A Review of Modeling Approaches for Sustainable Supply Chain Management

Stefan Seuring
Chair of Supply Chain Management
Faculty of Business and Economics
University of Kassel,
34117 Kassel, Germany
seuring@uni-kassel.de
http://www.uni-kassel.de/go/scm

Stefan Seuring is full professor of supply chain management at the University of Kassel, Germany. Previously, he worked at the Waikato Management School, Hamilton, New Zealand and was a visiting professor at the Copenhagen Business School. He hold a PhD and habilitation from the Carl von Ossietzky-University of Oldenburg, Germany. He has published widely on sustainability and supply chain management.
**Abstract:** More than 300 papers have been published in the last 15 years on the topic of green or sustainable (forward) supply chains. Looking at the research methodologies employed, only 36 papers apply quantitative models. This is in contrast to, for example, the neighboring field of reverse or closed-loop supply chains where several reviews on respective quantitative models have already been provided. The paper summarizes research on quantitative models for forward supply chains and thereby contributes to the further substantiation of the field. While different kinds of models are applied, it is evident that the social side of sustainability is not taken into account. On the environmental side, life-cycle assessment based approaches and impact criteria clearly dominate. On the modeling side there are three dominant approaches: equilibrium models, multi-criteria decision making and analytical hierarchy process. There has been only limited empirical research so far. The paper ends with suggestions for future research.

**Keywords:** Supply Chain Management, Sustainability Management, Quantitative Modeling, Literature Review, Environmental and Social Standards.

1 **Introduction**

Globalization places demands on supply chain management to reach beyond pure economic issues and includes matters like e.g. fair labor conditions and environmentally friendly production. This raises interest in its intersection with sustainable development, which is usually comprehended in an economic, an
environmental and a social dimension (see e.g. [45]; for the link to supply chain management see [70]; [42]). Managing supply chains in a sustainable manner has become an increasing concern for companies of all sizes and across a wide range of industries. Meeting environmental and social standards along all stages of the supply chain ensures that (at least) minimum sustainability performance is reached. This more reactive approach of responding to external pressure from governments, consumers and non-governmental organizations (NGOs) [71]) and media can be complemented by the development and introduction of sustainable products.

For the period 1990 to 2007 Seuring and Müller [70] reviewed a total of 191 papers. Against the end of 2010 this list has grown to about 308 related papers published on green and sustainable supply chain management. Yet, sorting these papers according to the research methodology employed, only 36 remain which build or use quantitative models. Hence, this paper aims at taking a longer period into account than Seuring and Müller [70], but focuses on one kind of research method, i.e. quantitative models, only. This allows detailed insights into this stream of research and should reach conclusions on how to develop it further. This small number and share of models is in clear contrast to, for example, the neighboring field of reverse or closed-loop supply chains, where Fleischmann et al. [46] already provided a first review on “quantitative models for reverse logistics”. Furthermore, (wider) literature reviews on related fields are available: (1) closed-loop supply chains [50]; (2) green supply chains, but also with a focus on reverse logistics [73] and (3) sustainable supply chain management [70]. Recently, further reviews have been published, which address
particular topics. Two examples are those on sustainable supply chain management and inter-organizational resources [48] or relating it to a wider set of constructs in supply chain management [49]. Mollenkopf et al. [61] have emphasized the link to lean management and globalization issues in their review. Carter and Easton [42] evaluate particularly related empirical research, restricting themselves to a set of papers taken from seven journals mainly in the domain of logistics and supply chain management. Yet, such a review has not been attempted for quantitative models applied to the forward supply chain.

The aim of this paper is to summarize existing research on quantitative models for forward supply chains, thereby aiming at substantive justification as an important step in theory building [58]. This provides insights towards future research directions and needs.

The paper is structured as follows: As the study deals with a literature review, a classical section labeled as such is not provided. Instead, the paper starts by outlining the content analysis method as applied in the research process. Next, some descriptive background on the papers (e.g. years of publication, major journals) is presented. Further, the findings from the content analysis are discussed, with a particular focus on the sustainability dimensions and modeling approaches. This will lead over to the discussion of the findings and brief conclusions.

2 Describing the Method and Base for the Literature Review

This study forms part of a wider literature review at the intersection of sustainability and supply chain management. The methodology applied has
already been described in detail [70]. Papers were identified by means of a structured key word search on major databases and publisher websites (Ebsco, Springerlink, Wiley Interscience, Elsevier ScienceDirect, Emerald Insight). Keywords such as “purchasing”, “sourcing”, “supply” and “supply chain”, and logistics/logistical” were combined with sustainability related ones, such as “sustainable/sustainability”, “sustainable development”, “environment(al)”, “green”, “social” and “ethics/ethical”. Subsequently, papers were screened in detail in a two-step process. First, there were three issues excluded from further analysis: (1) reverse logistics and remanufacturing, as they have already been subject to self-contained literature reviews already [46, 50], (2) ethical behavior of purchasing staff, and (3) public procurement. Second, the papers were unanimously assigned to one research method, where five categories were applied: modeling (the one used here), theoretical or conceptual, case study, survey or literature review.

A content analysis was conducted to systematically assess the papers [55, 56, 63]. Material collection has already been described by means of the literature search and reduction mode. For the analysis itself, a set of criteria is used at first for describing the sample. Then, the discussion is taken into the content analysis itself, where a mixture of deductive and inductive as well as quantitative and qualitative criteria is chosen. Respective criteria applied for the content analysis are outlined below.
2.1 Basic Terminology

- Sustainable Supply Chain Management (SSCM)

The definition of Seuring and Müller [70] who take standard definitions of supply chain management [59] serves as a starting point: “Sustainable SCM is the management of material, information and capital flows as well as cooperation among companies along the supply chain while integrating goals from all three dimensions of sustainable development, i.e., economic, environmental and social, which are derived from customer and stakeholder requirements. In sustainable supply chains, environmental and social criteria need to be fulfilled by the members to remain within the supply chain, while it is expected that competitiveness would be maintained through meeting customer needs and related economic criteria.”

- Quantitative modeling

According to Bertrand and Fransoo [39] this is “model-based quantitative research, i.e. research where models of causal relationships between control variables and performance variables are developed, analyzed and tested”. Such research methods are frequently used in supply chain management research (see e.g. [38, 60, 57]). Subsequently, four different quantitative approaches are distinguished, which are briefly introduced, while the full justification for using them as categories is provided later in the paper.
2.2 Sample and descriptive analysis

The overall sample contains 309 papers in total (status papers published up to the end of 2010). Out of this sample only 36 papers apply quantitative models, thereby only contributing little more than 12% of the total number of papers.

Figure 1 highlights the timely distribution of the 36 papers. Only two papers were published before the year 2002 [29, 31, 6, 7, 24]. There is a small peak in 2005 with seven papers, but this seems just accidental as there was no special issue which would easily explain it. In current years, there is an almost stable output with four or five papers published for each year in 2007-10 (see Figure 1).

![Figure 1: Time distribution of the analyzed papers](image)

Regarding journals, where such papers appear most often, Journal of Cleaner Production (JCLEPRO) is the leading journal with nine papers (or 24%) published. Four papers appeared in the European Journal of Operational
Research (EJOR), and three each in the International Journal of Production Economics (IJPE) and the International Journal of Production Research (IJPR), in total contributing another 27% of the sample. The rest of the papers are distributed across a range of other journals.

2.3 Criteria applied in the content analysis

Establishing criteria for content analysis can be based on a deductive or an inductive approach. Here, the criteria are mainly derived deductively and are based on the already mentioned literature reviews in the field (particularly [70] criteria). Yet, this would not be sufficient for addressing all relevant issues, so in some cases, criteria can only be established while working with the material. This was the case here for the assessment of the modeling approaches applied in the paper.

The following dimensions will be discussed, briefly explained and justified:

- First, the environmental, social and economic criteria or performance objectives are assessed. In a second step, the integration of environmental and/or social issues with economic objectives is analyzed. This is in line with the typical three dimensional comprehension of sustainability (see e.g. [45]) and has been discussed in the field of supply chain management before (see e.g. [71, 42]).

- The modeling approach taken in the paper is described. As there was no clear starting point for this analysis, the categories were derived inductively.

Three categories, i.e. life-cycle assessment models, equilibrium models and
analytical hierarchy process, were used right at the start, while the other two only appeared during the coding.

- The link to empirical data forms the final dimension of the analysis [42, 69]. This allows insights into the field research done towards filling the models with empirical data.

These findings from applying these dimensions are now presented.

3 Analysis of the papers

In the following sections, the different dimensions of the analysis will be presented. To allow easier presentation of the material, tables will be used summarizing the single dimensions as embedded in the papers. Unless stated otherwise, all figures refer to the sample of 36 papers analyzed here.

3.1 Sustainability dimensions

Conceptualizing sustainability in three dimensions seems to be widely accepted [45, 42]. It allows an easy comprehension of the integration of economic, environmental and social issues. This also offers the justification of applying it in this paper. Hence, the papers are categorized, based on how they relate to sustainable development. As all papers are taken from management related literature, the economic dimension forms an integral part and was therefore not taken as a separate category. Yet, the papers show a very strong dominance of addressing environmental issues (34 papers). There are no papers that exclusively focus on social issues, but also integrating all three dimensions of sustainability is only present in two of them (i.e. [5, 15]).
Seuring and Müller [70] emphasize the need for increasing cooperation along the supply chain, if sustainability goals are to be reached (also [49]). Hence, this should be reflected in related goals. A closer look is therefore taken on each dimension and on which goals are put forward.

- Economic dimension

As only papers dealing with supply chain management are taken into account, it is logical that economic issues are addressed. Most often, total cost or net revenue are taken as indicators. Yet, there are a number of papers not providing insights into what kind of economic goals are pursued. This holds for a first set of papers that mainly follow a life-cycle assessment (LCA) approach (e.g. [34]). Often, such papers compare different alternatives towards their environmental performance (e.g. [11, 13]). In a number of cases, the current economic situation is (inherently) seen as a kind of baseline for evaluating alternatives on their environmental impact. This holds particularly for the LCA related papers (e.g. [34, 35, 4, 11]) or those applying AHP [31, 19, 20, 25, 26].

- Environmental dimension

Most papers spend much more effort on explaining related environmental issues. In many cases, life-cycle assessment data forms the starting point for the analysis. Hence, energy demand and CO₂-emissions (e.g. [4, 11, 35, 28]) are among the frequently mentioned topics. Yet, in a number of cases, rather comprehensive lists of environmental impact criteria are taken up, such as referring to all kinds of natural capital (e.g. [36]) or resources, such as water or energy as well as waste (e.g. [26, 23, 17]). Overall a wide range of environmental aspects is taken into account. A deeper look provides some critique to the typical
approach chosen. The relationship between the LCA-based environmental impacts and their management in the supply chain often points to supplier selection (e.g. [29, 20, 25]) and optimization issues, such as transport to end customers [33, 11]. Hence, LCA based approaches seem to dominate here as they allow comprehending and modeling product-related impacts (for a conceptual note see [64]).

- Social dimension

The social dimension is the one that is addressed the least often in the papers. Building on a rather strict assessment, 34 of the 36 papers do not mention it at all. In four cases one could even argue that the term corporate social responsibility (CSR) is rather misused in the title of the papers looking at their content [8, 9, 10, 21]. While all carry CSR in their title, they rather model environmental issues, but not social impact related ones. Cruz [8, 9] as well as Cruz and Matsypura [10] briefly refer to risk associated with not having (enough) CSR. Hsueh and Chang [21] use it as starting point for a discussion on profit sharing.

Yet, turning to the definition of CSR (for an overview see [44]), it is evident that this is about voluntary measures of companies, particularly in the relation between business and society. Hence, CSR cannot be subject to a simplistic comprehension of just a single factor put into any kind of quantitative model. While this is a normative statement, the ongoing debate on CSR supports such a statement (e.g. [47]). This would basically leave all assumptions of supply chain management unquestioned and rather support a marginally changed business as usual, where sustainability is still subordinate to economic issues. Just as one
closely related example, Halldórsson et al. [52] pointed out that such an assumption as insufficient for addressing sustainability.

A much wider perspective is taken by a few other papers. Rather macro-economic social aspects are put forward by Clift [5], Foran et al. [15] and Ukidwe and Bakshi [36]. They cover employment and income distribution, thereby pointing to the wide range of responsibilities of companies.

- Integration of the three dimensions

The integration of all three dimensions plays a central role, but is not often addressed so far in related research [70]. Previous findings have rather confirmed that the social dimension needs much better integration with the economic and environmental one.

<table>
<thead>
<tr>
<th>Goal relations</th>
<th>Seuring and Müller 2008a (N = 191 papers) (n = 234, multiple counting allowed)</th>
<th>Modeling papers (N = 36 papers)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Win-win-situations</td>
<td>124 (53%)</td>
<td>7 (19%)</td>
</tr>
<tr>
<td>Trade-offs</td>
<td>72 (31%)</td>
<td>20 (56%)</td>
</tr>
<tr>
<td>Minimum performance for environmental and social issue</td>
<td>37 (16%)</td>
<td>9 (25%)</td>
</tr>
</tbody>
</table>

Table 1: Goal relations among the three sustainability dimensions

A second approach is taken by looking at the goal relations among the three dimensions (see Table 1). It has to be noted first that each paper is assigned here to one
category only, while Seuring and Müller [70] assigned papers into more than one category, therefore having a total of 234 entries for 191 papers. Comparing the figures, it can be seen that trade-offs among the environmental and the economic dimension are most often taken as a starting point for building the models. This will be discussed subsequently, after the modeling techniques have been introduced.

This analysis already points to a clear research gap regarding social aspects as well as the overall integration of the three sustainability dimensions. While this will not be an easy or simple task, such research is much needed and would also allow links of sustainable supply chain management towards other emerging fields, such as the Base-of-the-Pyramid debate (see e.g. [51, 66]).

### 3.2 Modeling approaches

Looking at the models proposed, they can be grouped into four categories (see Table 2). The four categories were not chosen deductively, but emerged inductively while trying to group them when reading and analyzing the material: (1) life-cycle assessment based models, (2) equilibrium models, (3) multi-criteria decision making (MCDM), and (4), applications of the analytical hierarchy process (AHP). The overall objective is usually a cost minimization effort, where the entities that incur costs and the respective cost elements are specified. Each approach and the typical elements pertained therein will be briefly presented.

It has to be mentioned that each paper is assigned to one category only. The equilibrium models and the multi-objective decision making (MCDM) models take somewhat similar starting points and both aim at finding a balance between
different (environmental and economic) performance criteria. As a further issue, there are three papers applying simulation as their method [24, 34, 14, 30]. Yet, they do so either for providing insights into LCA cases [24, 34] or for evaluating variables among a multi-objective decision making approach [14]. Hence, they are grouped into the respective categories.

Table 2 provides an outline of the different modeling approaches used, briefly describing the typical approach taken and listing the papers that were grouped into the respective category.

<table>
<thead>
<tr>
<th>Modeling approach</th>
<th>Typical element of the model</th>
<th>Related papers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Life-cycle assessment (LCA) models (11 papers)</td>
<td>Assessing environmental impacts along a supply chain and minimizing them.</td>
<td>[3, 4, 5, 6, 11, 13, 15, 18, 24, 34, 35]</td>
</tr>
<tr>
<td>Equilibrium models (9 papers)</td>
<td>Balancing environmental and economic factors and finding an equilibrium or optimal solution.</td>
<td>[7, 8, 9, 10, 21, 23, 27, 30, 36]</td>
</tr>
<tr>
<td>Multi-criteria decision making (6 papers)</td>
<td>Optimization of economic and environmental criteria, usually balancing trade-offs or identifying optimal solutions.</td>
<td>[14, 16, 17, 22, 28, 33]</td>
</tr>
<tr>
<td>Analytical hierarchy process (8 papers)</td>
<td>Structuring a decision process thereby obtaining a solution based on semi-quantitative criteria and respective weights.</td>
<td>[1, 2, 12, 19, 20, 25, 26, 29, 31, 32]</td>
</tr>
</tbody>
</table>

Table 2: Grouping papers according to modeling techniques
• Life-cycle assessment (LCA) based studies

Life-cycle assessment is a product based on environmental assessment techniques (e.g. [54]), which even were standardized in the ISO 14041. It is first discussed here, as it often forms a kind of background for the other modeling approaches. LCA-type data is pointed to in 29 of the 36 papers. The papers mainly present life-cycle assessment data and illustrate its use in a specific context or case application. This is well in line with earlier analysis, such as the conceptual suggesting by Pesonen [64], who already pointed to the use of life-cycle assessment based criteria in supply chains. Furthermore, Seuring [67] elaborates that LCA-based criteria usually provide the product optimization perspective which precedes the supply chain optimization. In this respect, it is no surprise that LCA type data serves as a background for subsequent optimization in the papers reviewed here (e.g [14, 13]). The link to products is evident, as a core line of related research is labeled as supply chain management for sustainable products (e.g. [70, 69]).

This also offers a link to the already discussed environmental dimension and related performance objectives (see section 3.1). In total, a broad range of environmental emissions and impacts is referred to, while related impact assessments usually concentrate on the direct emission level.

One further typical element is the focus of a number of papers on one product or industry, such as aluminum [24, 35, 13], milk [34], electronics [18] or services,
particularly book distribution [11] or wine distribution [4]. This allows reducing the environmental issues dealt with as well as making respective supply chain related decisions more evident. While the LCA-studies therefore often stay on general supply chain wide aspects and in many cases do not center on a single actor or actor network in the supply chain, such is usually the case in the other approaches taken in respective papers.

- Equilibrium models

The already mentioned line of research on assessing performance of an overall supply chain or even industry is continued within the papers aiming at indentifying an equilibrium. This is a standard modeling technique [62] and well established (e.g. [57]). Such an equilibrium would be established by assessing what the optimal level of investment into environmental (abatement) technologies and respective economic returns would be. Kainuma and Tawara [23] start this debate by proposing a multiple utility function approach, which builds on metrics in three dimensions: (1) LCA, (2) supply chain return on assets and (3) customer satisfaction. A starting point for related research was presented with the shared savings contract model for indirect material [7]. The environmental consideration is easy to comprehend as it aims at reducing the amount of indirect materials being applied. Staying with environmental considerations but aiming at a much wider equilibrium among natural and economic capital, Ukidwe and Bakshi [36] present their model, mainly building on thermodynamic input-output analysis. Nagurney and Toyasaki [27] formulate a more specific model based on manufacturers, retailers and consumers, but stay vague about what kind of emissions are actually dealt with.
The above already criticized papers modeling CSR activities also fall into this category. Hsueh and Chang [21] stay particularly vague about what CSR would imply: “Herein, undertaking CSR is originally utilized for coordinating the decentralized supply chain.” In the model itself, this is only present in a production function as “perceived production and inventory cost of manufacturer (considering CSR)” [21]. Cruz [8] handles this in a similar manner, even claiming: “We note that any level of social responsibility activities between any two parties in the supply chain requires a strong level of collaboration/cooperation between them." Such an approach is made somewhat clearer in the paper by Cruz and Matsypura [10] who claim that engagement in CSR is assumed to reduce transaction costs, waste, as well as risk.” This is one of the assumptions forming the background for modeling a respective network of manufacturers and retailers. In the equilibrium, an optimal solution is found for CSR related investments, products’ flows along the supply chain and respective prices.

A similar approach is presented by Saint Jean [30], but based on emission standards, which seems easier to comprehend. Here, the minimum performance level of environmental and social standards [70] is pointed to, which seems much more straightforward than unspecified investments into CSR. This refers to the overall contribution of these models, which evaluate the consequences of introducing some sort of minimum performance criteria. While the problem statement and model formulation for environmental issues seem straightforward, the integration of social issues needs further elaboration and a clearer positioning whether minimum standards, e.g. for working conditions and payment, are reached or whether voluntary CSR activities are expected. It is emphasized again
that these models evaluate the overall equilibrium among a given set of market actors, but do not directly aim at their decisions. Such a focus is taken within the other modeling approaches.

- Multi-criteria decision making (MCDM)

The link to the previous category is evident, in e.g. the paper of Sheu et al. [33], who use multi-objective programming but also assess the equilibrium among manufacturing chain and reverse chain, including e.g. transaction costs and recycling fees. This showcases the typical idea of the papers where different objectives have to be met at the same time, which makes the point for such multi-criteria decision making approaches (e.g. [60]). Hence, the focus is usually not so much on reaching an equilibrium situation, but rather dealing with trade-offs among conflicting objectives. There is a somewhat weak line among these papers looking more at single company/supply chain based decisions and the previous category. An efficient logistics’ network configuration is at the core of the arguments presented by Neto et al. [28]. In line with the LCA studies and equilibrium models, they mention that trade-offs would be based on societal decisions based on Pareto efficiency. Their model could help in making respective decisions and is clearly linked to the equilibrium models already described. Hugo and Pistikopoulos [22] also use LCA data as their starting point and integrate this into modeling the supply chain for “environmentally conscious strategic investment planning”.

More into detail are e.g. Fichtner et al. [14], assessing joint investments into inter-firm energy supply and respective savings. Quite similarly, Geldermann et al. [16] look at a bicycle manufacturer in China. Heat integration, water management and
solvent recovery are the environmental issues addressed and optimized. While these two papers already point to supply chain design, this is emphasized in the two papers remaining in this category.

- Analytical hierarchy process (AHP)

The logic of LCA-data is also evident in the paper applying the AHP, similar techniques or modifications thereof. The AHP is also a multi-objective decision making technique [65]. The major difference is that it is not based on a full mathematical formulation of a certain problem, but is called a semi-quantitative decision making technique simplifying and structuring decisions (e.g. [65, 53]). This justifies an own category, different from the two previous ones. The two papers published early in the entire data set are based on this semi-quantitative decision technique [29, 31]. The AHP allows evaluating complex decision situations, where environmental and economic goals are assessed at the same time (e.g. [31, 32, 19, 12]), but also more specialized decisions, such as looking at the role of hazardous substance management [20] or green supplier selection [29, 26, 25] and supplier development practices [1, 2]. The last two papers somewhat form an own category as they apply rough set theory. Yet, as this also deals with incomplete information and follows similar aims as the AHP, it was decided keeping them in the same category.

Overall, the decisions evaluated focus on improving environmental performance towards greening respective products [41, 70]. Compared to the previous two categories, the aim is not so much reaching an equilibrium or optimal approach but rather pointing towards the complexity of decision making and emphasizing the influence of the decision makers. AHP allows taking different decision criteria
into account and evaluating them without necessarily connecting all of them into one quantitative model. Hence, such an approach may also be called multi-objective decision making (e.g. [26]), but building on managerial judgments.

3.3 Interrelation of modeling approaches and goal relations

As a further step, it is interesting combining the two analytic dimensions of goal relations and modeling approaches. As briefly mentioned, the analytic dimensions and categories for the content analysis are often derived inductively and are then validated against the interpretation and understanding they offer.

<table>
<thead>
<tr>
<th>Goal relations</th>
<th>Modeling approach</th>
<th>Sum</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LCA model</td>
<td></td>
</tr>
<tr>
<td>Win-win situations</td>
<td>2</td>
<td>7</td>
</tr>
<tr>
<td>Trade-offs</td>
<td>6</td>
<td>20</td>
</tr>
<tr>
<td>Minimum performance for environmental and social issue</td>
<td>3</td>
<td>9</td>
</tr>
<tr>
<td>Sum</td>
<td>11</td>
<td>36</td>
</tr>
</tbody>
</table>

Table 3: Relationship among goal relations and modeling approaches

This kind of construct validity is derived from the two analytic dimensions, jointly offering interesting insights into how the typical models look and thus allowing a distinction among them (discriminant validity). This is shown in Table 3.

The equilibrium models as well as the multi-objective decision making build on trade-off situations among environmental and economic goals. There is only one MCDM paper which takes its starting point from a win-win situation [14]. This is also the only one building on data from a practical environment.
It almost seems obvious that these models take their starting point from trade-offs between the economic and environmental dimension. Such trade-offs are a critical aspect of sustainable supply chain management and often form the starting point for respective action [71]. Further, trade-offs are more straightforward to model in these approaches.

All three goal relations are observed only for the LCA based papers. This is in line with the previous finding that LCA data forms a background for many of the studies presented here. While the trade-offs dominate, the two other categories are also found. Foran et al. [15] as well as Tan and Khoo [35] take win-win-situations as their starting point. Both apply an analysis of statistical data. The latter looks at cleaner production and process improvements in the aluminium supply chain. Foran et al. [15] look at different products relevant for private consumption (e.g. cotton and vegetables).

There are three papers arguing for minimum conditions for environmental and social performance [34, 3, 18]. The paper by Sonesson and Berlin [34] is based on the milk supply chain, while Brent addresses the automotive one. All papers have in common that they rather argue on a macro-level, well in line with the win-win-category ones. It seems to be more straightforward to depart from a trade-off assumption if the level of analysis is not focused on just a single company and its respective supply chain.

For the AHP papers, there are contrasting findings as there are no papers dealing with trade-offs. While four look at win-win situations [31, 32, 26, 12], there are six taking environmental issues as minimum standards against which economic decisions have then to be made (see Table 2). The selection of the
decision criteria is more flexible within the AHP as they are rather connected in a logical but not in a mathematical matter. This allows choosing criteria that represent either win-win-situations or minimum standards. The most recent development in this category, namely being the application of rough set theory [1, 2], also allows evaluating performance issues of each company as well as the supply chain in total, an issue not addressed in the previous publications in this category.

3.4 Illustrations and empirical data

Many modeling papers contain a theoretical example of numerical illustration of the model presented. This is also found here, as 29 papers in total do so. The purpose of such an illustration usually emphasizes the consequences of the decision making for a real life application. Yet, very few papers actually build on empirical research. On most occasions, the illustration is “made up”. Only one paper is purely theoretical and does not contain any such information [5]. Few examples are found to be different. Fichtner et al. [14] use an industrial network in the Karlsruhe area, Germany, as background for their model, thereby relating to real world data. Others take industrial sector data, such as the example of the European pulp and paper industry [28], but stay at an illustrative level. Such statistical data is used most often in LCA-type studies, which make up four of the five papers offering such an approach [6, 15, 24, 34]. Only Ukidwe and Bakshi [36] build a thermodynamic input output model on 488 sector data sets for the USA, thereby assessing an equilibrium situation between natural and economic capital.
Empirical content | No. of papers (N = 36)
---|---
Theoretical or numerical example | 28 (all others not listed below)
Statistical data | 5 [6, 15, 24, 34, 36]
Empirical data | 2 [14, 19]
None | 1 [5]

Table 4: Empirical research presented in the papers

Besides the already mentioned model based on real technical data by Fichtner et al. [14], there is only one paper presenting empirical data. A survey feeding into the decision making process is found in Hsu and Hu [19], who take responses from 87 managers for validating their AHP model.

Overall, it has to be concluded that the link to empirical data is missing for most of the related research. Yet, combining the models presented with empirical data should offer interesting insights and hence provides a sound direction for future research.

4 Discussion

This paper provides a first review of publications applying a modeling approach for green or sustainable supply chain issues. The contribution of this review lies in aggregating the so far scattered publications on this topic and providing an overview on the approaches taken therein.

4.1 Sustainability dimensions

Several conclusions can be drawn, which first of all relate to the three dimensions of sustainability:
• The social dimension is almost completely missing or sometimes comprehended in a far too simplified manner. It might be difficult to model social impacts. This is in line with wider literature reviews (e.g. [73, 70, 49]), which also found a lack of research on social aspects. Hence, there seems to be a challenge for the wider range of related research, while social aspects might have to be evaluated in detail before they are suitably integrated in such (multi-objective) modeling approaches.

• The environmental dimension is mainly treated by building on life-cycle assessment-based categories. Yet, many papers stay vague about the kind of environmental impacts taken into account. Some specify the environmental impacts of a particular product or supply chain process and mention how to deal with them. Such models would offer the chance to look at particular impacts and offer guidance to practitioners on how to deal with them. This also points to a more theoretical stream of research, which assesses the role of LCA-data in supply chain decisions. Here, a link to empirical research on the decision makers would be relevant in particular.

• In the economic dimension, “total” cost-based or decision related cost and revenue approaches dominate. This does not really capture how proactive companies strive to implement green or sustainable supply chains and thereby actively managing a number of performance objectives. Some of the AHP related papers point to this and thereby get closer to what Seuring [69] calls supply chain management for sustainable products. Widening the scope of economic performance criteria would be a welcome contribution.
• Last but not least, the integration of the three dimensions as well as the interrelations among sustainability dimensions and objectives demand further research. Previous modeling research mainly looks at trade-offs. While this might be a sound starting point for decision making, the consequences of either win-win situations or environmental and social standards as minimum criteria also warrant further research.

4.2 Limitations

The first limitation of this paper comes from the small sample size of only 36 papers. This has been justified as no previous literature review or similar approach has been presented on quantitative modeling approaches in sustainable supply chain management. A second limitation is that only a number of quantifiable criteria is used for the content analysis. Only meaning embedded into these categories is extracted from the papers. Yet, it is obvious that each paper was read more than once during the coding and thereby other aspects came forward in a more inductive manner. The range of codes could be expanded, so that e.g. the environmental dimension is analyzed in more detail. Furthermore, the quantitative models could be assessed toward the constraints taken into account and based on the different variables being modeled. Taking the analysis to such depth might even require restricting the sample further. This leads over to directions for future research.

4.3 Research directions

Further conclusions are drawn regarding the modeling approaches taken as well as the so far weak link to empirical data:
• A critical link is the one to empirical research. While there is plenty of empirical research on sustainable supply chain management (see [42, 69]), such data is not linked to the formal assessments offered by quantitative models. While this might be challenging, building on empirical data for the model development should provide a sound link into other streams of research within the wider field.

• There is also the open question about the popularity of models for closed-loop supply chain management and reverse logistics and not for the forward supply chain in research. The reasons can only be speculated on. This cannot be concluded from the current body of literature, but might be an issue for further analysis.

• One further direction might be the link to supply chain contracts. While a review of this topic has already been provided by Tsay et al. [74], this has not been connected to environmental and sustainability issues. The single link to this topic is the analysis of shared savings contracts ([7], as a further paper see [43]).

• Finally, the link into the supply chain management literature should be strengthened. There is rarely a link into the literature on strategic supply chain design (e.g. [68]), supply chain performance and collaboration literature, which sees a number of interesting developments (see e.g. [72, 37]). One such attempt has been made in a recent paper by Wang et al. [75], who analyze supply chain network design against environmental criteria. A further example links green supply chain management to stock market performance [40].
The analysis needs further expansion. Future research can take up some of the challenges to fill gaps in the still emerging intersection of sustainability and supply chain management.

### 4.4 Future research questions

As a consequence of the previous analysis and research directions, a number of broader research questions can be raised. Two broad groups of research questions are proposed. The first one relates to aspects of sustainability, while the second group integrates with supply chain management thought.

Regarding questions on sustainability, it is obvious that the environmental side has been addressed more often so far. This also holds for the many contributions already looking at carbon based emissions. Therefore, the link into the social dimension of sustainability is emphasized here.

- How can the social dimension be integrated into respective models? Such approaches might have to build on the assessment of particular social impacts, thereby reducing the overall complexity.

- What is the interrelation among the social and the environmental dimension? This might be an issue where multi-objective optimization or the AHP allow reaching further conclusions.

- Can the interrelation among all three dimensions of sustainability be modeled? What are suitable approaches for doing so? Addressing this question, it would be worthwhile taking a look at functions other than logistics, operations and supply chain management. This should allow shedding light on the challenges but also respective opportunities?
Questions on supply chain management:

- How does environmental and social performance impact supply chain performance? While there are a number of contributions already on this question, a wider or more detailed analysis would still be beneficial.

- How can contracts and supply chain cooperations be understood further, so that sustainability issues are not just seen as trade-offs. As the analysis in Table 3 revealed, the assumption of trade-offs dominates this stream of research. It might be interesting to see alternative approaches and identify win-win solutions without being overly simplistic.

These research directions and questions would help developing the field further while only a selected set of them can be discussed here.

5 Conclusion

The paper provides a review of the status of research on sustainable supply chain management applying (mathematical) modeling techniques. The sustainability dimensions, the particular modeling approaches taken as well as the empirical content as presented in the papers have been assessed. It is evident that the environmental dimension clearly dominates and social aspects are widely ignored or interpreted in an unusual manner. Life-cycle assessment type studies and respective data form the backbone of the environmental debate in the papers, while cost minimization still seems to dominate the economic dimension. The different modeling approaches (equilibrium models, multi-objective optimization and analytical hierarchy process) form only a subset of the wider range of methods available. The findings of the paper summarize the
status of research on applying modeling techniques in sustainable supply chain management and offer insights into directions for future research.

References

Papers reviewed:


Further references:


