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Spatially differentiated sustainability assessment for the design of global supply chains

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Abstract

Supply chains of modern products are often characterized by globally dispersed activities that have ecological, economic, and social impacts. Life cycle-oriented sustainability assessment methods usually aim at compiling the total impacts of a product without explicitly considering their spatial distribution. This may be problematic because regional characteristics of technology and environment are ignored and opportunities for tradeoffs between local and global sustainability measures are hidden. This paper proposes a framework for spatially differentiated sustainability assessment to support the design of global supply chains. The framework comprises a resource flow model that links production processes to specific locations, multi-scale impact assessment to derive regional and global sustainability indicators, and multi-criteria evaluation balancing the preferences of different stakeholders. An illustrative example shows that the application of this framework to a simplified supply chain of beer production leads to different results when alternative supply chain structures are compared.

Keywords: Sustainability assessment; spatial differentiation; supply chain design; multi-criteria decision making

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1. Introduction

The sustainability of products is being increasingly scrutinized due to regulatory, societal, and competitive pressures [1]. Not only have the characteristics of the product, but its provenance and the impacts related to its production become important factors in consumers' choices. The supply chains of many modern products are complex and globally dispersed. For example, the raw materials that are needed to make a lithium-ion battery to be used in an electric car are sourced from South America and Africa; the battery cells are mainly produced in Asia, and the integration into cars takes place in European, North American, or Chinese assembly plants. The production and transportation processes that are involved in the supply chain result in various environmental, economic, and social impacts. While some of these impacts, such as the emission of greenhouse gases, are of global importance, other impacts, such as the emission of acidifying or toxic substances, are primarily applicable on a regional or even local scale.

The impacts in the supply chain are influenced by a series of design decisions. These comprise, amongst others, the locations of the factories where the production processes are carried out, the selection of suppliers from which the raw materials are sourced, and the distribution structures that are set up to serve the customers' demand. For example, the decision of a battery manufacturer to set up a new plant in Asia or in Europe would affect the sustainability performance of the supply chain due to different energy mixes in both countries and different transportation distances.

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Life cycle-oriented sustainability assessment methods [2–4] usually compile the total impacts of a product without explicitly considering the aforementioned design decisions and their influence on the spatial distribution of the impacts. For products with global supply chains, this approach may be problematic for the following reasons. First, there are many interregional trade flows. The raw materials and goods are transported over thousands of kilometers and the total transportation distance depends on the locations where the processes are carried out. Second, the location of the manufacturing process and of its supply sources is important to consider because of technological heterogeneity. For example, the technologies for electricity generation, and the associated impacts are quite different throughout the world. Third, there is also environmental heterogeneity. The same processes (with identical inputs and outputs) carried out in different regions may result in different local impacts. As an example, the negative impact of a toxic substance emitted in a populated area is likely to be much higher than if the same substance was emitted in an unpopulated desert. Fourth, the relevance of the impacts may vary due to heterogeneous preferences. A global decision maker may be most concerned about climate change, but to some stakeholders, local sustainability measures such as employment opportunities or local pollution may be ranked much higher than the global consequences. Thus, the geographic spread of the supply chain should not be ignored, especially if the results are used to support decisions regarding the design of the supply chain. Instead, spatially differentiated assessments should be carried out, taking into account the regional differences.

The topic of spatial differentiation has been discussed for many years in the life cycle assessment community [5–9] and approaches for regionalized impact assessment [10–12] and computational models [13–15] have been proposed. However, in practice, spatial differentiation is rarely applied in sustainability assessments [16–18]. A recent review of 120 articles in the context of operations research and sustainability assessment [19] revealed that in only 15% of the articles, a site-specific assessment, taking into account the local specifics, was carried out. In only 12% of the articles was the assessment site-dependent, considering at least some characteristics of the region or country. Most often, spatially explicit data was used at the inventory analysis level or with regard to the decision makers' preferences, but rarely with regard to impact assessment.

Based on the discussion above, the objective of this paper is to develop a framework for spatially differentiated sustainability assessment of products with global supply chains, which enables the comparison of alternative supply chains and supports decisions regarding the design or improvement of the supply chain. The key features of the framework are the integrated modeling of environmental, economic, and social indicators as well as the explicit consideration of technological and environmental characteristics of the locations at which the processes in the supply chain are carried out. The effect of this novel spatially differentiated modeling approach to derive both global and region-specific sustainability indicators is analyzed with an illustrative example with a simplified supply chain of beer production.

The remainder of this paper is organized as follows. The framework for spatially differentiated sustainability assessment is described in Section 2 and an illustration of its application to a simplified supply chain of beer production is presented in Section 3. Finally, the potentials and limitation of the approach are discussed and avenues for further research are identified in Section 4.

2. Framework for spatially differentiated sustainability assessment

A conceptual model for spatially differentiated sustainability assessment is illustrated in Fig. 1. Intended to support the design of sustainable supply chains, it considers a number of design decisions such as, the location of production processes, the selection of supply sources, and the structure of resource flows. For a given set of design parameters, a spatially differentiated resource flow model determines a regionalized inventory of resources. The inventory is subsequently transformed into local, regional, and global impact indicators in all three sustainability dimensions by a multi-scale impact assessment model. These indicators are then used in a multi-criteria evaluation model that allows for comparing design alternatives taking into account the preferences of particular stakeholders. Finally, the resulting sustainability performance of the design options is fed back into the design model and serves as the basis for further improvements. The individual modules are described below.

2.1. Spatially differentiated resource flow model

To determine a spatially differentiated inventory of resource withdrawals and releases, the supply chain is described as a network flow model. The network consists of nodes representing the locations where production processes are carried out and edges representing the transportation processes that realize the resource flows between the nodes. The term *resources* is used in a very generic sense and comprises natural materials, energy, emissions, labor, funds, and intermediate as well as final products. All locations are assigned to regions, which form the basic spatial units for the subsequent impact assessment.

Production processes are characterized by the transformation of input resources into output resources. They can be described by a set of coefficients that specify the quantities of resources required to make one unit of the process' reference product. Such coefficients can, for example, be derived from empirical observations of real production systems by means of activity analysis [20]. To account for technological heterogeneity, multiple variants of a production process with different input and output coefficients can be defined.

Each resource that is consumed in a production process is either provided by another production process or withdrawn from the environment in which the process is located. Similarly, each resource that is generated by a production process is either consumed by another production process or released into the environment of the process.

For a cradle-to-customer assessment, the last production process in the supply chain is the consumption of the final

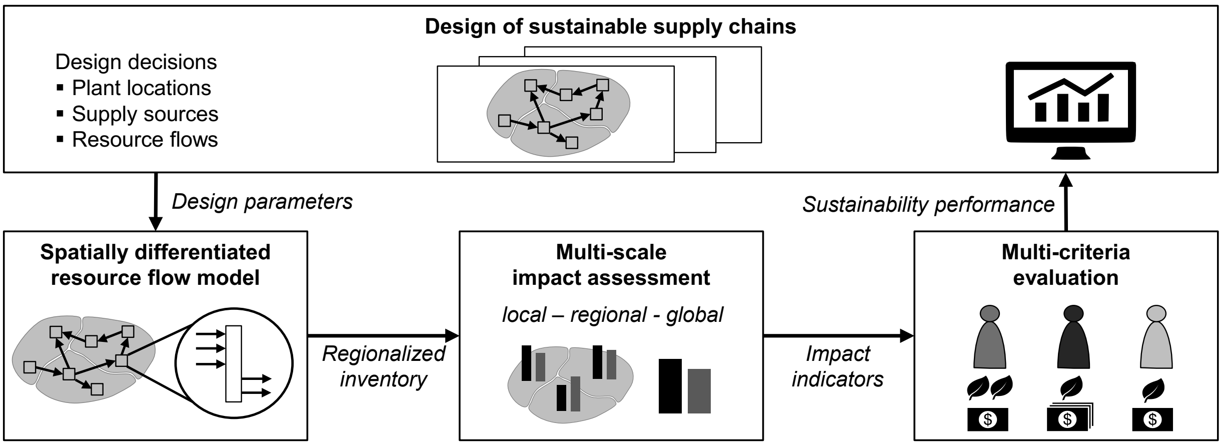

Fig. 1 Conceptual model for spatially differentiated sustainability assessment

product by the customer. This process has the final product as its only input and does not have any outputs. For a cradle-to-grave assessment, the consumption process is expanded by the resources that are required during the use phase, and the used product is added as an additional output. Furthermore, reuse and recycling processes as part of a reverse supply chain need to be integrated.

Transportation processes describe a spatial transformation of resources. They are characterized by an origin and a destination location as well as a transportation route between these locations. Similar to production processes, transportation processes consume resources and generate emissions. However, they cannot be assigned to specific locations. This means that some allocation logic is needed. For example, the transportation emissions can be allocated to the regions through which the transportation route goes according to the distance travelled in each region.

Based on the demand of the final product, which represents the functional unit for the assessment of supply chains, the resource requirements by all production and transportation processes are calculated, resulting in a regionalized inventory of the withdrawal and the release of resources.

2.2. Multi-scale impact assessment

Impact assessment transforms the regionalized inventory that has been determined in the spatially differentiated resource flow model into impact indicators at different scales, depending on the scope of the impact. According to ISO 14040, impact assessment involves (at least) the selection of impact categories, corresponding category indicators, and characterization models, the assignment of the inventory results to the selected impact categories (classification), and the calculation of the impact indicator results (characterization) [21]. Characterization, often considered as the core step in impact assessment, builds on the fact that some resources contribute to the same impact category (e.g. carbon dioxide and methane both contribute to climate change), but the magnitude of their impact differs. This is reflected by different characterization factors that are derived for each resource.

As explained in the introduction, regional heterogeneity should be taken into account when carrying out impact assessment, especially when the impacts are primarily of local or regional concern. In that case, there is not just one characterization factor with global validity, but individual characterization factors for each region are derived from region-specific characterization models. These factors are applied to the regionalized inventory results to determine the sustainability impacts in each region. This is done for environmental as well as economic and social impacts.

A large number of impact assessment methods have been developed for evaluating the environmental dimension of sustainability. The models differ in type and number of impact categories, number of resources considered, underlying environmental model, and their support for spatial differentiation. Exemplary methods that allow for spatially differentiated impact assessment, and can thus be used within the proposed framework, are EDIP 2003, LC-Impact, and IMPACT World+ [22–24]. These methods provide region-specific characterization factors, usually on a country level, that are applied to the regionalized inventory results for non-global impacts. They also comprise global characterization factors that are used for macro-scale impacts or if region-specific inventory data is not available.

In economic impact assessment, the total cost incurred along the supply chain is calculated. To this end, the resource flows in each process are evaluated with the regional or local prices for the resources. For transportation processes, the costs are derived from the freight rates under consideration of the distance of the route and the total quantity that is transported. The total cost perspective is mostly interesting for companies involved in the operation of the supply chain. Other stakeholders like workers or local communities can be integrated by considering, for example, the wages that are paid to the workers, or the contributions to regional GDP [25].

The development of methods for assessing social impact is still in its infancy [26–28]. Nevertheless, diverse statistics and databases on the social conditions in different countries are available [29]. This regionalized data can, for example, be related to the labor hours in each process in order to estimate the social impacts in that region.

The result of the multi-scale impact assessment is a set of local, regional, and global sustainability indicators that describe the various impacts related to the supply chain.

2.3. Multi-criteria evaluation of sustainability indicators

The multi-scale impact assessment is followed by the multi-criteria evaluation of the sustainability indicators. This step is required to compare alternative supply chain designs and to derive recommendations for improving the supply chain. Most often, deciding which design alternative performs best from a sustainability perspective is difficult because of conflicting indicators. For example, one design alternative might reduce the carbon footprint of the supply chain, but increase total cost. Another design alternative might lead to a reduction of total environmental impact, but increase the environmental impact in a certain region. To resolve these conflicts of objectives in a systematic way, a formal multi-criteria decision making (MCDM) model is applied.

The MCDM model evaluates the alternatives under consideration of the decision maker's preferences. The preferences describe how important each sustainability indicator is relative to the others from the perspectives of the decision maker. The evaluation can be carried out from the perspective of different decision makers in order to derive robust recommendations for the design of the supply chain.

Various MCDM models have been developed and the choice of a suitable model primarily depends on the characteristics of the scenario considered [30]. If the decision maker wants to compare a predefined, finite set of alternative designs, then multi-attribute decision making models, such as the analytic hierarchy process, are appropriate. If the design alternatives are described implicitly by the choice of design parameters and the best design alternative must be derived from mathematically constrained solution space, then multi-objective decision making (MODM) methods are used (cf. Section 2.4).

The evaluation module also includes different visualizations of the assessment results. These include choropleth maps that highlight regional sustainability hotspots by coloring the regions according to impact's magnitude. Other visualization like spider diagrams allow for a visual comparison of the different impacts on a global level. The visualizations support the decision maker in exploring the results and identifying improvement measures.

2.4. Design of sustainable supply chains

The purpose of the supply chain design model is to explore the multiple design options of the supply chain in a systematic way. It generates design options by varying the locations of production processes, the sources of materials, or the resource flow relations between the processes. These design parameters are passed to the resource flow model, and after impact assessment and evaluation, the sustainability performance is passed back to the design module. The application of multi-objective optimization techniques allows for finding the supply chain that satisfies the decision maker's preferences in the best way, considering that demand in each region must be fulfilled and regional supply of resources is limited [16].

3. Illustrative example: Beer production

The proposed framework can be applied to analyze the supply chains of many different products. In this section, we use it to examine a simplified supply chain of beer production in order to illustrate how the assessment is carried out and how the consideration of regional heterogeneity influences the results and the conclusions that can be drawn. The example is adapted from [15] and considers environmental sustainability aspects only. The original example contains spatially differentiated data on production technologies and environmental characteristics. For the purpose of our analysis, transportation processes and alternative supply chain configurations have been added.

3.1. Setting

The example considers a highly simplified supply chain of beer production. The supply chain comprises two production processes: grain cultivation and brewery. The final product beer is demanded in three different regions (R1, R2, R3), which constitute the geographic structure of the supply chain. While the production processes can be carried out in each of the regions, it is assumed that the production technology (grain yields, brewing efficiency) as well as the environmental characteristics (sensitivity to acidifying substances) are different in each region.

Despite the simple structure of the example with two processes and three regions only, there are various options for setting up the supply chain. For example, the demand in each region could be served by a local brewery, or there could be

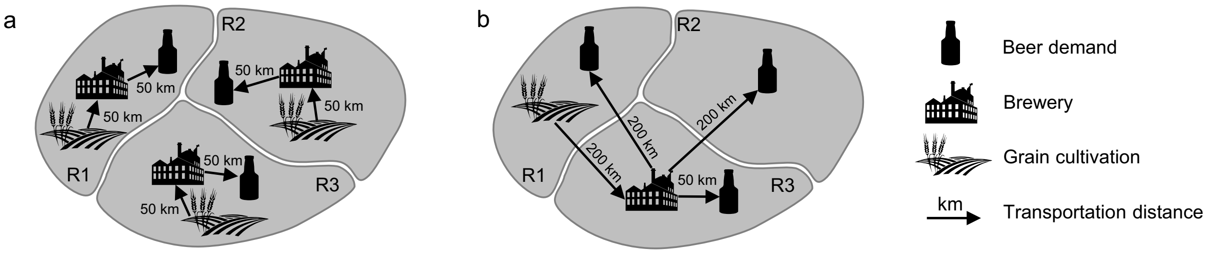

Fig. 2. Comparison of alternative supply chains: (a) Decentralized structure with local demand fulfillment in each region. (b) Centralized structure with grain cultivation in R1 and brewery in R3, serving the demand in all regions.

one brewery that serves the demand in all three regions. If there was only one brewery, it would be located in one of the regions. Similar options exist with regard to grain cultivation. For the purpose of illustration, we compare two design alternatives for the supply chains: one with a decentralized structure in which the demand in each region is served by a local brewery that sources barley from local producers, and one with a centralized structure in which the demand in each region is served from a central brewery in R3, which sources all barley from a producer in R1 (Fig. 2). The transportation distances are assumed to be 50 km within a region and 200 km across regions. The demand is normalized to 1 liter of beer in each region.

The technological and environmental properties of the three regions are summarized in Table 1. The yields of grain cultivation are assumed to be highest in R1, followed by R2 and R3. Consequently, the emissions per kg of barley are lowest in R1. The brewery technology is assumed to be identical in R1 and R2, and more efficient in R3, which is reflected by the lower barley input and lower emissions. The environmental properties are assumed to be identical in all regions for climate change (as a global impact category), but differ for acidification (as a regional impact category). This is reflected by the different characterization factors for nitrogen oxides (NO_x) with regard to acidification.

For both design options, a region-specific inventory of resources is calculated and impact assessment is carried out via a spreadsheet model that has been implemented in MS Excel.

Table 1. Technological and environmental properties of the three regions in the beer supply chain as well as global average values.

Parameter	Unit	R1	R2	R3	Global
Grain cultivation					
CO_2 emissions per kg barley	kg	0.15	0.18	0.3	0.2
NO_x emissions per kg barley	kg	0.2	0.24	0.4	0.3
Brewery					
Barley input per L beer	kg	3.2	3.2	2.5	3
CO_2 emissions per L beer	kg	0.45	0.45	0.25	0.4
NO_x emissions per L beer	kg	1.1	1.1	0.5	0.8
Characterization factors					
Global warming potential of CO_2	kg CO_2-eq	1	1	1	1
Acidification potential of NO_x	kg H^+-eq	0.9	1.5	1.3	1.2

3.2. Results

The results for the environmental sustainability indicators climate change and acidification are shown in Fig. 3. To analyze the effect of region-specific modeling, the results that have been calculated under consideration of technological and environmental heterogeneity in the regions (as proposed above) are compared to the results from an approach that ignores such differences and uses average values instead.

Fig. 3 illustrates that if regional heterogeneity is ignored (left side), the total climate change and acidification impacts are higher for the centralized supply chain structure than for the decentralized supply chain structure. While the total emissions and the resulting impacts of the production processes are identical, the centralized structure has higher impacts from transportation because of the longer distances due to interregional resource flows. Thus from a global sustainability perspective, the decentralized supply chain would be considered advantageous over the centralized structure.

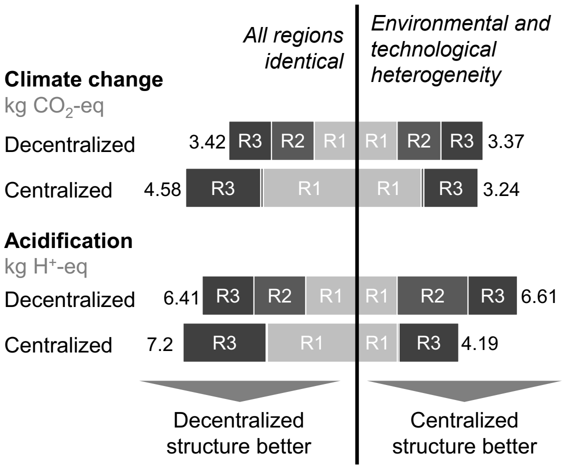

Fig. 3. Results of regionalized impact assessment. The decentralized structure appears environmentally advantageous if regional heterogeneity is ignored, but the centralized structured has lower impacts if regional heterogeneity is considered.

With a spatially differentiated assessment (right side of Fig. 3), the results are different. The reduced climate change impact of the centralized supply chain structure is because of technological heterogeneity. Since grain cultivation takes place in a region with high yields (R1), and R3 has highly efficient brewing technology, the aggregate inputs and outputs of these processes are much lower than the totals for the decentralized case, even when the additional emissions from transportation are factored in. Technological heterogeneity also partly explains the lower acidification impact of the centralized supply chain structure. Not only are the emissions of nitrogen oxides from grain cultivation lowest in R1 and those from the brewery lowest in R3, but also the barley input per liter of beer of the efficient brewery in R3 is lower than in both other regions. The remaining reduction in acidification is due to environmental heterogeneity. In this example, the effect of releasing the same amount of nitrogen oxides is lowest in R1 and highest in R2 due to different sensitivities to acidification of the environment. Since the production processes in the centralized supply chain structure are only located in R1 and R3, the impact of the emissions of nitrogen oxides is lower than in the decentralized structure, where production processes are also located in R2. Consequently, from a global sustainability perspective, the centralized structure should be preferred.

The results also reveal the spatial distribution of impacts. This is especially interesting for acidification as a regionally relevant impact category. It can be observed that although the total acidification impact is lower in the centralized structure, the regional acidification impact in R1 and R3 is slightly higher. Only in R2, the regional impact is much lower. Thus, a decision maker with a regional perspective on sustainability might prefer another design option than a decision maker with a global sustainability perspective. The results from multi-scale impact assessment as well as the specific preferences of the decision maker are both inputs to an MCDM model, which can be used subsequently to select the best supply chain structure.

4. Conclusion and outlook

This paper proposes a novel framework for spatially differentiated sustainability assessment to address challenges in sustainability assessment of products with global supply chains. With the location-specific modeling of production processes and the explicit consideration of transportation processes, the framework is particularly useful to assess complex supply chain structures in the presence of regional heterogeneity. It proposes a consistent methodology from resource flow modeling to multi-scale impact assessment and multi-criteria evaluation. The paper offers a consistent methodology from resource flow modeling to multi-scale impact assessment and multi-criteria evaluation. The proposed framework can be used to integrate the latest methods from spatially differentiated life cycle sustainability assessment into conventional supply chain network design models, laying the foundation for the design of sustainable supply chains.

The application of the framework is illustrated with a simplified supply chain of beer production. Despite the rather simple structure of the example and its focus on environmental sustainability, the analysis shows that the consideration of transportation processes, technological heterogeneity, and environmental heterogeneity leads to different results when alternative supply chain structures are compared. Furthermore, it gives insights into the geographic distribution of the impacts, highlighting potential conflicts of objectives between the perspectives of local and global decision makers.

In future work, more realistic supply chains and additional indicators for economic and social sustainability issues need to be investigated. To this end, the computational logic, which could be implemented in a spreadsheet model for the illustrative example above, needs to be formalized and implemented in a more sophisticated modeling environment. Furthermore, suitable data structures to handle the various resources and processes need to be developed.

With an increasing complexity of the supply chain, the number of possible design options will be much larger than in the illustrative example. Therefore, it will be difficult to derive plausible design options by hand. Instead the design of the supply chain should be supported by an optimization algorithm. This way, all possible design options can be explored in a systematic way and advantageous design option based on the decisions maker's preferences can be identified.

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