousness of impact categories.

A way to avoid the problems with the three-pillar approach is to define a new set of five 'impact categories' that together cover all dimensions of sustainability, and aim to serve subdivisions that are mutually more exclusive. Based on these criteria, we propose the following set of impact categories:

1. Impact on human health
2. Impact on social well-being
3. Impact on prosperity
4. Impact on natural environment
5. Impact on exhaustible resources

The choice of these impact categories and how they are composed is shown in Figure 2 and discussed in the sections below.

4.2 Impact on human health

The impacts on human health of a new technology include all changes in morbidity and mortality that are caused by the introduction of new technologies, through all possible pathways, including environmental, occupational and as consumer. This definition is adapted from the ILCD guidelines (European Commission, 2010b), where it is limited to environmental stressors only. Apart from impact on human health caused by environmental stressors, it makes sense to extend the impact also to occupational health (caused by work-related stressors) and consumer health (caused by stressors during use of products).

Impacts on human health can be quantified with the 'DALY-concept' (Disability Adjusted Life Years, Murray and Lopez, 1996). It combines information on quality of life and life expectancy in one indicator, deriving the number of healthy life years lost due to morbidity or premature mortality. As such, the DALY is the sum of years of life lost (YLL) and years of life disabled (YLD): DALY = YLL + YLD. In turn, the YLD is equal to $YLD = w \cdot D$ in which w is the disability weight between 0 (complete health) and 1 (dead) and D is the duration of the disease. The unit of the DALY is 'year'.–The DALY-concept is well-established in the literature and for many types of diseases disability weights have been established, see e.g. Murray and Lopez, 1996.

Impacts on human health can be determined by a careful analysis of impact pathways of substances, see e.g. (European Commission, 2010b).

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[2] This principle is taken from consultants McKinsey & Company (Friga, 2008)

4.3 Impact on social well-being

The social impact includes all impacts on human well-being that are related to inter-human relationships, both on an individual and collective basis. Extensive study has been performed by Weidema (2006), Grieshammer et al (2006) and Benoît et al (2009). Their research has focused on impact categories as well as stakeholder categories. The study of Benoît et al (2009) proposed a set of sub indicators based on stakeholder groups, including workers, consumers, local community, society and value chain actors. The impact categories proposed were equal opportunities, workers' rights and working conditions, respects of national and international laws, human rights, consumers protection (Grieshammer et al, 2006). The study of Weidema (2006) proposed to include impact categories on 1) autonomy, 2) safety, security and tranquility (SST), 3) equal opportunities and 4) participation and influence. This categorization is adapted because it is found to be covering all impacts on social well-being and it better fits our framework than a stakeholder oriented categorization.

Autonomy means 'being in control of one-self and one's resources'. Autonomy is negatively impacted by for example forced labour or slavery. Safety, security and tranquility are described as a combination of 'freedom from threats to personal health (safety)', 'freedom from threats to personal property (security)' and 'freedom from excessive stress (tranquility)'. Safety, security and tranquility are for example negatively impacted by unemployment and high perceived risks. Equal opportunity is a stipulation that all people should be treated similarly, unhampered by artificial barriers or prejudices or preferences, except when particular 'distinctions can be explicitly justified' (De Vries, 2012). Equal opportunities are negatively impacted by gender income inequalities and extreme income inequalities in general. Participation and influence can be defined as 'the act of taking part or sharing in something and affecting the course of event' (Farlex, 2012). More specifically, it involves the degree to which people have rights to participate in politics and trade unions. Participation and influence is for instance negatively impacted if people feel limited involvement in decision making processes that concerns them.

At present, there is no generally accepted measure available for social well-being. Most measures for social impact assessment are qualitative in character. In analogy to the DALY indicator for human health, one might define Well-being Adjusted Life Years, where weight factors are introduced that take the value zero for completely unimpacted well-being (in comparison to the baseline situation) to one for the lowest level of well-being[3].

Also the quantitative assessment of such measures along the cause-effect chain is still in an early stage of development; most assessment methods established so far have a semi-quantitative character, see, e.g. Ciroth and Franze (2011).

4.4 Impact on prosperity

Technology development is often pursued to increase the quantity and quality of goods and services for consumption. Consumption (or more precise: final consumption) can be either private or collective (via government expenditures). Final consumption can be increased in two distinct ways (Wood and Hertwich, 2012). The first way is through changes in factor productivity. For instance, decreases in the costs of labour or capital per unit of product will lead to lower costs of final products and hence make a higher final consumption possible. The second way is through the production of new products and services satisfying new consumer needs. Assuming that there is sufficient spare capacity in the economic system, these new products or services also will lead to higher final consumption.

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[3] Such indicator was proposed by Weidema (2006), indicated as QALY. Weidema also provides a first estimate of total impact on social well-being from the four categories mentioned.

Gross domestic product is a measure of the value of goods and services available for final consumption[4]. Gross domestic product[5] is expressed in monetary terms.

Although changes in GDP do not exactly represent the impact on prosperity (see e.g. Jackson, 2009), it is taken as the unit of this indicator because it is a generally accepted and quantitative method for measuring the impact on prosperity. The impact of a new technology on gross domestic products can be established through a variety of economic models, provided that they make use of a sufficiently detailed input-output framework to establish intersectoral and life cycle impacts (Wood and Hertwich, 2012).

4.5 Impact on natural environment

Impact on natural environment encompasses the impact on natural ecosystems around the world in terms of their function and structure (European Commission, 2010b). Negative effects on the function and structure of natural ecosystems can occur as a consequence of exposure to e.g. chemicals, biological or physical interventions. These negative effects can be studied by means of e.g. the percentage of invasive species, the area of set aside land, decaying wood, species occurrence data, the potentially affected fraction of species, the species sensitivity distribution, the effect concentration of a substance for 50% of the population or the ecosystem damage potential (Curran et al, 2012). Since natural ecosystems are highly complex, with multiple interactions between different populations at the same or different trophic levels and with different physical and chemical surroundings, it is difficult to assess effects on their structure and functions. Therefore, it is recommended that the focus should be on the occurrence of different species in the ecosystem, i.e. biodiversity (European Commission, 2010a). The Rio Convention's definition of biodiversity is 'the variability among all living organisms from all sources, including, inter alia, terrestrial, marine and other aquatic ecosystems and ecological complexes of which they are part; this includes diversity within species, between species and of ecosystems' (UNCED, 1992). The impact on natural environment is then expressed in terms of 'potentially disappeared fraction of species (PDF)', which can be interpreted as the fraction of species that has a high probability of no occurrence in a region due to unfavorable conditions.

Impacts on the natural environment can be determined by a careful analysis of impact pathways of stressors, see e.g. (European Commission, 2010b).

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[4] A weakness of using GDP as indicator for prosperity is that it does not take into account that there are diminishing returns with increasing GDP. This also means that increasing GDP by one Euro in developing countries will likely lead to higher increase in perceived prosperity than one Euro increase in a developed country. Another weakness of GDP is that it does in its standard form not include external effects. It is not ensured that resource and environmental constraints are not transgressed. However, in the method that we propose here, such impacts are covered under the other impact categories; that justifies the use of a 'naked' GDP definition.

[5] Whilst most components of GDP are generally acknowledged as "positive" aspects of development (compensation of labour, for example) part of the GDP may include expenditure to off-set negative effects of development (health care for traffic accidents or air pollution; policing to fight crime), or consist of a monetization of previously non-monetary activities (child and elderly care), so that GDP gains are not necessarily equivalent to welfare gains (Stiglitz et al, 2009). The fact that we sum over these inherently different costs of production means that the calculation of GDP is in fact a normative (or social) construct – a GDP calculation implicitly states that we value each type of factor input equally (Wood and Hertwich, 2012). As such, GDP is clearly an endpoint indicator in the Impact Assessment hierarchy.

4.6 Impact on exhaustible resources

Impact on natural resources is concerned with the removal of resources from the environment (and their use) which results in a decrease in the availability of the total resource stock (European Commision, 2010b). This impact category comprises abiotic resources: fossil fuels and mineral ores (Udo de Haes et al, 1999), together indicated as exhaustible resources. Biotic resources, such as wood and fish, are excluded from this impact category, as depletion of such resources is already measured under 'Impact on the natural environment'.

To measure the impact on natural resources, different ways of quantifying have been proposed, e.g. on a mass, monetary, energy or exergy basis (Lindeijer et al., 2002; Stewart and Weidema, 2005). We propose to treat fossil fuel resources and mineral ore resources separately. As fossil fuels, like coal, oil and natural gas, can be substituted to a considerable extent as energy carriers, it makes sense to aggregate them on an energy basis, expressed, e.g., in kg oil-equivalent. For the quantification of depletion of the mineral ore often a relationship is used between ore extraction and what is left in the reserves. This relationships can be based on a physical amount (kg) as is done in the so-called CML baseline methodology (Guinée et al., 2001b) or quantified in monetary terms as is done in so-called Recipe method (Goedkoop et al., 2012) reflecting increased costs of mining in case of depleting resources. In both cases the midpoint indicator for 'depletion' is expressed in relation to a reference substance, i.e. kg antimony-equivalents in the CML baseline methodology and kg iron-equivalents in the Recipe method. Fossil fuel resource depletion and mineral resource depletion can then be further aggregated.

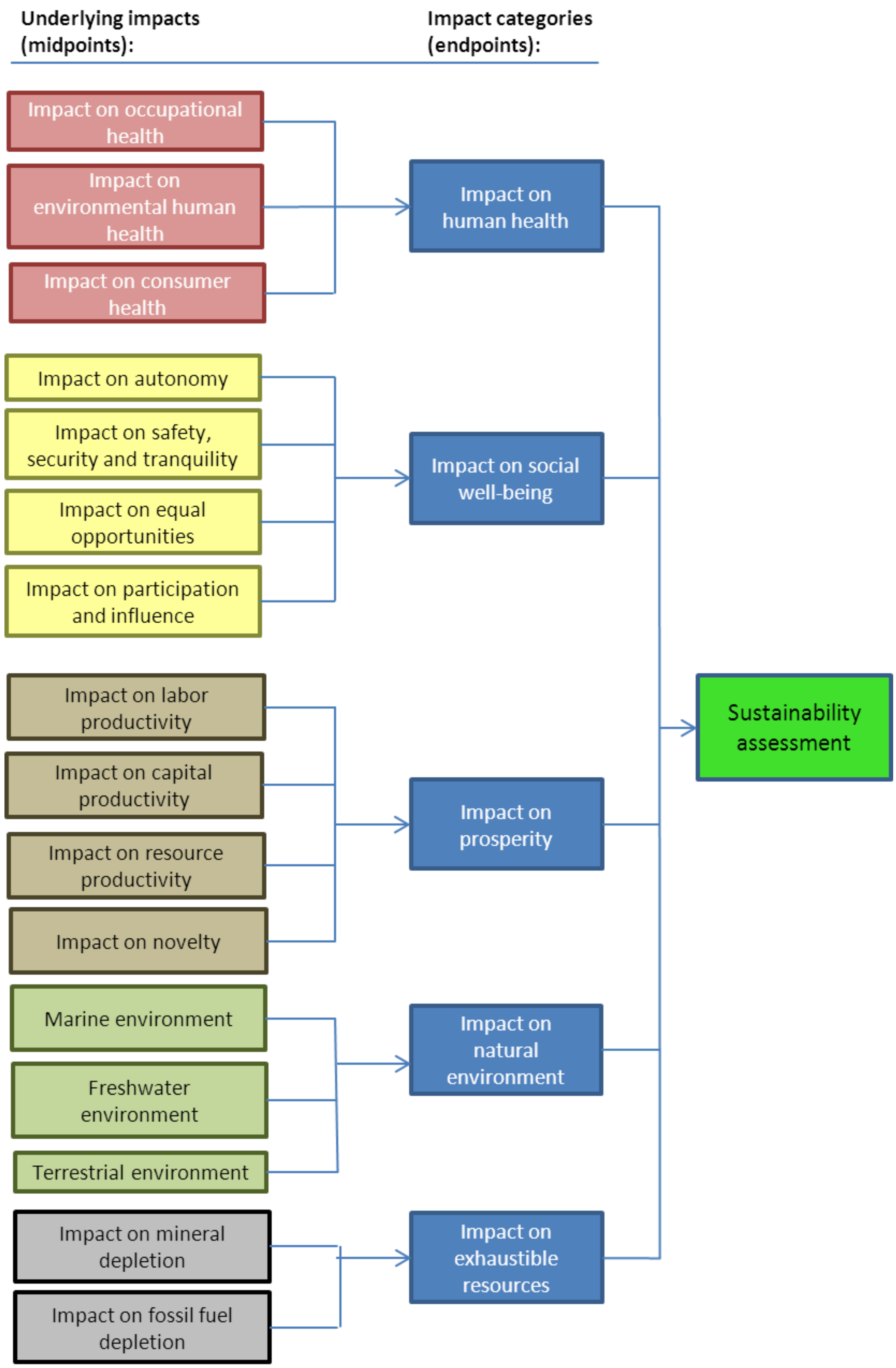

Figure 2: Schematic representation of the overall sustainability framework.

Endpoint indicator	Description	Scores
Human health	Morbidity and mortality values caused by the introduction of new technologies, through all possible pathways, including environmental, occupational and as consumer	Number of disability adjusted life years associated Unit: DALY Direction: minimize
Social well-being	All impacts on human well-being that are related to inter-human relationships, both on an individual and collective basis. These include impacts on: 1) autonomy; 'being in control of one-self and one's resources' 2) safety, security and tranquillity (SST); 'freedom from threats to personal health, personal property and excessive stress' 3) equal opportunities; 'similar treatment for people, except when distinctions can be explicitly justified' 4) participation and influence; 'the act of taking part or sharing in something and affecting the course of event'	The preliminary method involves scoring based on expected negative impacts on the change in: 1) knowledge-intensive jobs, total employment, risks perceived, possibility of misuse, e.g. terrorism 2) child labour, forced labour 3) income inequalities within countries (Gini-index), global inequalities (between countries; Human Development Index) 4) trust in risk information, involvement of stakeholders in decision making processes, trust that long term control will be safeguarded Unit: 1-5 weighting scale (likert scale) Direction: minimize
Prosperity	Impacts on economic system	Change in GDP Unit: € Direction: increase
Natural environment	Impact on natural ecosystems around the world in terms of their function and structure, focusing in biodiversity	Potentially disappeared fraction of species (PDF) Unit: species*year Direction: minimize
Exhaustible resources	Comprises abiotic resources: fossil fuels and mineral ores	Fossil resources extracted/ mineral ore resources extracted Midpoint unit for fossil resources: kg oil equivalent Midpoint unit for mineral ore resources: *CML methodology*: factor that expresses the depletion as a physical flow, related to the reserves, and defines the midpoint unit as kg Sb equivalents. *Recipe methodology*: factor that expresses the depletion in monetary terms and defines the midpoint unit as kg Fe equivalents. Endpoint unit: € Direction: minimize

Table 1: Overview of indicators and their preliminary operationalization

4.7 Overall sustainability assessment

Once we have established a set of impact categories that are constructed using a comparable approach, the next challenge is how to come to an overall sustainability assessment of the sustainability. So, in order to analyse the sustainability of a product, service or technology, we need an overall assessment across all impact categories. An integrated and holistic assessment allows for a sufficient level of detail to be integrated within the broader picture.

We see various approaches that could be applied. One could, first of all, apply no aggregation at all and leave the results as they are; second, one could apply a multi criteria analysis where the results are shown as a hierarchy, and third one could aggregate the results for the impact categories into one single score.

1. The approach of leaving the impact category scores as they are is the most straightforward approach. The advantage is that no artificial aggregation occurs and no information is lost; the impact category values are transparent. The values could possibly be displayed in a graphical representation, e.g. a spider diagram (like e.g. Traverso et al, 2012). For this purpose, the values might need to be normalized (i.e. relating impact scores to the total European or global impact per capita) in order to give them a comparable scale. Normalization is also an important first step for the other two options.
2. The second approach of multi-criteria analysis can be defined as 'a decision-making method used to evaluate problems, when one is faced with a number of different alternatives and expectations and wants to find the "preferred" solution with regard to different, and often conflicting, objectives'. In case of a sustainability assessment of alternative products/technologies/product systems, it allows ranking the alternatives from 'most preferred' to 'least preferred', or in this context from 'most sustainable' to 'least sustainable'. Many MCA methods are available. They can be subdivided into methods that have a compensatory approach and methods that have a non-compensatory approach. Compensatory approaches allow for poor performance in one criterion to be compensated by good performance in other criteria. The scoring of criteria are aggregation to one meta-criterion. The most widely used example of a compensatory methodology is weighted summation, where a weighted average of the criteria scores for each alternative is computed and the one with the best overall value is chosen. Non-compensatory approaches on the other hand do not allow for poor performance in one criterion to be compensated by good performances in other criteria (although sometimes partial compensation is allowed). An example of a non-compensatory methodology is outranking analysis, which chooses 'winning' alternatives in comparisons on specific criteria while 'outranking' the others (Antunes et al., 2011). The application of a compensatory aggregation method is in contradiction with the strong sustainability standpoint, since it allows for trade-offs between the endpoint indicators.
3. When a multi-criteria analysis is applied the results for the five impact categories can be aggregated into one value. As the impact categories are widely varying, it is clear that it is not straightforward to bring them to a common metric. The weight that will be given to the various impact categories will be strongly determined by individual or collective preferences. For environmental life cycle impact assessment it turned out to be possible to determine several weighting sets based on panel data. A similar approach could also be pursued to aggregate the five impact categories defined in this paper, involving the important stakeholders of the study.

The aggregation methodology that we propose is a combination of the three approaches described above (graphical displays, weighted sum and outranking analysis). This will allow for transparent presentation of the analysis that includes all relevant aspects and do justice to the fact that sustainability is a multi-dimensional phenomenon.

An operational open-source software tool is applied where a sufficient level of detail is combined with a holistic view to cover the broader picture.

5 Discussion

5.1 Diversity of indicators

One of the requirements of a collection of sustainability impact indicators is that the categories should be sufficiently diverse to make an overall assessment meaningful. The total set should allow for investigating ‘strong’ sustainability scoring of products, services and technologies. In our view, the set that we have defined here satisfy that diversity:

- They contain impact categories that primarily concern the present generation (human health, social well-being, prosperity) and impact categories that primarily concern future generations (natural environment, natural resources).
- They contain impact categories that are currently valuated in the market place (prosperity, natural resources) and impact categories for which this is not the case (human health, social well-being, natural environment).
- The impact categories group the underlying impacts in a way that allows respecting the non-substitutability requirement inherent in strong sustainability definitions.

The three major normative elements that were identified by Renn et al. (2009) (guarantee continuity of ecological systems, act in accordance with inter- and intragenerational justice and to ensure an optimal level of quality of life) are all well covered by the five impact categories described.

The current list satisfies the principle that the total list should be mutually exclusive and collectively exhaustive. The list of impacts is exclusive to the extent that no double-counting of impacts occur. This does not mean that underlying interventions will not lead to impacts in different categories. For instance, higher economic activity may lead to both higher prosperity and lower unemployment. And a more resource-efficient production process may lead both to conservation of exhaustible resources and higher prosperity. But these are multiple impacts of primary interventions, which is different from overlaps.

It is difficult to identify whether the list of impact is exhaustive. So far, we have not identified impacts that do not logically fit in one of the five impact categories.

5.2 Merging or splitting

One could consider further splitting of indicators. Natural resources could for instance be split into fossil fuel resources and mineral resources; or social well-being could be split into elements that have a more individual character (autonomy; safety, security and tranquility) and those that have a more collective character (equal opportunities; participation and influence). However, we should be cautious to have too many impact categories, as this will make meaningful overall assessment more difficult.

On the other hand further aggregation would be a possibility. Human health and social well-being could for instance be combined, since both indicators affect the quality of life. Nevertheless, within this project it has been decided that these indicators are sufficiently different in character to keep them separate.

5.3 Towards overall sustainability assessment

In order to perform an integrated sustainability life cycle assessment the applied aggregation methodology is an important element. The aggregation methodology that is proposed within the PROSUITE project is a combination of different approaches, which allows for transparency of the process. It should be noted though, that the clarity (but also the ambiguity) would be increased when only one approach would be applied.

5.4 Operationalization

The choice of operationalization methodology is a main part of the proposed framework. For some impact categories the operationalization methodology is built on extensive research performed in the past and based on large databases that have proved their validity. However for other impact categories (like the impact on social well-being) the methodologies are quite new and have not been tested yet.

6 Conclusions

We have proposed a framework for sustainability assessment that covers all dimensions of sustainability: 1) impact on human health; 2) impact on social well-being; 3) impact on prosperity; 4) impact on natural environment; 5) impact on exhaustible resources.

For all the impact categories proposed here, it is possible to assess the impact on a life cycle basis for the assessed technology and across the full cause-effect chain. For none of the impact categories identified here such methodologies are fully available yet. They are most well established for human health and prosperity, modestly established for impacts on the natural environment and natural resources and still in an early stage of development for impacts on social well-being.

The five impact categories form a limited, nevertheless comprehensive set, which could serve as a good basis for overall sustainability assessment.

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