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Options for broadening and deepening the LCA approaches

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ABSTRACT

Life Cycle Assessment (LCA) has matured over the past decades and become part of the broader field of sustainability assessment. To strengthen LCA as a tool and eventually increase its usefulness for sustainability decision-making, it is argued that there is a need to expand the ISO LCA framework by integration and connection with other concepts and methods. This paper explores the potential options for deepening and broadening the LCA methodologies beyond the current ISO framework for improved sustainability analysis. By investigating several environmental, economic and social assessment methods, the paper suggests some options for incorporating (parts of) other methods or combining with other methods for broadening and deepening the LCA.

1. Introduction

Life Cycle Assessment (LCA) has evolved significantly over the past three decades to become more systematic and robust tool for identifying and quantifying potential environmental burdens and impacts of a product, process or an activity. It has become an invaluable decision-support tool that can be used by manufacturers, suppliers, customers, policy-makers and other stakeholders [1]. Despite that, application of LCA and its integration into decision-making process has not been as widespread as expected. Although in principle LCA can inform consumer and policy decisions on environmental grounds, often decision-makers need information on other sustainability dimensions as well. In order to provide such information, it has been argued that there is a need to expand the ISO LCA framework for sustainability assessment by taking into account broader externalities, broader interrelations and different application/user needs with often conflicting requirements [2,3]. There are two complementary potential approaches for expanding the ISO LCA framework [4-7]:

i) "deepening" – improving ISO 14044 guidance related to definition of system boundaries, allocation methods, dynamic aspects, scenarios specification, etc.; and
ii) "broadening" – i.e. integration into LCA of social and economic dimensions of sustainable development.

Expansion of the ISO LCA framework has both advantages and disadvantages. On the one hand, its integration and connection with other concepts and methods could strengthen LCA as a tool and eventually increase its usefulness. However, on the other hand, expanding the ISO LCA framework might lead to ever more complex LCA which could damage the reputation of the tool and eventually decrease its value for decision-makers in business and politics.

In view of these opportunities and risks, this paper explores the potential options for deepening and broadening the LCA methodologies beyond the current ISO framework for improved sustainability analysis. By investigating several environmental, economic and social assessment methods, the paper indicates options for incorporating (parts of) other methods or combining with other methods to expand the LCA framework. However, before ways of deepening or broadening the existing ISO LCA framework can be chosen, the various related methods must be defined and analysed with respect to sustainability assessment. Principal assumptions of different methods need to be formulated, and their strengths and weaknesses for assessing social, economic and environmental aspects of sustainable development need to be compared. Therefore, this paper first reviews environmental, economic and social assessment methods and appraises the demand for and supply of sustainability assessment approaches.

Different authors have suggested frameworks for categorising LCA-related concepts methods and models [6,8]. There seems to be

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consensus that more research needs to be invested in combining and integrating the different approaches. Yet, there is no generally accepted way of integrating different LCA concepts, models and methods. Neither will there be an uncontested way of integrating them, as it will depend on the purpose of analysis and assessment. Research and development on concepts, models and methods and their combinations remain "open ended". Therefore, this paper does not claim to give a complete overview of all possible options, but provides guidance with regard to a multitude of procedural and analytical methods.

2. Overview of methods

Earlier overviews of sustainability and/or environmental assessment methods and tools have demonstrated that approaches can be categorised based on numerous factors or dimensions [6,9,10]. Here, the methods are first broadly grouped based on their type, i.e. procedural frameworks and analytical methods (Table 1). The focus in procedural frameworks is on procedures to guide the process to reach and implement environmental decisions, whereas analytical methods provide technical information for a better-informed decision-making by modelling the system in a quantitative or qualitative way [5]. The methods in these categorises are discussed and differentiated with respect to their characteristics such as coverage of sustainability dimensions (environment, economic and social) and focus (product, project or policy level). The list is not exhaustive but indicative of the categories of different methods which could be used for broadening and deepening LCA. Note that review of models, software packages and databases is beyond the scope of this paper.

2.1. Procedural methods/assessment frameworks

The assessment frameworks discussed here include Environmental Impact Assessment (EIA), Strategic Environmental Assessment (SEA), Sustainability Assessment (SA) and Multi-Criteria Decision Analysis (MCDA). These are forecasting procedural methods which are used ex ante to support the decision-making process for policies and projects [9]. In practice, various analytical methods are applied as part of the assessment process.

2.1.1. Environmental Impact Assessment (EIA)

EIA can include several different methods and tools for analysis, depending on the technical/environmental content of the decision at hand. EIA is generally used to ensure environmental and social impacts are considered explicitly both during the design of a new development and in the project authorisation decision [11]. It is used as an aid to public decision-making on larger projects and is a mandatory requirement for certain development projects in many countries.

Unlike LCA, which is time and location-independent, EIA is a procedural tool for evaluation of local environmental impacts, which generally takes into account time-related aspects, the specific local geographic situation, and the existing background pressure on the environment [12]. Besides assessing quantifiable aspects, EIA also provides qualitative assessment of "soft" issues like landscape, archaeological and cultural assets, concerns of potentially affected people, etc. and requires involvement/participation of the public and other stakeholders in the process. However, mainly due to the lack of data and subjective evaluation of impacts, uncertainty of results is often an issue.

2.1.2. Strategic Environmental Assessment (SEA)

SEA is similar to EIA but tends to operate at a "higher" level of decision-making (i.e. for strategies and policies). Since SEA is conducted at an early stage, it is normally performed in conditions involving less information and high uncertainties [10]. SEA application in Europe is mostly found during policy development, leading to policy selection. However, the adoption of the EU SEA Directive is now forcing way for enhanced SEA implementation throughout the EU [13].

Within the SEA framework a range of different analytical tools and methods can be applied including, LCA, Risk Assessment (RA), Cost Benefit Analysis (CBA) and Multi-Criteria Decision Analysis (MCDA) [14,15]. With respect to the time horizon, SEAs can be retrospective or prospective as the tools used within its framework. By presenting such a framework, SEA facilitates environmental as well as broader sustainability policy integration in every political or strategic decision [13]. However, like EIA, SEAs especially in Europe, have tended to focus on environmental impacts related to emissions of pollutants and some social aspects. Moreover, due to the large uncertainties in data and knowledge gaps the assessment often only shows general trends for environmental and social impacts.

SEA thinking may contribute in making LCA more transparent through increased documentation and an increased dialogue with stakeholders throughout the planning process. With the involvement of relevant stakeholders early in the planning processes, it is

Table 1
Environmental, economic and social assessment methods.

Assessment methods	Focus/level	Sustainability dimensions
Procedural methods (assessment frameworks)		
Environmental Impact Assessment (EIA)	Project (micro)	Environmental and social
Strategic Environmental Assessment (SEA)	Policy (meso/macro)	Environmental and social
Sustainability Assessment (SA)	Policy (macro)	Environmental, economic and social
Multi-Criteria Decision Analysis (MCDA)	Policy/project (micro/meso/macro)	Decision-support tool which can include environmental, economic and social dimensions
Analytical methods		
Material Flow Analysis (MFA)	Policy, plan (macro)	Environment (natural resources)
Substance Flow Analysis (SFA)	Specific substance (macro)	Environment (natural resources)
Energy/Exergy Analysis (EA)	Process, Product/service (micro)	Environment (natural resources)
Environmental Extended Input Output Analysis (EIOA)/Hybrid LCA	Policy, product/service (meso/macro)	Environment
Risk analysis (RA/ERA/HERA)	Chemicals/Projects (micro)	Environmental and health impacts
Life Cycle Costing (LCC)	Product/service (micro)	Economics
Cost–Benefit Analysis (CBA)	Policy/project (micro/meso/macro	Economics (includes cost of environmental and social impacts)
Eco-Efficiency (EE) Analysis	Product/service (micro)	Integration of environmental and economic
Social Life Cycle Assessment (SLCA)	Product (micro)	Social

also possible to identify social and economic aspects and address potential conflicts of interests early in the process.

2.1.3. Sustainability Assessment (SA)

Sustainability Assessment is an umbrella term that includes a range of methods and tools that may be known as 'Sustainability Appraisal', 'Sustainability Impact Assessment', 'Integrated Sustainability Assessment', or 'Integrated Assessment', amongst others. It is being applied to an ever-increasing range of decisions across the world, from policies, to strategic plans, to projects to trade agreements, at different levels from micro to macro and with different timing (ex ante, during, ex post) to identify synergies and trade-offs among the different sustainability dimensions.

In Sustainably Assessment there is a strong emphasis on stakeholder engagement as well as inducing a reframing and learning process among participants in the process. Since the concept of sustainable development is contested, both scientifically and socially; Sustainability Assessment could also be subjective and ambiguous. Often in Sustainability Assessments, the three pillars (social, economic and ecological) are used as conventional categories to represent the main broad areas of concerns as well as for the structuring of sustainability indicators. Although this approach is comprehensive and familiar way of organising sustainability assessment criteria, it does not integrate and deal with cross-pillar issues [16]. Moreover, integration of qualitative and quantitative information into a single framework is also a critical issue for Sustainability Assessment.

Literature and some research projects recommend that Sustainability Assessment process should combine various existing assessment tools and indicators to help decision-making [6,10]. For example, Azapagic [17] and Azapagic and Perdan [4] propose a life cycle approach to Sustainability Assessment of industrial systems, using LCA and indicators of sustainable development as the tools. However, the research on how to organise and deploy different tools and methodologies in assessments is still in its infancy.

2.1.4. Multi-Criteria Decision Analysis (MCDA)

MCDA methods support comparison of different options based on a set of decision criteria [18]. Consideration of multiple criteria is particularly applicable to cases where a single-criterion approach (such as CBA) falls short, especially where significant environmental and social impacts cannot be assigned monetary values. Furthermore, MCDA tends to be more transparent than other methods such as CBA since objectives and criteria are usually clearly stated, rather than assumed [19].

A large number of multi-criteria evaluation methods have been developed and applied for different purposes in different decision contexts. In the simplest of MCDAs, the final outcome is a weighted average of the scores, with the option providing the highest weighted score being the one that is "best". More sophisticated techniques might be used for more complex decisions [18]. The selection of an appropriate method for MCDA depends on the decision rule preferred (compensatory, partial-compensatory and non-compensatory) and the type of data available (quantitative, qualitative or mixed) [20,21].

Because of its capacity to handle conflicting decision situations, MCDA is particularly suited for sustainability problems, where the aim is the integration of economic, environmental and social values. MCDA can be effective in supporting the assessment of and decision-making on complex sustainability issues because they can integrate a range of criteria in a multi-dimensional guise and they can be adapted to a large variety of contexts [6]. By incorporating both qualitative and quantitative data and by counting monetary and non-monetary aspects, MCDA allows decision-makers to include a full range of economic, environmental, social and technical criteria [10]. The ability to deal with non-monetary aspects is crucial for certain sustainability problems because not all impacts can be quantified in terms of monetary values; for example the risks of nuclear proliferation. Moreover, social impacts are practically impossible to reduce to monetary values, and therefore MCDA could be helpful for broadening LCA to consider social impacts. Furthermore, in relation to LCA, MCDA can be used for interpretation of the obtained results which come in different units of measurements and often show goal conflicts [22].

2.2. Analytical methods

Methods under this category include those which are used to identify and analyse the environmental, social or economic impacts related to policies, projects, products and substances. Most of these methods primarily focus on one particular sustainability dimension, while there are some methods that integrate two or more sustainability aspects.

2.2.1. Environmental methods

Environmental methods are used to evaluate resource use and environmental impacts of systems under study. The key differences among these methods include the scope (national, regional, sector, etc), application (product, project or policy), methodologies and data requirements. The following review of these methods highlights these differences which could potentially be helpful for broadening and deepening the LCA.

2.2.1.1. Material Flow Analysis (MFA). Material Flow Analysis (MFA) represents a systematic accounting of the flows and stocks of a material within an economic system [23]. It provides an overview of material inputs into and outputs of an economy. As such, MFA addresses the environmental dimension of sustainability.

MFA data can be used by other methods, which require quantitative units and indicators, including LCA and MCDA [23,24]. However, it must be noted that MFA is directed towards reducing the number of substances of study as much as possible to maintain transparency and manageability, while LCA aims for completeness in assessing as many as possible substances and compounds [23]. Moreover, MFA may serve as a basis for quantifying the resource productivity of an overall economy, but it is not suitable for the optimisation of single production systems. Combining MFA with micro-level analysis such as LCA is limited by several incompatibilities including system boundaries and allocation rules [25].

2.2.1.2. Substance Flow Analysis (SFA). Substance Flow Analysis (SFA) is a specific type of MFA, dealing only with the analysis of flows of chemical substances or compounds of special interest through a defined system. The core principle of SFA is the mass balance principle, derived from the law of mass conservation. It provides systematic, physical and quantitative information about the key stocks and flows of a specific substance or substances, about possible imbalances in the stocks and flows and about unsustainable use of resources in a certain time period and for a certain region. The general aim of the most SFA studies is to provide the relevant information for management strategy regarding specific chemicals at a regional or national level [26].

More recently SFA in combination with LCA has been applied in an integrated framework for mapping pollution from products, processes and activities in the urban environment [24]. The framework enables tracking of substances and their impacts in the area of immediate interest ('foreground') and in the rest of the life cycle of an activity ('background'). In this way, the integrated SFA and LCA can be used to support decision-making at the local, regional and wider levels.

2.2.1.3. Energy/Exergy Analysis (EA). Energy analysis is a family of different methods which focus on energy flows. Unlike energy analysis which measures quantity of energy, exergy analysis measures quality of energy, or the maximum amount of work that can be theoretically obtained [23]. Exergy analysis can help gain an understanding of the effectiveness of resource utilisation; show where losses occur and where technological improvements can be made to improve energy efficiency.

Although energy analysis has traditionally focused on production processes at the micro-level, the method is flexible enough to be used at all levels (micro, meso and macro). Due to its flexibility, it also has a potential to be integrated with life cycle approaches. However, there is the risk of focusing too much on energy aspects and leaving out other important aspects. The exergy results can also be used in more approximate calculations such as in streamlined or simplified LCA where the aim is to identify critical areas of the life cycle [27]. However, the usefulness of exergy analysis is questionable for non-energy systems. Many users also find it difficult to estimate and interpret the meaning of exergy.

2.2.1.4. Environmental Input–Output Analysis (EIOA)/Environmental Extended Input Output Analysis (EEIOA)/Hybrid Analysis. Environmental Input–Output Analysis (EIOA) and Environmental Extended Input Output Analysis (EEIOA) are expansions of conventional Input–Output Analysis (IOA) which introduce the environmental dimension into the conventional monetary analysis. EIOA includes environmental impacts either by adding emissions coefficients to the monetary IOAs or by replacing the monetary input–output matrices with matrices based on physical flows. The EIOA model provides the possibility to include a lot of different environmental indicators such as air emissions, waste, energy input, material input, land use, and so on. Social aspects, such as employment, can also be integrated into EIOA [14].

EIOA determines the overall environmental impact of an entire sector of the economy and may be viewed as a macro-level LCA covering the "cradle to gate" portion of the life cycle. EIOA's limitations are that it often assumes an identical production technology of imported products and the domestic economy, homogeneity (each sector produces a single product) and a single technology in the production process. Also in EIOA, the attribution of environmental loads to sectors, products and services is proportional to the economic flows. However, as a method for environmental impact analysis (or LCA at the macro or national level), it has some advantage over LCA as it captures all the intra-sector flows, both direct and indirect, without "double-counting" [28]. Therefore, it is potentially more useful to support high-level (e.g. national) policy decision-making rather than for decision-making on specific products or activities.

EIOA and EEIOA are computationally compatible with LCA and flexible at integrating other data sources. EEIOA has the methodological advantage of a coherent framework where environmental, economic and social data can be inventoried. However, currently the data are often indirect and/or based on partial measurements of resource extraction and emissions corresponding to economic inputs and output.

Recently, EIOA has been recognised as an important method to support Life Cycle Inventory (LCI) [29]. Several successful applications of EIOA have already been reported and its possibilities and areas of applications are still broadening. For example, hybrid analysis offers the possibility of combining process-based LCA and an environmentally extended input–output analysis (EEIOA) [30]. Hybrid approaches in general provide more complete system definition, while preserving specificity with a relatively small amount of additional information and inventory data [1]. Hence the combination promises to reduce data collection effort and avoid cut-off errors inherent in process-LCA [2]. In principle hybrid LCA allows the user to select the boundary between foreground-process-based and background-EIO-based in a case-dependent way. Combining physical process-based data and monetary IO-based data opens the possibility of combining environmental and economic aspects.

2.2.1.5. Risk Assessment (RA). Risk assessment is commonly used in assessing the environmental, health and safety related risks posed by chemicals, harmful substances, industrial plants, etc. The risks examined in the assessment can be physical such as radiation, biological such as a genetically modified organism or a pathogen, or chemical such as an immuno-toxic substance [31].

Like LCA, RA is an analytical method used to support decision-making in environmental management; however the following are the key differences between LCA and RA [32]:

- RA focuses on a specific harmful endpoint arising from product, process or event and their occurrence in specified scenarios;
- unlike traditional LCA, the absolute magnitude of a product or activity is very important in RA;
- In RA site-specific impact modelling is sometimes feasible as it is concerned with objects located at one or limited number of sites; and
- RA results are defined in time and hence provide information concerning the timing of impacts, which is not possible with LCA.

The integration of LCA and RA provides an opportunity for data exchange between LCA and RA to get a fuller picture. For instance, emission data for industrial processes can be used for risk assessment and in life cycle inventories. The same is true for toxicity information usable in risk assessment and life cycle impact assessment. In practice, LCA and RA can be applied in several different combinations: completely separated RA as a subset of LCA, LCA as a subset of RA and as complementary tools to get the whole picture [33]. The most common approach of combining LCA and RA, which has been performed in a number of well-known impact assessment methods, is to include eco-toxicological and toxicological parameters in Life Cycle Impact Assessment (LCIA) used in LCA.

Although risk assessment and management techniques are used as decision-support tools for policy and regulation, the RA approach and results are more prone to public distrust because of the complexity of the issues, the potential for subjectivity of the assessor(s) and under- or over-estimation of risks due to multiple uncertainties.

2.2.2. Economic methods

There are various techniques for economic evaluations of policies, projects plans and products. Some of these are also widely used in environmental economics. These include Life Cycle Costing (LCC), Cost Benefit Analysis (CBA) and Eco-Efficiency (EE). LCC and CBA are used to calculate general costs including environmental, while Eco-Efficiency (EE) analysis is the combined analysis of economic and ecological aspects of goods and services. These methods are discussed below.

2.2.2.1. Life Cycle Costing (LCC). LCC calculates the total costs of a product, process or an activity over its life span. Traditionally, LCC is used for an investment calculation to rank different investment alternatives to help decide on the best alternative [34]. Similar to LCA, it is possible to identify economic 'hot-spots' with LCC, if set up as value added analysis. In combination with LCA, it enhances the application of life cycle approaches for decision-making. The use of common data and models and many synergies between LCA and LCC offer additional advantages of their combined use. The comparable structure of the two methods also provides the possibility to combine their results in terms of eco-efficiency measure (i.e. costs per unit of environmental improvement or environmental improvement per unit of cost) [30].

2.2.2.2. Cost Benefit Analysis (CBA). CBA is a well-established analytical method for assessing the total costs and benefits of a project or an activity. In the context of sustainability assessment, CBA can be used for weighing the social costs and benefits of different alternatives. CBA has some similarities with LCC when applied to products, although LCC typically does not include benefits [9]. A strength of CBA is that it presents the results as a single-criterion – money – that can be easily communicated. However, measuring expected benefits, or placing monetary value on the benefits in a simplistic way is often problematic with CBA [10].

LCA provides essential inputs into CBA for environmental impacts, but due to the different conventions of measurement the "marriage" between CBA and LCA is complex [19]. Unlike LCA and other methods for environmental decision support, CBA can take the time horizon of effects into account by discounting future costs and benefits [5]. A variant of CBA is Cost-Effectiveness Analysis (CEA) whereby the focus is on finding the best alternative activity, process, or intervention that minimises the costs of achieving a desired result.

2.2.2.3. Eco-Efficiency (EE) Analysis. The concept of eco-efficiency (EE) has become popular after the adoption by the World Business Council for Sustainable Development (WBCSD) in 1992. Although, there is as yet no unambiguous and generally accepted definition of eco-efficiency, consensus seems to be growing that an eco-efficiency indicator expresses the ratio between an environmental and a financial variable [35].

EE and its indicator(s) can be applied for comparing companies, products, etc., as well as for monitoring and benchmarking. Since there is no explicit agreed-upon framework for EE analysis, there are varieties of methods being used. These differ on various aspects including the type of impacts to be considered, weighting of impacts, etc.

2.2.3. Social methods

Some of the approaches discussed earlier also consider social aspects along with environmental and/or economic aspects. More specifically, social aspects are qualitatively assessed for projects and policies in EIA, MCDA and SA. Social Life Cycle Assessment (SLCA), discussed below, is a recently introduced methodology to assess social impacts throughout the product life cycle.

2.2.3.1. Social Life Cycle Assessment or Societal LCA (SLCA). SLCA is at an early stage of development and a Code of Practice for social LCA is in preparation. The proposed methodological framework the UNEP-SETAC Life Cycle Initiative is based on the ISO LCA structure and can either be applied on its own or in combination with LCA [36]. SLCA together with LCA and LCC can contribute to the interpretation of the product sustainability to stakeholders and decision-makers. Since social aspects are often of qualitative nature and could be highly subjective, their assessment poses several different challenges. Some of these challenges include finding consensus on impact categories to be included in the assessment and how to measure these; how to find balance between participative and analytical approaches. Contributions of different stakeholders in participative approaches would provide knowledge and awareness about the system and its complexities, but often remains at qualitative level. While a more analytical approach can "quantify" impacts, it would produce a simplified model of the system.

From the practical point of view, LCA software developers have begun to add features to their software tools to enable users to track social variables. Data collection is a challenging aspect due to the problem of data availability and reliability, especially for complex supply chains. Geographic location of unit processes is fundamental for the assessment of social impacts. Therefore generic and non-site-specific data may be poor representations of the actual impacts. However, collecting site-specific data is a very demanding task and may not facilitate wider adoption of the method.

3. Options for deepening and broadening the LCA

The central purpose of broadening and deepening the LCA would be to improve decision-making processes with respect to the sustainability of human activities. The primary aspect of "deepening" the present LCA models and tools is to improve their applicability in different contexts while increasing their reliability and usability. Such improvements could be reached by indicating additional aspects in terms of spatial differentiation, temporal specification and integration of additional indicators. Broadening LCA towards social, cultural and economic aspects would move LCA from environmental towards sustainability assessments. This would be an opportunity to increase the significance of LCA in political spheres beyond environmental policy, e.g. towards social and economic policies. Integrated sustainability assessments could be the basis for identifying synergies, win–win options and trade-offs between the different dimensions of sustainability. However, broadening LCA also bears risks as it would introduce an even larger number of criteria to consider. By definition, the choice of criteria will be subjective thus making LCA more vulnerable to interest-guided controversy. The following criteria could be applied in deciding whether broadening and deepening LCA move us closer to the improved decision-making process.

3.1. Spatial differentiation

An important deepening aspect is the integration of environmental impacts on different system levels such as global, regional and local. Environmental impacts range from a global systems changes (e.g. global warming, ozone depletion), over regional phenomena (e.g. acidification), down to the local level (e.g. soil pollution). Today most impact categories in ISO LCA make no distinction between different spatial categories even if the environmental impact is a regional or local one. For example, acidification is most of the time summed up into one category of acidification potential without taking into account the region where the acid fall-out occurs (e.g. by taking into account regionalised critical loads). An important case where spatial differentiation is needed is the case of biofuels. Several aspects that directly influence the environmental impacts of the production of biofuels and other products from agriculture depend on the regional or local climate, soil fertility, natural vegetation and water availability. In such cases ISO LCA may be a starting point, but results need to be placed in a broader context, indicating consequences of land use shifts or opportunity costs. In that respect, tools like EIA, RA, SFA are useful, which assess local and regional impacts.

3.2. Temporal differentiation

Most LCA studies even if they address future oriented questions do not cover time as an important aspect for changes in the investigated system, although changes over the time could be a key issue. This includes uncertain developments of technologies, e.g.

increased or decreased efficiency, new processes or constraints and the availability of secondary materials. These are important aspects of the environmental impacts of specific production systems.

Impacts in the future are often regarded to be less important than the impacts right now. In economic tools such as CBA, the net present value of an impact may be calculated by applying a discount rate. However, the use of discounting in the context of inter-generational sustainability is disputed [37]. Another feature that is essential for sustainability assessment is the detection of inter- or intra-generational burden shifting. Intra-generational burden shifting occurs if negative environmental impacts are mitigated at the expense of other social, economic or environmental assets of the current generation. Inter-generational burden shifting happens when negative environmental impacts are compensated for at the expense of social, economic or environmental assets of future generations. In general, all methods that related impacts to regions have the ability to assess burden shifting between regions as part of the intra-generational burden shifting e.g. between developed and developing countries. This is a strength, especially of macro-level methods like MFA.

3.3. Development of the ecological scope of LCA

ISO LCA addresses the most pertinent environmental problems; however, this does not necessarily mean that these indicators are adequate for all applications. For example, the case of first-generation biofuels shows that consideration of additional aspects is necessary, including the knowledge on pesticides, the influence of agriculture on biodiversity or the effect of land use change on albedo, water evaporation or wind speed.

Further development of LCA is needed in the area of other environmental impacts and indicators (e.g. land use, biodiversity, genetic pollution, erosion, indoor air quality and odour). Aspects, such as biodiversity and odour, are qualitative hence difficult to integrate in a quantitative tool such as LCA. Furthermore, some impacts occur only locally or regionally (like odour, noise, biodiversity or electro magnetic radiation). These aspects are often integrated in other assessment frameworks such as EIA.

3.4. Integration of or links to economic aspects

Material flows which are analysed in LCA are often driven by economic exchange processes and have repercussions on economic performance. Thus, it is desirable to model these interlinkages. However, the earlier discussion of economic assessment method showed that they vary in scope and concepts and are not necessarily compatible with LCA.

CBA is a widely accepted and used approach for evaluating environmental projects and policies. For many applications, upstream and downstream impacts are evaluated in CBA, using the inventory phase of LCA. CBA takes into account the both direct and indirect costs and benefits of an option, and converts them into monetary values; however these values could be highly uncertain and often controversial.

LCC is viewed as the economic counterpart of LCA. The methodology of LCC is capable of fully integrating a life cycle inventory to provide monetary information as decision support. LCA and LCC, when carried out in an integrated manner and from a systems perspective, have a high potential for moving industrial practice towards sustainable development [34]. Combining LCC and LCA also facilities eco-efficiency assessments which can make understanding easier and further extend target audience for the use and interpretation of LCA [38]. However, the integration of LCC into LCA can be hampered by the lack of a standardised LCC methodology and difficulties in defining some of the cost factors. Another argument against including LCC analyses in the LCA is that it is difficult to find reliable and adequate data. It is also feared that LCC adds to the already complex LCA methodology, which can result in a lack of interest and hesitation in using the integrated tool.

While the above methods are mainly economic methods, EE analysis is the combined analysis of economic and ecological aspects of goods and service systems, without the use of monetarisation or another form of converting these two aspects into one indicator. The EU sustainable consumption and production policies such as Thematic Strategy on the Sustainable Use of Natural Resources (TSURE), which aim to de-couple environmental impacts and economic growth, offer opportunities for broadening current LCA to LCA-based EE. However, EE methods need to be standardised and harmonised in order to overcome the weaknesses such as the lack of clear terminology, methodical framework and type of environmental impacts considered.

3.5. Integration of or links to social aspects

Parts of economic consumption and production patterns are within the system boundaries of LCA. People are the actors within these patterns and subject to economic and physical transfer. Consideration of social aspects of these transfer processes would be desirable for a complete assessment of sustainability; SLCA provides an opportunity for this. It can be applied on its own or in combination with LCA. Since social aspects are often qualitative, normative and often subjective, the assessment poses several challenges. This includes the finding of a consensus on social impact categories and how to measure it.

In addition, EIA, SEA and MCDA integrate participative methods for assessing social aspects. These methods offer the opportunity to involve stakeholders in decision-making processes. Integration with participatory approaches could improve the social framing of problems, the scoping of analysis and the use of results.

It is obvious that a number of relevant economic and social aspects are overlapping. The link to EIOA seems quite relevant here as well, as many social aspects can more easily be framed in an IOA, e.g. income distribution or the value added per working hour. Nevertheless, the integration of social aspects is still a difficult challenge, because they depend on a wide range of different behavioural aspects, cultural identities and world views.

3.6. Consistency between micro-, meso- and macro-levels

For supporting systemic analysis and multi-level governance, a compatibility of assessments with the possibility of aggregating and disaggregating data flows would be desirable. Ideally this would lead to the possibility to use LCA data relating to production systems for analysis and decision-making at higher levels of governance (e.g. firm, sector, region, country, and world) and vice versa. This does not mean that a single assessment would capture macro-, meso- and macro-impacts, but that the provisions in the framework of different assessments would allow linkages in data and flows (e.g. by choosing the same units of measurements).

The consistency between micro-, meso- and macro-level is especially relevant for physical accounting methods like MFA or Energy Analysis where inconsistency between the levels can occur by varying the allocation methods or system boundaries. Obviously, there is a large gap between investigations at the micro- and macro-levels [25]. Most investigations at the macro-level are time specific but most investigations at the micro-level are not. Making LCA time specific could improve the connection between micro- and macro-levels.

4. Conclusions

Life cycle thinking is increasingly permeating various sustainable development policies and is becoming a part of the way we conceptualise environmental issues and the way we deal with them. Sustainable consumption and production policies are setting the demand for life cycle thinking, particularly in Europe. To support sustainability decision-making, there is a need for structuring different life cycle approaches and combining with economic and social assessments. Therefore, the options for broadening and deepening LCA approaches should be selected according to one paramount objective: improved decision-making towards sustainability. Thus the assessment approaches should provide intelligence for a sustainable development in a coherent and consistent way. Vertically, the methods should reach from the micro-level of individual households, companies and products up to the macro-level of entire economies. Horizontally, concepts, methods, models and tools should encompass the social, economic and ecological dimensions. However, the challenge lies in combining and integrating these aspects in a conceptually consistent and logical way. It is even more challenging to have one comprehensive method which meets the needs of diverse users. The latter is particularly difficult because different users have different needs and capacities to apply these approaches in sustainability decision-making.

Therefore, the main message is that there is no "one size-fits-all" solution to integrating different LCA-related concepts, methods and models for better sustainability assessments. Thus, it is difficult to offer a system, recipe or a decision-tree to allow optimum integration of the different procedural or analytical instruments. Moreover, options and possibilities for deepening and broadening the LCA depend highly on the field of application and the users, their requirements and the goal and scope of an investigation. Hence it is reasonable to expect that development of LCA for research purposes will be different than that for policy-making or business use. For example, from the research point of view, there is a tendency to integrate other sustainability aspects into the LCA context, as well as to increase the reliability of LCA by integration of additional environmental impacts or by combining LCA with macro-oriented methods to ensure that rebound and growth effects are considered. With respect to policy-making, there is a demand for both simplification and standardization, and broadening and deepening. On the other hand, industry and similar users have a clear need for simplification and standardization of LCA. Simplifications are necessary in the context of decision-making when details are of minor relevance (e.g. during day-to-day decisions of enterprises, producers and consumers) but also as a step for reducing complexity in political decision-making. Future research will therefore have to deal with the conflicting motives for research and applications. Review of various approaches suggests that there is no single approach which satisfies these motives simultaneously. Therefore, it is suggested that further research should develop life cycle approaches which would be customised (and possibly standardised) according to the type of demand, the user questions and the application.

If a micro-perspective on sustainability is required, the combination of LCA, LCC and SLCA is able to address the three pillars of sustainability in a consistent way. If the scope is even smaller, e.g. in case of decision-making in a company, EE can be adequate as well. However, use of three separate methods each addressing one of the sustainability dimensions, which are not only complex but require huge data for sustainability analysis, could hamper their acceptability. The other option could be to integrate economic and social methods into LCA for an integrated sustainability assessment. This would increase the significance of LCA in political spheres beyond environmental policy, e.g. towards social and economic policies. Integrated sustainability assessments could be the basis for identifying synergies, win–win options and trade-offs between the different dimensions of sustainability. However, broadening LCA also bears risks as it would introduce an even larger number of criteria to consider. By definition, the choice of criteria will be subjective thus making LCA more vulnerable to interest-guided controversy.

The other option would be to use different tools separately under a procedural framework to carry out sustainability assessments. Conceptually LCA and the above discussed procedural frameworks – e.g. EIA, SA, MCDA, etc. – are different but also complementing methodologies. The frameworks, while not directly linked with LCA, could in theory be related to the tool in the broad context of sustainability assessments. Use of participative, qualitative and prospective elements of these procedural frameworks can complement LCA. However, experience shows that the use of LCA-thinking in these frameworks is more likely than the other way round.

Combinations of LCA with some of these methods can be used to provide a more comprehensive picture. For instance, at a project level, EIA can complement LCA by providing information on local, site-specific aspects and vice versa (LCA providing information on global impacts). Data generated from RA are useful in assessing toxicity, an impact category estimated used in LCA. Similarly, Input Output Analysis (IOA) can be used to support Life Cycle Inventories (LCI). Combination of IOA with LCA, as in hybrid approaches, reduces the data collection effort and provides more complete system definition. However, the IOA and hybrid LCA are only useful at the macro-level.

The combination of approaches on different levels (micro, meso and macro) offers interesting options from the scientific perspective. For example, the combination of LCA with EIOA offers the opportunity to capture intra-sectoral flows on the meso-level, both direct and indirect, without double counting which would increase the reliability of LCA. The combination of a micro-LCA with macro-methods like MFA and SFA could strengthen the application of mass and energy balances.

The investigated methods offer only limited options for the ecological development of LCA. Most relevant for integrating a broader range of societal concerns are participative and qualitative concepts like EIA or SEA. They offer the opportunity to integrate qualitative aspects that have not been covered yet by a quantitative method like LCA. RA and EIA provide the opportunity to integrate site-specific (regional or local) environmental impacts while EIA additionally enables the integration of time-related aspects.

By broadening and deepening the LCA we should be able to link the analysis of a product system at different levels of governance i.e. micro, meso and macro. It could also eventually lead to integrated assessments covering all dimensions of sustainability. Although the need and opportunities for broadening and deepening are numerous, the attached risks should also be kept in mind: the LCA would be 'stretched out' beyond recognition or a manageable scope as well as leading to the increased human and financial resources requirements. This might lead to the need to trade-off between broadening and deepening of LCA. Broadening assessments may ultimately result in more superficial assessments of each economic, social and environmental dimension while at the same time increasing the number of criteria that need to be considered. Its use would require substantial analytical know-how and significantly more time and financial resources. Since LCA is already viewed as a complex tool and too time-consuming for everyday use, more complexity could increase uncertainties and decrease acceptability even further.

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