Environmentally conscious supply chain design

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German summary

Das Thema Nachhaltigkeit stellt für eine Vielzahl von Unternehmen eine der Kernherausforderungen in der heutigen Zeit dar. Aufgrund der ökonomischen, ökologischen und sozialen Dimensionen, die in diesem Kontext zu beachten sind, nimmt die Komplexität von Unternehmensentscheidungen dramatisch zu. Besonders im Kontext des Supply Chain Managements, das nicht nur die unternehmensinternen Wertschöpfungsaktivitäten, sondern alle Prozesse der Produktentstehung über mehrere Akteure hinweg berücksichtigt, führt dies zu einer Zunahme an Parametern, die in die Planung einbezogen werden müssen. Neben anderen Treibern stellen Kundenanforderungen eine wesentliche Motivation zur nachhaltigkeitsorientierten Ausgestaltung von Supply Chains dar.

Im Rahmen dieser Arbeit liegt der Fokus auf der strategischen Planung von Wertschöpfungsnetzwerken. Um die Wirkungszusammenhänge zwischen den zugrundeliegenden Planungsentscheidungen sowie möglichst alle relevanten Planungsparameter zu berücksichtigen, eignen sich mathematische Modelle zur Unterstützung von Entscheidungsträgern. Auf Basis von Literaturanalysen lassen sich jedoch nur wenige quantitative Ansätze in der Literatur identifizieren, die sich mit dem nachhaltigkeitsorientierten Supply Chain Design beschäftigen. Zudem kann eine Forschungslücke in der Berücksichtigung von Kundenanforderungen bei der strategischen Planung von nachhaltigkeitsorientierten Supply Chains festgestellt werden. Durch die Bearbeitung der folgenden Forschungsfragen, trägt die vorliegende Arbeit zur Schließung dieser Lücken bei:

Wie können ökologieorientierte Kundenanforderungen bei der strategischen Planung von Wertschöpfungsnetzwerken berücksichtigt werden?

Wie beeinflusst das Kundenverhalten in Bezug auf die Nutzung und die Rückgabe von Produkten Supply Chain Design-Entscheidungen im Kontext eines ökologieorientierten closed-loop Wertschöpfungsnetzwerks?

Nach einer Einführung in die Themenstellung und der Vorstellung des Aufbaus der Arbeit in Kapitel eins, wird die erste Forschungsfrage in den Kapiteln zwei und drei näher betrachtet. Hierzu wird im Kapitel zwei ein Optimierungsansatz präsentiert, der kundenspezifische Anforderungen in Bezug auf die Umweltleistung von Produkten in ein mehrperiodiges Supply Chain Design-Modell integriert. Zur Berücksichtigung der Unsicherheit bezogen auf die Ausprägungen der Parameter Produktpreis und Kundenanforderungen

wird ein robuster Optimierungsansatz vorgestellt. Hierdurch wird das Auffinden einer Modelllösung ermöglicht, die unabhängig vom Eintritt einer potenziellen Parameterausprägung möglichst gut ist. Die Anwendung dieser Technik ist besonders aufgrund der Tatsache relevant, dass Supply Chain Design-Entscheidungen kaum oder nur mit einem hohen finanziellen Aufwand revidiert werden können und Kundenanforderungen bezüglich der Nachhaltigkeitsleistung von Produkten nur schwer zu prognostizieren sind. Weiterhin werden in dem vorgestellten Modellansatz verschiedene, aufeinander aufbauende Produktionsprozesse erfasst, wodurch das Modell dem Entscheidungsträger eine Hilfestellung bei der Ausgestaltung aller Wertschöpfungsprozesse bis hin zum Endprodukt bietet. Das Modell wird abschließend mit Hilfe eines numerischen Beispiels evaluiert.

Im dritten Kapitel wird die Annahme getroffen, dass die Nachfragemengen der Kunden bei zunehmend negativer Umweltleistung der Produkte abnehmen. Dieser Zusammenhang wurde in der bestehenden Literatur bisher nicht berücksichtigt. Um diese Lücke zu schließen, wird eine stückweise lineare Nachfragefunktion im Kontext eines Supply Chain Design-Problems modelliert. Analog zum Modell in Kapitel zwei wird von einem Produktionsprozess ausgegangen, der in mehrere Schritte unterteilt werden kann. Die einzelnen Schritte können jeweils von unterschiedlichen Maschinen durchgeführt werden, die sich hinsichtlich der negativen Umweltleistung unterscheiden. Somit wird ein direkter Zusammenhang zwischen der Investition und Allokation von Maschinen sowie der kundenspezifischen Nachfrage aufgebaut. Ein Entscheidungsträger hat damit annahmegemäß die Möglichkeit, durch die Investition in eine umweltorientierte Wertschöpfung die finanzielle Performance eines Unternehmens, getrieben durch höhere Absatzmengen, zu verbessern. Das Modell wird auf ein numerisches Beispiel angewendet. Mit Hilfe einer Sensitivitätsanalyse bezogen auf die Nachfragemengen kann ein deutlicher Zusammenhang zwischen den umweltorientierten Kundenanforderungen und Supply Chain Design-Entscheidungen identifiziert werden.

Kapitel vier betrachtet die zweite Forschungsfrage. Neben vorwärtsgerichteten Strömen werden zudem rückwärtsgerichtete Produktströme berücksichtigt. Besonders im Kontext einer nachhaltigkeitsorientierten Ausgestaltung von Wertschöpfungsnetzwerken ist diese closed-loop Sichtweise relevant, da Wiederverwendungsmöglichkeiten von gebrauchten Produkten beachtet werden können. Schwerpunkt des Kapitels ist die Entwicklung eines closed-loop Supply Chain Design-Modells, welches die Unsicherheit hinsichtlich der

Quantität und Qualität der Produkte berücksichtigt, die vom Kunden zurückgegeben werden. Analog zu Kapitel zwei wird an dieser Stelle ein robuster Optimierungsansatz vorgestellt. Neben der Minimierung der totalen Kosten wird als zweite Zielgröße die Minimierung der emittierten CO_2-Äquivalente in die Optimierung aufgenommen, weshalb es sich um einen Mehrziel-Optimierungsansatz handelt. Auf Basis eines anonymisierten Datensets aus der Unternehmenspraxis wird das Modell evaluiert, wodurch die Vorteilhaftigkeit der Nutzung der robusten Optimierung im Vergleich zur Anwendung eines deterministischen Planungsmodells herausgestellt wird.

Ausgehend von Praxisprojekten wird im fünften Kapitel ein Anwendungsrahmen zur Nutzung der vorgestellten Modelle in umweltorientierten Supply Chain Design-Projekten vorgestellt. Hierzu werden die relevanten Projektschritte skizziert sowie deren Inhalte erläutert.

Im sechsten Kapitel werden die Erkenntnisse zusammengefasst und weitere Forschungslücken im Bereich der nachhaltigkeitsorientierten Planung von Wertschöpfungsnetzwerken präsentiert.

This dissertation consists of a number of papers published either in scientific journals or in conference proceedings. Please consult the following overview for detailed information about manuscript titles, coauthors as well as journal or book titles and review process:

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List of Abbreviations

DM	Deterministic model
EI	Environmental impact
EMAS	Eco-Management and Audit Scheme
ER	Environmental requirements in tons
ERP	Enterprise resource planning
F	Facility
FGP	Fuzzy goal programming
GRI	Global Reporting Initiative
ISO	International Organization for Standardization
IT	Information technology
LCA	Life cycle analysis
MILP	Mixed-integer linear programming
MINLP	Mixed-integer nonlinear programming
NPV	Net present value
PP	Product price
R	Production resource
SMIP	Stochastic mixed-integer programming
RM	Robust model
RMIP	Robust mixed-integer programming
S	Supplier
TC	Total costs
TE	Total emissions
TP	Total profit

1 Introduction and organization of the research

1.1 The relevance of sustainability in the context of supply chain management issues

Over the past three decades, the issues that have to be considered in business have changed fundamentally. Various topics emerged and increased the complexity of business planning. First of all, the impacts of globalization on companies changed the business environment to a large extent. At least since the collapse of the old world order and the fall of the Iron Curtain, companies have broadened their scope for purchasing, production and sales.[1] Various free trade agreements, particularly in North America and Europe, have supported this trend. Amongst other factors, strengthening of new markets in Asia and other worldwide regions has led to an increasing degree of competition on global markets. Hence, companies are forced to concentrate on their core competencies to improve their ability to compete. Accordingly, the depth of in-house added value is decreasing due to outsourcing decisions.[2] As a consequence, the relevance of supply chain management has emerged substantially.[3] Traditionally, companies plan and optimize their own businesses separately. Supply chain management concepts that cover large parts or even the entire interorganizational value chain ask for an integrated planning approach covering problem fields starting from raw material creating to the distribution of the final product to the customer and thus an inclusion of all actors on the various supply chain stages.[4] In addition, companies need to consider various parameters such as tariffs, regulations or exchange rates that vary depending on regional or company-specific factors.[5] Consequently, the increasing amount of impact factors leads to a high degree of both complexity and

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[1] Cf. Song, J.-S.; Yao, D. D., Supply Chain Structures, 2002, p. V.
[2] Cf. Christopher, M., Supply Chain Management, 2005, p. ix; Halldorsson, A. et al., Supply Chain Management, 2007, p. 284.
[3] Cf. Andersen, M.; Skjoett-Larsen, T., global supply chains, 2009, p. 75. As described in chapter 1.2.1 we define a supply chain as an integrated network organization consisting of various entities which collaborate with each other in order to acquire raw materials, convert them, after cycling various production processes, into final products and deliver these final products to customers with the goal to increase customers satisfaction related to the demanded values. Considering backward flows of goods in addition, the supply chain is defined as a closed-loop supply chain.
[4] Cf. Christopher, M., Supply Chain Management, 2005, p. 15. Particularly in sustainable supply chain management, also backward flows of used products need to be taken into account.
[5] Cf. Cohen, M. A.; Mallick, S., Global supply chains, 1997, p. 194.

uncertainty of business decisions, particularly in a supply chain environment. Thus, appropriate methods and approaches are needed and have to be evaluated in order to help decision makers to cope with these circumstances.

Besides globalization, sustainability is seen as a second major challenge for companies in recent years.[6] As sustainability contains three dimensions (economic, environmental as well as social), complexity of planning increases when sustainability issues are considered.[7] Numerous motivations for sustainability-oriented business organization can be identified that can be classified into exogenous and endogenous drivers.[8] Focusing of the research presented here, internal drivers such as e.g. the corporate strategy[9] are covered, as they are influencing variables of supply chain design decisions. Therefore, only the major external motivations are listed: One major external motivation for implementing the concept of sustainability is caused by final customers. Since sustainability is not only relevant for companies but also for society, customers are changing their requirements regarding products and production conditions.[10] As recent cases illustrate, erratic behavior of companies regarding sustainability issues can result in damaging of reputation and consequently decreasing of competitive advantages.[11] In times of the World Wide Web and the resulting rapid flow of information, non-governmental organizations can put great pressure on companies in order to fulfill environmental and social standards and norms.[12] Governments and other regulative institutions are further important stakeholders. Since there are no consistent global regulatory standards, decision makers are confronted with regional regulative characteristics.[13] These circumstances limit options of business planning and increase planning complexity simultaneously. Finally, both competitors and investors can be identified as drivers for implementing sustainability orientation into the business strategy.[14]

[6] Cf. Kleindorfer, P. R.; Singhal, K.; van Wassenhove, L. N., Sustainable operations management, 2005, p. 482.
[7] Cf. Lee, D. H.; Dong, M.; Bian, W., sustainable logistic network, 2010, p. 159.
[8] Cf. Schrettle, S. et al., Turning sustainability into action, 2014, p. 76.
[9] Cf. Labuschagne, C.; Brent, A. C.; van Erck, R. P. G., sustainability performances, 2005, p. 376.
[10] Cf. Kleindorfer, P. R.; Singhal, K.; van Wassenhove, L. N., Sustainable operations management, 2005, pp. 484-485.
[11] Cf. Rao, P., Greening the supply chain, 2002, p. 632.
[12] Cf. Seuring, S.; Müller, M., sustainable supply chain management, 2008, p. 1699.
[13] Cf. Christmann, P.; Taylor, G., Globalization and the Environment, 2001, p. 441.
[14] Cf. El Ghoul, S. et al., corporate social responsibility, 2011, p. 2400; Thun, J.-H.; Müller, A., Green Supply Chain management, 2010, p. 126.

In addition to a changing environment of business activities, findings of recent studies illustrate that supply chain management plays a major role for the sustainability performance of companies.[15] Hence, most decision makers are driven to realign their processes and structures according to the triple bottom line concept.[16] The challenging topic for supply chain management that covers large parts or the entire value chain is ensuring compliance with sustainability issues in the whole supply network and not only in the own company. Hence, all supply chain stages, particularly the supplier stage, should be taken into account. Therefore, specific planning indicators and models are needed that do not only focus on economic objectives.[17] In addition to the ability to capture not only the economic dimension of sustainability, these indicators should be selected according to the relevant planning issues.

The following subchapter describes the planning issues that are considered in the present thesis. We focus on supply chain design, as the strategic part of supply chain management. Supply chain design has a high impact on the sustainable performance of a supply chain, since all other supply chain planning topics are based on these design decisions.[18] Therefore, we first introduce the relevant terminology.

1.2 Supply chain design as part of supply chain management

1.2.1 Supply Chain

The idea of the supply chain goes back to PORTER, who introduced the concept of vertical cooperation between companies.[19] In the literature, a large number of definitions can be found addressing the term supply chain. According to BEAMON, a supply chain can be defined as a cooperation of various companies working together to create a final product out of raw materials and deliver them to retailers. Between the chain members forward as well as backward flows occur. Traditionally, forward flows represent materials while backward flows represent information from one supply chain stage to another.[20] This definition points out the vertical integration of companies as well as the process-oriented

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[15] Cf. Green Jr, K. W. et al., Green supply chain management, 2012, p. 300.
[16] Cf. Zhu, Q.; Sarkis, J.; Lai, K.-h., green supply chain management, 2008, p. 261. The triple bottom line includes the economic, environmental and social dimension of sustainability. Cf. Elkington, J., Cannibals, 1997, pp. 69-96.
[17] Cf. Hervani, H.; Helms, M. M.; Sarkis, J., green supply chain management, 2005, p. 348.
[18] Cf. Beamon, B. M., Environmental and sustainability ethics, 2005, pp. 226-227.
[19] Cf. Porter, M. E., Competitive Advantage, 1985, p. 33.
[20] Cf. Beamon, B. M., Supply Chain, 1998, p. 281.

view of the concept of the supply chain. Since a large number of actors may be involved until the final product is produced and because single organizations might be part of other value-adding relationships as well, the term “chain” is not necessarily accurate. Thus, definitions in the literature also use the term supply network as a synonym for supply chain,[21] thus highlighting the interwoven structure of inter-organizational value-adding relationships. MENTZNER et al. defines supply chain “as a set of entities directly involved in the supply and distribution flows of goods, services, finances, and informations from a source to a destination”.[22] Also CHRISTOPHER mentioned that a supply chain is a network of entities that are involved creating value in the form of products and services delivered to the customer.[23] Keeping the topic of this thesis in mind, the last definition shows that value creating processes are the linking elements of the supply chain. The final customer, as the last participant in the network, is the origin of demanded value. This is also emphasized by IVANOV, who classified a supply chain as a network organization consisting of a number of various collaborating companies with the goal to “acquire raw materials, convert these raw materials into specified final products, and deliver these final products to customers”.[24] In addition, it is stated that the supply chain members use a wide range of concepts and methods, “to make supply chains agile, responsive, flexible, robust, sustainable, cost-effective, and competitive in order to increase customers´ satisfaction […].”[25] Particularly during the last decade, backward flows in the supply chain were analyzed. Under the topics of reverse- as well as closed-loop supply chains, materials, intermediate and final products are not only considered in their forward but also in their backward flows. Consequently, a closed-loop supply chain can be defined as “[…] a system to maximize value creation over the entire life cycle of a product with dynamic recovery of value from different types and volumes of returns over time”.[26]

Figure 1.1 summarizes and illustrates the key aspects of the above mentioned definitions.

[21] Cf. Christopher, M., Supply Chain, 2005, p. 5.
[22] Mentzner, J. et al., supply chain, 2001, p. 4.
[23] Cf. Christopher, M., Supply Chain, 2005, p. 5.
[24] Ivanov, D., supply chain strategy, 2010, p. 4000.
[25] Ivanov, D., supply chain strategy, 2010, p. 4000.
[26] Guide, V. D. R.; Van Wassenhove, L. N., Closed-Loop Supply Chain, 2009, p. 10.

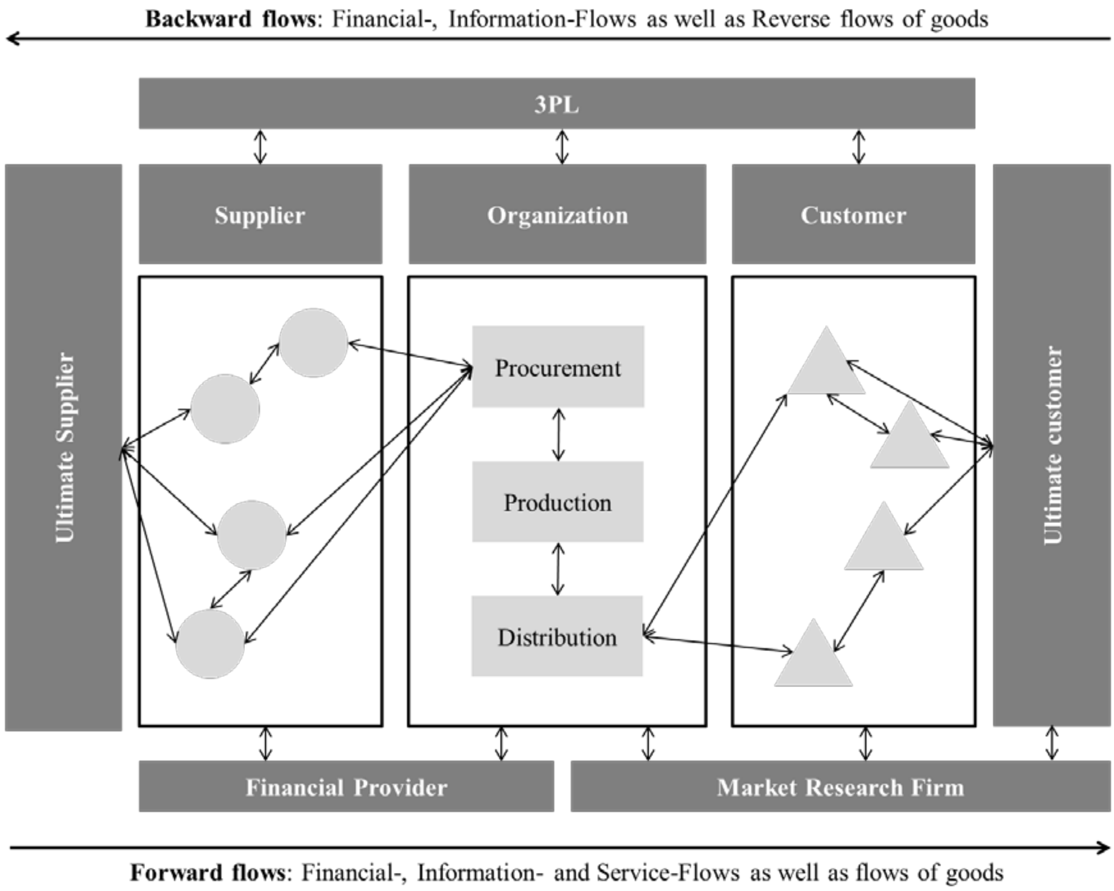

Figure 1.1: Illustration of a supply chain[27]

For the objective of this work, we use the following definition to describe our understanding of a supply chain:

A supply chain is an integrated network organization consisting of various entities which collaborate with each other in order to acquire raw materials, convert them, after cycling various production processes, into final products and deliver these final products to customers with the goal to increase customers satisfaction related to the demanded values. Considering backward flows of goods in addition, the supply chain is defined as a closed-loop supply chain.

This definition highlights various characteristics that are important for the following chapters. First, it is necessary to identify which values are relevant when designing a sustainable supply chain according to the economic, environmental as well as social dimension of sustainability. Second, companies need to consider all production steps that

[27] The figure is based on Bowersox, D. J.; Closs, D. J.; Cooper, M. N., Supply chain, 2007, p. 6 and Mentzner, J. et al., Supply Chain, 2001, p. 5.

are necessary to create the final product and deliver it to the customer. Finally, both company internal processes and those related to other supply chain entities are relevant when talking about a supply chain.

1.2.2 Supply Chain Management

In the last decades management topics regarding supply chain issues emerged. Besides the developments of concepts and practical application cases, also definition approaches regarding supply chain management have increased. Simultaneously, no common definition is known, that includes all relevant issues of this topic. Thus, we introduce some relevant definitions and discuss the important findings in order to develop a useful definition in context of the research field of this thesis.

CHRISTOPHER aligned the definition of supply chain management closely to supply chain characteristics by saying "Supply Chain Management is the management of upstream and downstream relationships with suppliers and customers to deliver superior customer value at less cost to the supply chain as a whole".[28] This definition points out the intercompany-wide characteristics of management topics in the supply chain context, leading to a higher complexity in decision making. SIMCHI-LEVI, KAMINSKY and SIMCHI-LEVI define supply chain management as „[…] a set of approaches utilized to efficiently integrate suppliers, manufacturers, warehouses, and stores, so that merchandise is produced and distributed at the right quantities, to the right locations, and at the right time, in order to minimize system-wide costs while satisfying service level requirements."[29] This definition highlights not only the management objects and goals but also emphasizes that the management of supply chains asks for a broad set of techniques and approaches in order to be successful. The definition of the supply chain management task according to STADTLER reaches deeper into the cooperation between the various supply chain participants. He defines supply chain management as „[…] the task of integrating organizational units along a supply chain and coordinating material, information and financial flows in order to fulfill (ultimate) customer demands with the aim of improving competitiveness of a supply chain as a whole."[30] The reference to competitiveness emphasizes the strategic relevance of supply chain management for companies´ success.

[28] Christopher, M., Supply Chain Management, 2005, p. 5.
[29] Simchi-Levi, D.; Kaminsky, P.; Simchi-Levi, E., Supply Chain, 2000, p. 1.
[30] Stadtler, H., Supply Chain, 2002, p. 9.

Recognizing the broad field of tasks included in the supply chain management concept, researchers developed supply chain management frameworks to distinguish different supply chain management topics. Traditionally, these frameworks use the time frame as a criterion for delimitation. ROHDE et al. also use company sectors, which are involved in the supply chain management topics, as a second criterion.[31] According to their planning framework, strategic network planning is a long-term planning topic in which all supply chain areas (purchasing, production, distribution as well as sales) are involved. The other planning topics are basically mid-term-oriented (master planning, demand planning, production- and distribution planning and material requirements planning) or short-term topics (scheduling, transportation planning and available to promise).[32]

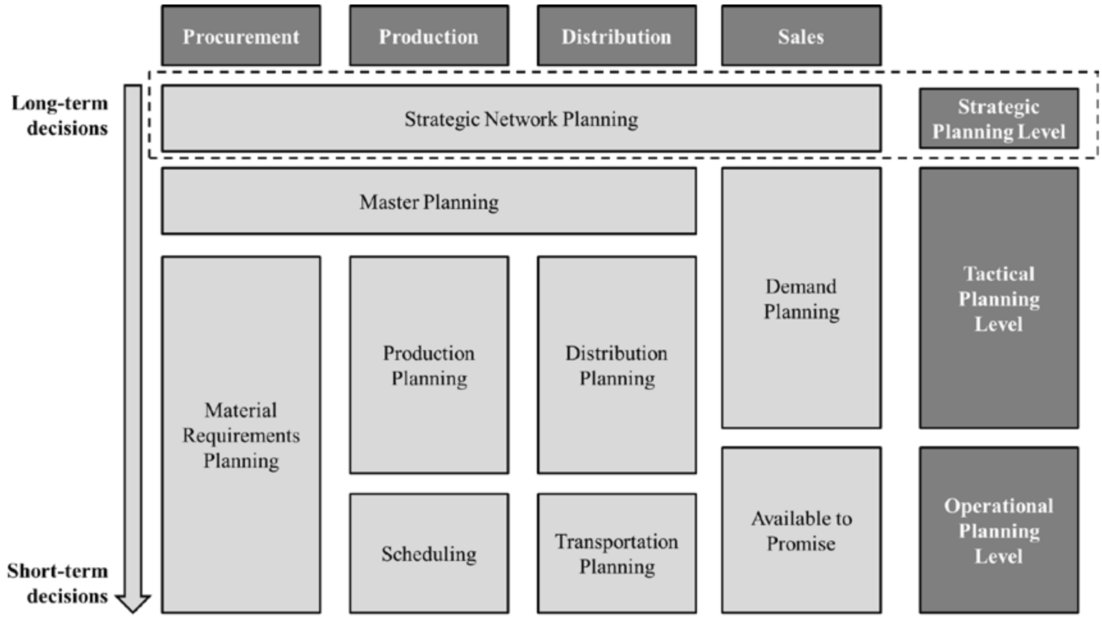

Figure 1.2: Supply Chain Planning Matrix[33]

Another framework is presented by IVANOV.[34] The main outcome is the interaction of various supply chain management topics, starting from the definition of supply chain goals and going further until supply chain adaption.

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[31] Cf. Rohde, J.; Meyr, H.; Wagner, M., Supply Chain Planning Matrix, 2000, p. 10.
[32] See Figure 1.2.
[33] The figure is based on Rohde, J.; Meyr, H.; Wagner, M., Supply Chain Planning Matrix, p. 10.
[34] Cf. Ivanov, D., supply chain strategy, 2010, pp. 3999-4017.

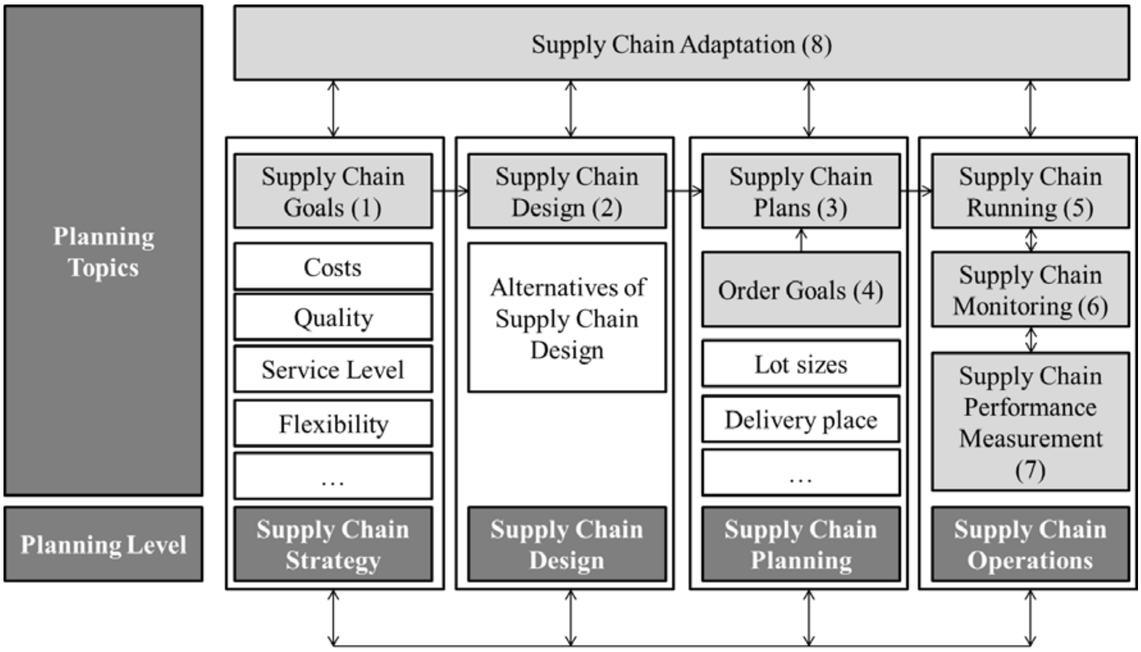

Figure 1.3: Supply Chain Planning Framework[35]

The important findings of this approach are the interactions between the management topics. While most research argues that the supply chain management fields can be arranged according to a hierarchical concept, IVANOV particularly illustrates the interrelations. Following this assumption, it is necessary to consider both upstream and downstream impacts when managing a specific supply chain topic. Transferring this finding on the supply chain design topic, as it is the key aspect in the present research, on the one hand supply chain goals and on the other hand impacts on the tactical as well as the operational supply chain management level need to be integrated into the planning considerations.

1.2.3 Supply Chain Design

As mentioned above, supply chain design is the strategic element of supply chain planning. The time horizon of the planning topics has a long-term character and lasts from three up to twenty years. HARRISON defined supply chain design as "[…] the process of determining the supply chain infrastructure – the plants, distribution centers, transportation modes and lanes, production processes, etc. that will be used to satisfy customer demand."[36] The definition highlights the main topic of supply chain design: the infrastructure planning. In addition to the location of facilities, supply chain design incorporates decisions regarding the allocation of flows between the various supply chain

[35] The figure is based on Ivanov, D., supply chain strategy, 2010, pp. 4004-4005.
[36] Harrison, T. P., Supply Chain Design, 2001, p. 413.

stages.[37] As SANTOSO et. al. pointed out, supply chain design also includes decisions of both capacity and technology of facilities.[38] Hence, capacity is a crucial determinant for economies of scale with a focus on both financial and environmental issues. Furthermore, installed technologies influence the environmental performance according to their production-oriented characteristics. These rather technical aspects of supply chain design incorporate important impacts on the sustainable performance of supply chains.[39] Since the design of a supply chain design is normally multi-product oriented, it is also possible to analyze Make-or-buy decisions.[40] This can be extended to the intermediate product level. Summarizing it, supply chain design has an impact on all company functions. Therefore, it is necessary to involve all relevant functions into a supply chain design planning team in order to identify and consider all relevant planning issues. Once a supply chain design is fixed, it is very complicated, expensive or even impossible to change it. Hence, a multi-period planning environment should be considered and forward-looking analyses have to be performed in order to get a robust solution.[41]

A cost-oriented definition of supply chain design is presented by SABRI and BEAMON: "The primary objective of strategic optimization models is to determine the most cost-effective location of facilities (plants and distribution centers), flow of goods throughout the supply chain (SC), and assignment of customers to distribution centers (DCs)."[42] This definition emphasizes the optimization topic of supply chain design. Hence, the application of optimization techniques is recommended. According to traditional approaches, the objective would be defined by either a financial figure, e.g. costs, or quality. However, the consideration of sustainability requires a multidimensional set of objectives, in accordance to the focused dimensions of sustainability. Besides costs, the net present value or the free cash flow, lead times, service levels and flexibility can be found in the literature.[43] Sustainable supply chain design approaches incorporate sustainability issues by introducing objectives such as carbon emission equivalents or other environmental and social measures.[44] Another, but rather simplified option is the integration of costs that are

[37] Cf. Truong, T. H.; Azadivar, F., configuration of supply chains, 2005, p. 2220.
[38] Cf. Santoso, T. et al., supply chain network design, 2005, p. 96.
[39] This issue is discussed in chapter 2.
[40] Cf. Truong, T. H.; Azadivar, F., configuration of supply chains, 2005, p. 2220.
[41] Both ex ante and ex post approaches as stochastic programming and scenario analysis or sensitivity analysis respectively, can be applied. See chapter 4.2 for details.
[42] Sabri, E. H.; Beamon, B. M., supply chain design, 2000, p. 581.
[43] Cf. Ziegler, H.-P., Supply Chain Network Design, 2012, p. 8.
[44] For a recent literature review cf. chapter 3.3.

associated with sustainability dimensions in order to align the planning environment according to a single financial objective.[45] However, this approach is hard to apply in practical application cases, as the impacts of supply chain design on sustainable performance objectives are both difficult to quantify and in many cases impossible to transform into cost-based values. Therefore, multi-objective planning approaches have been developed.[46]

1.3 Research questions and methodology

Based on the short discussion on sustainability and supply chain design as outlined above, it can be summarized that decisions made on the supply chain design level have a strong impact on the environmental performance of a supply chain. In the present research we focus on impacts of customers´ behavior on supply chain design decisions. Following the basic assumptions of supply chain management, fulfillment of customer´s demand is of outstanding importance in supply chain management.[47] Taking a broader sense of customers´ demand into account, demand is not only determined by the quantity of products but also by the quality and further performance characteristic. Therefore, the supply chain design should be chosen that fulfills customers´ requirements best. Following this, the first research question is:

Research question 1:

What is the appropriate way to design a supply chain according to environmentally-oriented requirements of customers?

In addition, customers influence supply chains by their behavior regarding the usage of products. This is particularly of interest, when a company wants to perform a lifecycle analysis (LCA) of a product. According to the defined scope of the LCA, not only the product creation processes need to be considered, but also usage as well as post-usage processes as backward logistics, recycling, remanufacturing and disposal. In this context, the behavior of customers determines important issues as the quantity and the quality of returned products. Particularly in times of scarcity of raw materials, alternative procedures to satisfy the demand of raw materials are of relevance for production companies.

[45] See e.g. Elhedhli, S.; Merrick, R., Green supply chain network design, 2012, pp. 370-379.
[46] See the literature in chapter 3.3.
[47] See supply chain management definitions above.

Usually, a lack of knowledge regarding these customer-specific planning parameters exists, particularly in multi-period planning situations.[48] Accordingly, planning approaches need to be used that incorporates uncertainty. Hence, the second research question is:

Research question 2:

What is the impact of customers´ behavior regarding both usage and return of products on supply chain design decisions in an environmentally-conscious closed-loop supply chain environment?

In literature, a few basic research concepts for supply chain design can be identified. For instance, according to SEURING and MÜLLER who performed a literature review focusing on sustainable supply chain management, five different research methodologies can be differentiated:

(1) Theoretical and conceptual approaches
(2) Case studies
(3) Surveys
(4) Modeling approaches
(5) Literature reviews[49]

While theoretical and conceptual approaches are not focusing on specific business situations, both case studies and surveys are based on practical applications. Case studies are used to analyze a problem by identifying relationships of one certain example to a generalized set of cases. In contrast, surveys are used to gather a broad dataset that is used to test hypotheses empirically. Mathematical models represent certain business situations in order to evaluate specific topics by implementing datasets and solving the model. In addition, various data constellations can be tested to find evidence concerning the considered research questions. In the present research we focus on quantitative models for sustainable supply chain design. Accordingly, we briefly delineate optimization, simulation and heuristic approaches for supply chain design. The application of mathematical optimization is a very common approach in order to design a supply chain. The advantage of this approach is the ability to get an optimal solution for the supply chain design. Therefore it is necessary to represent the relevant supply chain characteristics mathematically.

[48] Cf. Ilgin, M. A.; Gupta, S. M., Environmentally conscious manufacturing, 2010, p. 569.
[49] Cf. Seuring, S., Müller, M., sustainable supply chain management, 2008, p. 1702.

For this purpose, supply chain locations are interpreted as nodes and the flow allocations as arcs. Both nodes and arcs are then characterized with various parameters in detail. In accordance with the degree of freedom, decision variables that represent the above mentioned supply chain design topics are specified. In real-world cases, the complexity of these models increases rapidly, caused by plenty of network characteristics and other factors as the dynamic planning environment or uncertainty. In those cases, classical optimization techniques are replaced by heuristics, e.g. evolutionary algorithms, to get good results.[50] Finally, simulation approaches compare a larger number of fixed supply chain designs to find the best set-up.[51]

According to the structure of the mentioned research questions, we develop appropriate mathematical models. Hence, a quantitative research method is applied in order to analyze the research questions 1 and 2. Research question 1 is treated in chapters two and three using two different models. Research question 2 is analyzed in chapter four.

1.4 Outline of the thesis

The outline of this thesis is organized as follows. After the general relevance of the topic as well as the research questions and methodology have been illustrated in this chapter, we propose three chapters which deal with the mentioned research questions.

In chapter 2 a robust optimization approach is developed in order to design an environmentally conscious supply chain. The environmental performance of the supply chain is considered on the product level. It is assumed that customer requirements regarding the environmental performance of a product is a key motivation for companies to realign their supply chain according to environmental issues, as a direct impact on the revenue situation can be identified. The research question is treated, how customers´ requirements affect sustainable supply chain design decisions. Chapter 2.1 introduces the topic. As customers´ requirements are assumed to be pre-defined parameters, they are modeled as being uncertain. Chapter 2.2 deals with environmental issues that are influenced by supply chain design decisions. In addition, a literature review regarding sustainable supply chain design modelling approaches is proposed. Chapter 2.3 gives basic insights into the robust

[50] Cf. Melo, M. T.; Nickel, S.; Saldanha-da-Gama, F., supply chain management, 2009, p. 409.
[51] Cf. Persson, F.; Olhager, J., simulation of supply chain designs, 2002, p. 234.

optimization approach. After the presentation of the model assumptions, both the model objective function and the constraints are proposed. Finally, the model is evaluated using a numerical example with an integrated scenario analysis. A conclusion completes the second chapter. The appendix contains the relevant parameter and variable notations.

Following the research question that is analyzed in chapter 2, chapter 3 focuses on customers that are characterized by a demand function which decreases in case of increasing negative environmental impacts of a product. After an introduction, chapter 3.2 includes a description of sustainable supply chain design issues in the first subchapter. The derivation of the assumption of an environmentally sensitive customer demand is presented in a second subchapter. The status-quo of relevant, optimization models that can be found in the literature is proposed in chapter 3.3. Based on the identified lack of models, an optimization model is proposed in chapter 3.4. Therefore, chapter 3.4.1 contains a description of both the underlying problem and the model assumptions. The mathematical model is presented in chapter 3.4.2. It is featured with a decreasing piecewise-linear demand as a function of the environmental performance of a product which is calculated in a customer-specific way. Hence, the model solution is able to give important insights, how a decision maker should allocate the production steps along the supply chain for each customer. Therefore, we integrate a multi-step production process as well as intercompany flows of intermediate products in a multi-period, multi-product planning environment. A numerical example emphasizes the advantages of considering customer´s demand behavior while designing a supply chain. The last subchapter summarizes the findings and gives further ideas for research directions.

In chapter 4, not only forward but also reverse network flows are considered in a supply chain design problem. We propose an environmentally conscious robust closed-loop supply chain design model. After an introduction in chapter 4.1, environmental aspects in supply chain design are discussed in chapter 4.2. A short introduction to possible approaches to consider uncertainty in supply chain design models and robust optimization is presented in chapter 4.3. The model development is focused in chapter 4.4. After the presentation of the relevant assumptions and notations, both the objective functions and constraints are proposed. We assume that the quantity as well as the quality of reverse flows are uncertain and therefore apply the robust optimization approach presented by

MULVEY, VANDERBEI and ZENIOS.[52]. As we consider both costs and carbon equivalents as objective values, we propose a multi-objective optimization approach. The model is applied to an anonymized real-world case that is described in chapter 4.5.1. The results illustrate the advantages of a robust optimization model compared to a deterministic one. A conclusion is drawn in chapter 4.6 and future research ideas are presented.

Chapter 5 presents guidelines to use the presented models in practical application cases. The major steps for implementing a successful supply chain design project considering environmental issues are illustrated.

Finally, chapter 6 summarizes the thesis. The findings concerning the defined research questions are specified and directions for future research in the area of sustainable supply chain design are depicted.

[52] See Mulvey, J. M.; Vanderbei, R. J.; Zenios, S. A., Robust Optimization, 1995.

2 A robust optimization approach for designing an environmentally conscious supply chain with consideration of customer-specific environmental product requirements[53]

2.1 Introduction

With the increasing application of global sourcing activities and the allocation of facilities and production processes all around the world, not only the distance in value creating networks but also the complexity of supply chain planning has grown. In addition, sustainability has become more and more critical for companies.[54] Beside financial goals, both environmental and social issues need to be considered according to the triple bottom line approach.[55]

According to the examination of prior research, the motivation of companies to adopt environmental and social practices can be found particularly in pressures of various stakeholders. In this context, especially customers are of interest, since their behavior has a considerable impact on the financial result of enterprises. If a company does not comply with customers´ requirements, customers might reduce their orders or will not be ready to pay a given price.[56] Examples of companies, that failed to include sustainability issues, illustrate the risk of damaging reputation resulting in lower sales volume.[57] Thus, we focus on customers´ requirements as one of the major drivers for adopting sustainable practices. Following the growing stream of literature, we analyze the interaction of economic and environmental issues in a supply chain design context. Therefore we exclude the consideration of the social dimension of sustainability. Following this assumption, we consider the environmental requirements of customers via the environmental impact of the ordered products.

Since it is not possible to exactly predict customers´ behavior and since supply chain design decisions are exposed to changes regarding the planning parameters, it is necessary

[53] This chapter is published as Altmann, M., environmentally conscious supply chain, 2014.
[54] Cf. Kleindorfer, P. R.; Singhal, K.; Van Wassenhove, L. N., Sustainable Operations Management, 2005, p. 482; Srivastava, S. K., Green supply-chain management, 2007, p. 53.
[55] Cf. Elkington, J., Cannibals, 1997, p. 71.
[56] Cf. Rao, P.; Holt, D., green supply chains, 2005, p. 906.
[57] Cf. Preuss, L., Corporate Greening, 2005, p. 127.

to develop a model under uncertainty considerations. In the context of supply chain design problems in which decision makers are often not able to restructure the supply chain in the short term, a solution should be found that is robust to possible parameter variations. Therefore, we apply the robust optimization technique[58] to handle uncertainty in our decision support tool.

The rest of the paper is organized as follows: In the next section we analyze the impact of supply chain design on the environmental supply chain performance and review the relevant literature considering environmentally conscious supply chain design models. The basic concept of robust optimization is presented in section 3. In section 4 we present a supply chain design model under consideration of uncertain environmental product requirements of the customers. A numerical example illustrates the advantages of the proposed model. Finally, the conclusions of the paper are drawn.

2.2 Sustainable supply chain design

2.2.1 Sustainability considerations in supply chain design decisions

Supply Chain Management is the management of "[…] a network of organizations that are involved, through upstream and downstream linkages, in the different processes and activities that produce value in the form of products and services in the hand of the ultimate customer".[59] According to IVANOV (2010) the planning dimensions supply chain strategy, supply chain design, supply chain planning and supply chain operations are highly interlinked. As supply chain design involves decisions about the structure of a value network (e.g. facility location and capacity allocation decisions), it has a large impact on the consecutive areas of planning.[60] As ARONSSON and BRODIN (2006) examined, strategic supply chain design decisions affect the environmental impact of a supply chain more than tactical or operational decisions.[61] Hence, we focus on supply chain design in this paper as one important element of the supply chain management concept.

Supply chain design decisions can be classified into location and allocation decisions as well as flow planning decisions. While location decisions determine the supply chain

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[58] Cf. Mulvey, J. M.; Vanderbei, R. J.; Zenios, S. A., Robust Optimization, 1995, pp. 264-281.
[59] Christopher, M., Supply Chain Management, 2005, p. 17.
[60] Cf. Ivanov, D., supply chain strategy, 2010, pp. 4004-4005.
[61] Cf. Aronsson, H.; Brodin, M. H., environmental impact, 2006, p. 397.

nodes and therefore the supply chain structure, allocation decisions characterize the nodes in detail. In contrast, flow decisions link the considered supply chain stages and hence determine logistic processes. Starting with the supplier level, an environmentally conscious selection of business partners at this stage contributes to a higher environmental supply chain performance.[62] Hence, facilities and production resources can be characterized by their environmental impact, the number and locations of production facilities as well as the allocation of production capacities play a major role in the environmental assessment of supply chain processes. Closely interlinked to these decisions is investment planning. An investment in both new facilities and production equipment, featured with a higher level of ecological efficiency, improve the environmental performance. In addition, bundling production at certain locations, leads to an increase of the utilization ratio of the facilities, which in turn may influence the environmental performance positively. Furthermore, the environmental impact of various transportation modes needs to be considered.[63]

Although environmental norms and standards (e.g. GRI) may provide some advice, many companies struggle with determining the right indicators related to their own environmental purposes.[64] Since a decision maker has an aggregated view on the value network when designing a supply chain, we use carbon equivalents as a general performance indicator to analyze the basic relations between supply chain design decisions, environmental performance and customers´ requirements in this paper.

2.2.2 Literature Review

Reviewing the literature of sustainable supply chain management leads to the assumption that most approaches are favoring a qualitative research stream developing concepts or frameworks, while quantitative models are still underrepresented.[65] Focusing on strategic supply chain design models, only a few approaches can be identified which consider environmental or social coefficients (Table 2.1).

[62] Cf. Goebel, P. et al., sustainable sourcing, 2012, p. 7.
[63] Cf. McKinnon, A. C., Logistics, 2003, p. 673.
[64] Cf. Hervani, A. A.; Helms, M. M.; Sarkis, J., green supply chain management, 2005, p. 341.
[65] Cf. Seuring, S.; Müller, M., sustainable supply chain management, 2008, p. 1702; Brandenburg, M. et al., sustainable supply chain management, 2014, p. 300.

Table 2.1: Sustainable supply chain design models[66]

Research	Network stages						Modelling					Objectives
	Supply	Production	Distribution	Redistribution	Customer	Logistics	MILP	MINLP	SMIP	RMIP	FGP	
Chaabane et al. 2011	x	x	x			x	x					TC, TE
Chaabane et al. 2012	x	x	x			x	x					TC, TE
Cruz 2008		x	x		x	x		x				TP, TE, Risk
Cruz/Matsypura 2009		x	x		x	x		x				Net Return, TE, Risk
Cruz/Walkobinger 2008		x	x		x	x		x				TP, TE, Risk
Elhedhli/Merrick 2012		x	x			x		x				Pollution costs of the environment (carbon emissions)
Guillen-Gosal-bez/Grossmann 2009		x	x		x	x			x			NPV, EI
Hugo/Pestikopoulos 2005	x	x			x		x					NPV, EI
Nagurney/Toyasaki 2003		x	x		x			x				Profit, TE
Nagurney/Nagurney 2010		x	x		x							TC, TE
Quariguasi Frota Neto et al. 2008		x	x		x	x		x				TC, EI
Pinto-Varela et al. 2011	x	x	x				x					TP, EI

[66] Abbreviations: EI: Environmental Impact; FGP: Fuzzy Goal Programming; MILP: Mixed-integer linear programming; MINLP: Mixed-integer nonlinear programming; NPV: Net present value; SMIP: Stochastic mixed-integer programming; RMIP: Robust mixed-integer programming; TC: Total costs; TE: Total emissions; TP: Total profit.

Pishvaee et al. 2012		x	x							x		TC, Social responsibility
Ramudhin 2008	x	x	x		x	x	x					TC, TE
Tsai/Hung 2009	x	x	x								x	TC, TE
Wang et al. 2011	x	x			x			x				TC, TE
You et al. 2012		x	x			x	x					TC, TE

Furthermore, only very few models capture uncertainty. Guillen-Gosalbez and Grossmann (2009) present a bi-criterion optimization approach and incorporate uncertainty on the environmental impact level. Therefore, they modify classical stochastic programming by introducing a pre-defined probability level to control variability of the environmental impact.[67] Pishvaee, Razmi and Torabi et al. (2012) propose a robust possibilistic programming approach for supply chain design problems by combining advantages of both possibilistic programming and robust programming to capture various uncertain parameters.[68] In addition, a lack of research can be identified that integrates customer requirements regarding the environmental impact of products into a modeling approach. Similar to supply chain design models that focus on monetary objectives only and which often integrate lead-times as a customer requirement,[69] it can be assumed that environmental product characteristics, as required by customers, have an impact on supply chain design decisions. To the best of our knowledge, no model has been published yet that covers these considerations in total.

2.3 Robust Optimization

In case of long-term planning, uncertainty of planning data becomes a major issue. Consequently, capturing uncertainty is an important element of supply chain design modeling. Focusing on supply chain planning problems Peidro et al. (2009) mentioned that uncertainty is particularly of high relevance regarding demand, production as well as supply data.[70] Following the assumption that requirements of customers regarding environmental issues could not be predicted with certainty, we consider uncertainty at the demand

[67] See Guillen-Gosalbez, G.; Grossmann, I. E., Sustainable Chemical Supply Chains, 2009, pp. 99-121.
[68] See Pishvaee, M. S.; Razmi, J.; Torabi, S. A., responsible supply chain network design, 2012, pp. 1-20.
[69] See e.g. Hammami, R.; Frein, Y., design of global multi-echelon supply chains, 2013, pp. 2760-2775.
[70] Cf. Peidro, D. et al., supply chain planning under uncertainty, 2009, p. 401.

level in our approach by integrating both, environmental requirements and sales prices as uncertain parameters. Stochastic programming, fuzzy programming, and robust optimization provide different approaches to implement uncertain parameters into mathematical models. Compared to the other two mentioned approaches, the main objective of robust optimization is the detection of a solution that is less sensitive to varying input data (solution robustness). In addition, the solution should be feasible in a possible set of uncertain scenarios (model robustness). Already MULVEY, VANDERBEI and ZENIOS (1995) mentioned that robust optimization is preferable against other optimization approaches for planning situations with a high level of uncertainty, particularly when the decision maker is not able to change a decision once it is fixed in the short term.[71] Since this description is very well suited for supply chain design problems, we apply the robust optimization approach to our environmentally conscious supply chain design model. In the literature various robust optimization techniques are discussed.[72] Basically, they differ in the assumptions concerning the probability distribution of uncertain parameters. According to the approach proposed by KOUVELIS, KURAWARWALA and GUTIERREZ (1992), the solution of a planning model should be robust regarding variations of all considered parameters.[73] Hence, all possible situations are considered as equiprobable, including worst case scenarios. Therefore, this assumption leads to a very conservative planning solution. As an advantage of this approach, information about possibility values or probability distribution functions is not required. In addition, the decision maker knows that the computed solution of the model is robust even to a worst case scenario.[74] Since this approach is based on a very pessimistic view, the solution would lead to higher costs compared to more optimistic models. The approach proposed by MULVEY, VANDERBEI and ZENIOS (1995) considers a trade-off between both robustness and the cost of robustness. Using probabilities, the possible scenarios can be weighted by the decision maker.[75] In our view, the robust optimization approach of MULVEY, VANDERBEI and ZENIOS (1995) is also suitable for the above mentioned planning problem, since we incorporate uncertainty on the level of customers´ requirements. The application of the approach of KOUVELIS, KURAWARWALA and GUTIERREZ (1992) would lead to the assumption that a situation, in which all customers have very high requirements regarding environmentally

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[71] See Mulvey, J. M.; Vanderbei, R. J.; Zenios, S. A., Robust Optimization, 1995. p. 269.
[72] See Pishvaee, M. S.; Razmi, J.; Torabi, S. A., responsible supply chain network design, 2012, pp. 6-7.
[73] See Kouvelis, P.; Kurawarwala, A. A.; Gutierrez, G. J., robust, 1992, pp. 287-303.
[74] Cf. Ben-Tal, A.; El Ghaoui, L.; Nemirovski, A., Robust Optimization, 2009, p. xii.
[75] Cf. Mulvey, J. M.; Vanderbei, R. J.; Zenios, S. A., Robust Optimization, 1995, p. 265.

friendly products, is equiprobable to a parameter set that is characterized by heterogeneous requirements. It can be stated that this is extremely unrealistic. Due to the flexible and thus problem-specific evaluation of the probability of parameter values, the selected robust optimization approach of MULVEY, VANDERBEI and ZENIOS (1995) is applicable to many real business cases.[76]

By integrating environmental product requirements of customers into a supply chain design model and incorporating uncertainty using the robust optimization technique, we try to make a contribution for answering the question, whether it pays to align supply chain design decisions to the concept of sustainability or not and provide a robust decision support approach in such a planning environment.

2.4 Model description

2.4.1 Assumptions

We assume a three echelon supply chain with numerous suppliers, production facility locations and customers. To execute the production of a product, various production steps need to be processed for which appropriate resources need to be installed at each production facility. It is not required to execute all steps in the same facility, thus intercompany flows are considered. As mentioned in section 2, a proactive environmental supply chain strategy might help companies to meet customers´ demand. Therefore, we assume that investments in environmentally friendly production processes, machines as well as facilities offer the opportunity to increase the environmental performance of a product. By allocating production steps next to customers, logistical transactions might be reduced. Obviously, there is a trade-off between economic and environmental performance. We capture this trade-off by considering customers´ environmental requirements as a constraint. Since we assume uncertainty associated with the customer-specific environmental impact requirements, we apply a robust optimization technique based on YU and LI (2000).[77]

2.4.2 Model presentation

First, we present the elements of the objective function as formulated in the equation (2.1). Usually, structural decision variables are distinguished from flow variables. While

[76] See e.g. Yu, C.-S.; Li, H.-L., robust optimization, 2000; Leung, S. C. H. et al., robust optimization model, 2007.

[77] See Yu, C.-S.; Li, H.-L., robust optimization, 2000, pp. 385-397.

structural variables are fixed before the uncertain situation occurs, flow decision variables can be adjusted according to the relevant scenario.[78] We assume that both structural and decision variables determine one solution for all scenarios. The objective function contains the mean value of the discounted free cash flow as well as the linearized formulation of the deviation of scenario-specific objective values to the mean objective value. In addition, the last term of (2.1) determines violations of the customer-specific environmental impact constraint. The formulation of the objective function is a modified version of the objective function used by YU and LI (2000).[79] With the second and third term of the objective function, both model and solution robustness are integrated.

$$Max\, Z = \sum_{\tau \in \mathrm{T}} \rho_\tau Z_\tau - \lambda \sum_{\tau \in \mathrm{T}} \rho_\tau \left[\left(Z_\tau - \sum_{\tau' \in \mathrm{T}} \rho_{\tau'} Z_{\tau'} \right) + 2\theta_\tau \right] - \omega \sum_{\tau \in \mathrm{T}} \rho_\tau \sum_{c \in C} \sum_{p \in P} \sum_{t \in T} \delta_{cpt\tau} \tag{2.1}$$

The scenario-specific mean value is calculated by the discounted free cash flow to the firm ($fcf_{t\tau}$) and the time-adjusted terminal value (tv). The weighted average cost of capital ($WACC$) is used as a discount factor.[80]

$$Z_\tau = \sum_{t \in T} \frac{fcf_{t\tau}}{(1 + WACC)^t} + \frac{tv}{(1 + WACC)^T}, \quad \forall \tau \in \mathrm{T} \tag{2.2}$$

To determine the free cash flow for each period (2.3), the ebitda (2.4) is tax-adjusted by using the facility specific tax rate (tax_{ft}). In addition tax advantages of depreciations (dep_{ft}) less capital expenditures ($Invest_t$) (2.3) are integrated.

$$fcf_{t\tau} = \sum_{f \in F} \left(1 - tax_{ft}\right) \cdot ebitda_{ft\tau} + \sum_{f \in F} tax_{ft} \cdot dep_{ft} - Invest_t, \quad \forall t \in T, \tau \in \mathrm{T} \tag{2.3}$$

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[78] Cf. Mulvey, J. M.; Vanderbei, R. J.; Zenios, S. A., Robust Optimization, 1995, p. 265.
[79] Cf. Yu, C.-S.; Li, H.-L., robust optimization, 2000, p. 389.
[80] The underlying deterministic model is a modified version of Kohler, K., Supply Chain Design, 2008, pp. 119-157.

$$ebitda_{ft\boldsymbol{\tau}} = \sum_{c\in C}\sum_{p\in P}\sum_{l\in L} TP_{fcplt}PP_{cpt\tau} - fix_{ft}x_{ft} - cf_{ft}rx_{ft} - \sum_{r\in R} fixR_{frt}y_{frt} - \sum_{r\in R} cr_{frt}ry_{frt} - \sum_{c\in C}\sum_{p\in P}\sum_{r\in R}\sum_{q\in Q^*} PA_{fcprqt}PC_{fprqt} - \sum_{g\in F}\sum_{c\in C}\sum_{p\in P}\sum_{r\in R}\sum_{q\in Q}\sum_{l\in L} TAIP_{fgcprqlt}PC_{fprqt} - \sum_{g\in F}\sum_{c\in C}\sum_{p\in P}\sum_{r\in R}\sum_{q\in Q}\sum_{l\in L} TAIP_{fgcprqlt}TCIP_{fgprqlt} - \sum_{c\in C}\sum_{p\in P}\sum_{l\in L} TP_{fcplt}TCP_{fcplt} - \sum_{s\in S}\sum_{c\in C}\sum_{m\in M}\sum_{l\in L} SA_{sfcmlt}\left(SC_{smt} + TSC_{sfmlt}\right) \tag{2.4}$$

The ebitda is calculated in a facility-specific way. Components are the total revenue, calculated via the product of the amount of products sold (TP_{fcplt}) and the product prices ($PP_{cpt\tau}$), less the fix costs for opening (fix_{ft}) and closing facilities (cf_{ft}), installing ($fixR_{frt}$) and reinstalling (cr_{frt}) resources, production costs (PC_{fprqt}), transaction costs of intercompany flows for intermediate products ($TCIP_{fgprqlt}$) as well as delivery (TCP_{fcplt}), purchasing (SC_{smt}) and transportation costs (TSC_{sfmlt}). In all cases, the cost parameters are multiplied by the regarding amounts. As mentioned above the product price is uncertain.

$$dep_{ft} = depF_{ft}x_{ft} + \sum_{r\in R} depR_{frt}y_{frt} \quad \forall\, f \in F, t \in T \tag{2.5}$$

Depreciations on facility ($depF_{ft}$) and resource level ($depR_{frt}$) are calculated in constraint (2.5).

$$tv = \sum_{f\in F} tvf_f + \sum_{f\in F}\sum_{r\in R} tvr_{fr} \tag{2.6}$$

The terminal values of the facilities (tvf_f) (2.7) and resources (tvr_{fr}) (2.8) are calculated by summarizing capital expenditures ($invF_{ft}$, $invR_{frt}$) over all periods less depreciations ($depF_{ft}$, $depR_{frt}$).

$$tvf_f = \sum_{\substack{t\in T\\ t=1}} invF_{ft}x_{ft} + \sum_{\substack{t\in T\\ t>1}} invF_{ft}\left(x_{ft} - x_{ft-1}\right) - \sum_{t\in T} depF_{ft}x_{ft} \quad \forall f \in F \tag{2.7}$$

$$tvr_{fr} = \sum_{\substack{t\in T\\ t=1}} invR_{frt}y_{frt} + \sum_{\substack{t\in T\\ t>1}} invR_{frt}\left(y_{frt} - y_{frt-1}\right) - \sum_{t\in T} depR_{frt}y_{frt} \quad \forall f \in F, r \in R \tag{2.8}$$

According to inequalities (2.9) and (2.10) only terminal values of those facilities and resources are integrated into the aggregated terminal value (2.6) which are opened in the last period.

$$tvf_f \le BigMx_{ft} \quad \forall f \in F, t = T \tag{2.9}$$

$$tvr_{fr} \le BigMy_{frt} \quad \forall f \in F, r \in R, t = T \tag{2.10}$$

Equation (2.11) illustrates the calculation of capital expenditures on facility ($invF_{ft}$) and resource ($invR_{frt}$) stages for each period.

$$Invest_t = \begin{cases} \sum_{f\in F} invF_{ft}x_{ft} + \sum_{f\in F}\sum_{r\in R} invR_{frt}y_{frt} & \forall\, t = 1 \\ \sum_{f\in F} invF_{ft}\left(x_{ft} - x_{ft-1}\right) + \sum_{f\in F}\sum_{r\in R} invR_{frt}\left(y_{frt} - y_{frt-1}\right) & \forall\, t > 1 \end{cases} \tag{2.11}$$

Constraints

The flow of final products (TP_{fcplt}) from facilities to customers according to their demand (D_{cpt}) on the specific product in each period is ensured in constraint (2.12):

$$\sum_{f\in F}\sum_{l\in L} TP_{fcplt} = D_{cpt} \quad \forall\, c \in C, p \in P, t \in T \tag{2.12}$$

The required production amounts of intermediate ($TAIP_{gfcprolt}$) and final products (PA_{fcprqt}) at each facility location are determined by considering constraints (2.13) and (2.14). $ExIn_{oq}$ indicates how many intermediate products of process o are necessary for the next production step q.

$$\sum_{l\in L} TP_{fcplt} = \sum_{r\in R^q} \sum_{q\in Q^{p*}} PA_{fcprqt} \quad \forall\, f \in F, c \in C, p \in P, t \in T \tag{2.13}$$

$$\sum_{r\in R^q} \sum_{q\in Q^{p*}} PA_{fcprqt}\, ExIn_{oq} = \sum_{g\in F} \sum_{l\in L} \sum_{r\in R} TAIP_{gfcprolt} \quad \forall\, f \in F, c \in C, p \in P, t \in T, o \in Q \tag{2.14}$$

Material flows (SA_{sfcmlt}) from suppliers to facilities required for production are calculated according to the relevant bill of materials (BoM_{rqm}).

$$\sum_{e\in F} \sum_{p\in P} \sum_{r\in R} \sum_{q\in Q} \sum_{l\in L} TAIP_{fecprqlt}\, BoM_{rqm} + \sum_{p\in P} \sum_{r\in R} \sum_{q\in Q^{p*}} PA_{fcprqt} BoM_{rqm} = \sum_{s\in S} \sum_{l\in L} SA_{sfcmlt}\ \forall\, f \in F, c \in C, m \in M, t \in T \tag{2.15}$$

Inequality (2.16) ensures the capacity of installed production resources ($CapR_{frt}$) according to the capacity utilization rate (β_{prq}):

$$\sum_{e\in F} \sum_{c\in C} \sum_{p\in P} \sum_{q\in Q} \sum_{l\in L} \beta_{prq} TAIP_{fecprqlt} + \sum_{c\in C} \sum_{p\in P} \sum_{q\in Q^{p*}} \beta_{prq} PA_{fcprqt} \le CapR_{frt} y_{frt} \quad \forall\, f \in F, r \in R, t \in T \tag{2.16}$$

Intermediate and final products can only be produced at opened facilities:

$$\sum_{e\in F} \sum_{c\in C} \sum_{p\in P} \sum_{r\in R} \sum_{q\in Q} \sum_{l\in L} TAIP_{fecprqlt} + \sum_{c\in C} \sum_{p\in P} \sum_{r\in R^q} \sum_{q\in Q^{p*}} PA_{fcprqt} \le BigM x_{ft} \quad \forall\, f \in F, t \in T \tag{2.17}$$

Constraint (2.18) links the binary decision variables for opening and installing facilities (x_{ft}) and resources (y_{frt}), respectively. Production resources can only be installed at opened facilities.

$$y_{frt} \le x_{ft} \quad \forall\, f \in F, r \in R, t \in T \tag{2.18}$$

Restructuring of facilities and resources over the planning horizon is determined according to inequalities (2.19) – (2.24).

$$0 \ge -x_{ft-1} + rx_{ft} \quad \forall f \in F, t > 1 \in T \tag{2.19}$$

$$0 \geq -(1 - x_{ft}) + r x_{ft} \quad \forall f \in F, t > 1 \in T \tag{2.20}$$

$$1 \geq x_{ft-1} + \left(1 - x_{ft}\right) - r x_{ft} \quad \forall f \in F, t > 1 \in T \tag{2.21}$$

$$0 \geq -y_{frt-1} + r y_{frt} \quad \forall f \in F, r \in R, t > 1 \in T \tag{2.22}$$

$$0 \geq -(1 - y_{frt}) + r y_{frt} \quad \forall f \in F, r \in R, t > 1 \in T \tag{2.23}$$

$$1 \geq y_{frt-1} + \left(1 - y_{frt}\right) - r y_{frt} \quad \forall f \in F, r \in R, t > 1 \in T \tag{2.24}$$

According to Yu and Li (2000) constraint (25) is modeled for linearization purposes.

$$\sum_{\tau' \in \mathrm{T}} \rho_{\tau'} Z_{\tau'} - Z_{\tau} - \theta_{\tau} \leq 0, \quad \forall \tau \in \mathrm{T} \tag{2.25}$$

Environmental impact modeling

To capture customers´ environmental product requirements, we introduce constraint (2.26). According to our assumptions, the requirement-data ($\Upsilon_{cpt\tau}$) are uncertain. $\delta_{cpt\tau}$ determines violations of the considered requirements.

$$\Pi_{cpt} - \Upsilon_{cpt\tau} - \delta_{cpt\tau} \leq 0, \quad \forall c \in C, p \in P, t \in T, \tau \in \mathrm{T} \tag{2.26}$$

Constraint (2.27) determines the product-specific environmental impact (Π_{cpt}) for each period. The allocation of production processes might differ from customer to customer. Hence, the environmental impact is calculated customer-specific as well. It contains the emissions of raw materials as well as emissions from the supply processes (EPS_{sfmlt}). In addition, emissions of intermediate ($EPI_{feprqlt}$) and final production processes (EPP_{fprqt}) and distribution processes (EPC_{fcplt}) are considered.

$$\begin{aligned} \Pi_{cpt} = & \sum_{s \in S} \sum_{f \in F} \sum_{m \in M} \sum_{l \in L} EPS_{sfmlt} SA_{sfcmlt} \\ & + \sum_{f \in F} \sum_{e \in F} \sum_{q \in Q^p} \sum_{r \in R^q} \sum_{l \in L} EPI_{feprqlt} TAIP_{fecprqlt} \\ & + \sum_{f \in F} \sum_{r \in R} \sum_{q \in Q} EPP_{fprqt} \, PA_{fcprqt} \\ & + \sum_{f \in F} \sum_{l \in L} EPC_{fcplt} TP_{fcplt} \quad \forall c \in C, p \in P, t \in T \end{aligned} \tag{2.27}$$

The decision variables considering opening and closing facilities (2.28) as well as investments in and reinstallation of resources (2.29) are binary:

$$x_{ft}, rx_{ft} \in \{0,1\} \quad \forall\, f \in F, t \in T \tag{2.28}$$

$$y_{frt}, ry_{frt} \in \{0,1\} \quad \forall\, f \in F, r \in R, t \in T \tag{2.29}$$

The other decisions variables are non-negative (2.30):

$$SA_{sfcmlt} PA_{fcprqt}, TAIP_{fecprqlt}, TAIP_{gfcprolt}, TP_{fcplt}, \Pi_{cpt}, \theta_{\tau}, \delta_{cpt\tau} \geq 0 \quad \forall\, c \in C, e \in E, f \in F, g \in G, l \in L, m \in M, o \in O, p \in P, r \in R, t \in T, \tau \in T \tag{2.30}$$

2.4.3 Numerical Example

In this section a numerical example is presented to evaluate the proposed model. Since the model is a mixed-integer linear programming model type, a standard solver (e.g. CPLEX, LINGO) can be used to find the optimal solution.[81] Table 2.2 summarizes the relevant information of the considered sets.

We consider five suppliers which differ in production capacities for materials. In addition they are characterized by different locations, costs and environmental performance values for the various materials. Suppliers can deliver the materials to one of the three production facility locations, where the three production processes can be executed. Therefore, installation of production resources (e.g. machines) is required. Each process step results either in an intermediate or in a final product. If an intermediate product cannot be further processed at the same production facility, an intercompany logistic flow is triggered. The different production resources have the ability to execute at least one of the considered production processes. It is considered that both costs and environmental impacts are heterogeneous. In addition, in accordance to the selected resources, material consumptions for the processes are different and can be derived from the corresponding bill of materials. The production of the two considered products is characterized by the process structure.

[81] CPLEX is a mathematical linear programming solver offered by IBM. LINGO is a solver suite produced by LINDO Systems.

While the production of product 1 includes production processes 1 and 2, product 2 also needs production process 3.

Finally, six customers vary in their requirements regarding the accepted environmental impact of the products and the resulting demand volume. To link the supply chain nodes, two logistic modes with different environmental impacts are considered. Since supply chain design is a long-term planning problem, three different planning periods are taken into account.

Table 2.2: Sets of the numerical example

Set	Notation	Number
Suppliers	$s \in S$	5
Materials	$m \in M$	5
Production facilities	$f \in F$	5
Production processes	$q \in Q$	3
Production resources	$r \in R$	4
Products	$p \in P$	2
Customers	$c \in C$	6
Logistic modes	$l \in L$	2
Planning periods	$t \in T$	3
Scenarios	$\tau \in \mathrm{T}$	4

According to these assumptions, table 2.3 illustrates an extract of the relevant information of the numerical example.

To analyze the proposed supply chain design model, we compare the solution of the robust model (RM1) (with $\lambda = 1$ and $\omega = 1000$) with the results of the optimization of a deterministic model (DM) which considers each scenario separately. As it is illustrated, the probability of scenario 1 is higher than the probability of the others. Therefore, we take another scenario constellation into account, which is characterized by alternative scenario probabilities ($p_1 = 0.4, p_2 = 0.2, p_3 = 0.2, p_4 = 0.2$). The results are summarized in table 2.4.

Table 2.3: Scenario-specific data (Period 1)[82]

Scenario	Probability	Product	Parameter	Customer					
				1	2	3	4	5	6
1	0.7	1	ER	5000	3000	6000	10000	8000	10000
			PP	15000	15000	15000	15000	15000	15000
		2	ER	10000	8000	6000	10000	8000	4000
			PP	22500	22500	22500	22500	22500	22500
2	0.1	1	ER	4500	2700	5400	9000	7200	9000
			PP	13500	13500	13500	13500	13500	13500
		2	ER	9000	7200	5400	9000	7200	3600
			PP	20250	20250	20250	20250	20250	20250
3	0.1	1	ER	3500	2100	4200	7000	5600	7000
			PP	12000	12000	12000	12000	12000	12000
		2	ER	7000	5600	4200	7000	5600	2800
			PP	18000	18000	18000	18000	18000	18000
4	0.1	1	ER	3250	10000	10000	10000	10000	10000
			PP	9000	9000	9000	9000	9000	9000
		2	ER	10000	10000	10000	10000	10000	10000
			PP	13500	13500	13500	13500	13500	13500

Table 2.4: Results[83]

		Scenario 1	Scenario 2	Scenario 3	Scenario 4
Free Cash Flow (T€)					
	DM	389600.4	348615	300164.1	225958.6
	RM1	381820.1	340881.5	300092.6	218365.1
	RM2	381821.5	340882.8	300093.9	218366.3
Free Cash Flow (% of DM)					
	DM	100.000	100.000	100.000	100.000
	RM1	98.003	97.782	99.976	96.639
	RM2	98.003	97.782	99.977	96.640
Opened Facilities					
	DM	F2	F2	F2, F3*	F2
	RM1	F2, F3*	F2, F3*	F2, F3*	F2, F3*
	RM2	F2, F3*	F2, F3*	F2, F3*	F2, F3*
Installed Resources					
	DM	R1, R2	R1, R2	R1, R2	R1, R2
	RM1	R1, R2	R1, R2	R1, R2	R1, R2
	RM2	R1**, R2	R1**, R2	R1**, R2	R1**, R2

As table 2.4 illustrates, the free cash flow values of the three models vary only slightly.

[82] Abbreviations: ER: Environmental Requirements in tons; PP: Product Price.
[83] *Starting in Period 2; **At F2 not in Period 2; F: Facility; R: Production resource.

The maximum difference is 3.361% in scenario 4. Simultaneously, the standard deviation decreases by 1.67% and 1.21%, respectively. Looking at the supply chain structure, the results show the advantage of the robust optimization approach. While applying deterministic model leads to one supply chain configuration for each scenario, the robust model provides a solution considering all scenarios. As a result of the deterministic model, facility locations 2 and 3 are opened only in scenario 3. Under robustness considerations, both facility locations should be opened in all scenarios. The solution of RM2 deviates from RM1 regarding the installation of the production resources: Production resource 1 is reinstalled at facility location 2 in period 2, when facility location 3 starts to produce. Hence, the supply chain structure is robust to varying customer requirements. This could be particularly of interest for decision makers in the industry of (fast moving) consumer goods. Their customers are highly sensitive to negative news concerning environmental impacts of products and increasingly up to buy products with a good environmental balance.[84] In our numerical example, the decision maker should allocate the production of the products to two facilities. In the case that customers increase their requirements, the decision maker does not need to change the network design. Since we consider only fictitious data, the results are only preliminary and cannot be interpreted in a general sense. However, the basic advantage of robust optimization in an uncertain planning environment is illustrated.

2.5 Conclusion

Supply chain design decisions have a high impact on the environmental performance of the produced goods. Simultaneously, customers are increasingly up to formulate requirements regarding the environmentally consciousness of products. To analyze this interaction, we focus on environmental considerations in supply chain design models. To provide a decision supporting approach, this paper presents a multi-echelon, multi-product and multi-period supply chain design model, which considers both economic and environmental impact of value adding activities in the supply chain. Compared to previous literature, our approach particularly focuses on customer requirements regarding the environmental impact of the delivered products. We apply robust optimization to capture uncertainty regarding both environmental requirements and price parameters. By using

[84] Cf. Jayaraman, V.; Singh, R.; Anandnarayan, A., sustainable manufacturing practices, 2012, p. 1406.

this technique the solution is less sensitive to a changing planning environment. In addition, the difficulty to quantify customers´ environmental requirements can be cushioned. In order to integrate the environmental performance at the process level, we consider production processes as well as intercompany product flows. In a numerical example the capabilities of our model have been illustrated.

A shortcoming of our paper is the use of a fictitious numerical example to evaluate our model. Thus, our results are preliminary. To verify the results, a future extension could be the integration of data from a real life case. Another interesting research field might be the comparison of the different approaches for considering uncertain data. At the content level, the development of an integrated strategic and tactical supply chain planning model can lead to further insights of the interactions of the sustainability dimensions in a supply chain context.

2.6 Appendix

The following notations are used in the model formulation:

β_{prq}	Capacity coefficient of process q executed on resource r to produce product p
$\delta_{cpt\tau}$	Violation of the environmental impact requirements of customer c regarding product p in period t and scenario τ
θ_{τ}	Auxiliary variable for linearization in scenario τ
λ	Weighting factor for deviations of scenario-specific free cash flows to the mean free cash flow
Π_{cpt}	Environmental impact in period t concerning product p ordered by customer c
ρ_{τ}	Probability of scenario τ
$\Upsilon_{cpt\tau}$	Environmental impact requirements of customer c regarding product p in period t and scenario τ
ω	Weighting factor for violations of environmental impact requirement constraints
$BigM$	Sufficient large number
BoM_{rqm}	Bill of materials of process q executed on resource r and material m

$CapR_{frt}$	Capacity of resource r at facility location f in period t
cf_{ft}	Fix costs of closing facility location f in period t
cr_{frt}	Fix costs of uninstalling resource r at facility location f in period t
D_{cpt}	Demand of customer c of product p in period t
dep_{ft}	Depreciations at facility location f in period t
$depF_{ft}$	Depreciation at facility location f in period t
$depR_{frt}$	Depreciation at facility location f regarding resource r in period t
$ebitda_{ft\tau}$	Ebitda at facility location f in period t and scenario τ
EPB_{cptb}	Environmental impact assigned to environmental impact level b of customer c considering product p in period t
EPC_{fcplt}	Environmental impact of delivering product p from facility location f to customer c using logistic mode l in period t
$EPI_{feprqlt}$	Environmental impact of producing an intermediate product of product p on resource r with process q and delivered from facility location f to facility location e using logistic mode l in period t
EPS_{sfmlt}	Environmental impact caused by delivering material m from supplier s to facility location f using logistic mode l in period t
EPP_{fprqt}	Environmental impact of production of final product p on resource r with process q at facility location f in period t
$ExIn_{oq}$	Bill of intermediate products of process *o* which are necessary to perform process *q*
$fcf_{t\tau}$	Free cash flow in period t and scenario τ
fix_{ft}	Fix costs at facility location f in period t
$fixR_{frt}$	Fix costs of installing resource r at facility location f in period t
$Invest_{t}$	Capital expenditures in period t
$invF_{ft}$	Capital expenditure at facility location f in period t
$invR_{frt}$	Capital expenditure at facility location f regarding resource r in period t
PA_{fcprqt}	Production amount of final product p produced at facility location f for customer c on resource r with process q in period t
PC_{fprqt}	Production costs of final product p produced at facility location f on resource r with process q in period t
$PP_{cpt\tau}$	Price of product p paid by customer c in period t and scenario τ

rx_{ft}	Binary variable that indicates whether a facility location f should be closed or not in period t
ry_{frt}	Binary varible that indicates whether a resource r at facility location f should be uninstalled or not in period t
SA_{sfcmlt}	Amount of material m supplied by supplier s to facility location f to meet the demand of customer c using logistic mode l in period t
SC_{smt}	Costs of material m at supplier s in period t
$TAIP_{fgcprqlt}$	Production amount of an intermediate product of final product p produced at facility location f for further processing at facility location g for customer c on resource r with process q, distributed by logistic mode l in period t
tax_{ft}	Tax at facility location f in period t
$TCIP_{fgprqlt}$	Production costs of an intermediate product of product p produced at facility location f for further processing at facility location g for customer c on resource r with process q, distributed by logistic mode l in period t
TCP_{fcplt}	Transportation costs of delivering final product p from facility location f to customer c using logistic mode l in period t
TP_{fcplt}	Amount of product p delivered from facility location f to customer c using logistic mode l in period t
TSC_{sfmlt}	Transportation costs of delivering material m from supplier s to facility location f using logistic mode l in period t
tv	Terminal value
tvf_f	Terminal value of facilities
tvr_{fr}	Terminal value of resources
$WACC$	Weighted average cost of capital
x_{ft}	Binary variable that indicates whether a facility location f is open or not in period t
y_{frt}	Binary variable that indicates whether a resource r is installed at facility location f or not in period t
Z_τ	Objective value of scenario τ

3 Environmental supply chain design with a customer specific, environmental impact dependent demand function[85]

3.1 Introduction

Sustainability has become more and more critical for companies.[86] Consequently, the planning processes of companies need to be redesigned to integrate sustainability issues. According to the definition of sustainable development published in the BRUNDTLAND REPORT it is necessary to meet "the needs of the present without compromising the ability of future generations to meet their own needs".[87] This definition points out the long-term aspect of sustainability. In addition to monetary planning parameters, decision makers now need to include environmental as well as social issues into their planning processes. This triple bottom line approach[88] and the fact that value creating processes are increasingly located all over the world lead to supply chain planning situations with increased complexity. Examples of companies that failed to include sustainability issues as needed when coordinating their value chain processes can particularly be found in the apparel industry.[89] Prior research examined the motivation of companies to adopt environmental and social practices. These motivations are particularly externally driven. Among others, regulation and legislation play major roles as they may impact the financial performance of a company due to penalties or other negative consequences when environmentally conditions are violated.[90] In addition to governments, non-governmental organizations put more and more pressure on companies. Nowadays publications in the media, especially the World Wide Web, claiming undue social or environmental behaviour of a company could damage a company´s reputation severely. Consumers are increasingly willing to boycott these companies. Customer requirements have changed in the direction of higher expectations regarding environmental and social performance of the firm.[91] However,

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[85] A revised manuscript of this chapter is published as Altmann, M., A supply chain design approach considering environmentally sensitive customers: the case of a German manufacturing SME, in: International Journal of Production Research, DOI: 10.1080/00207543.2014.961203.
[86] Cf. Kleindorfer, P. R.; Singhal, K.; Van Wassenhove, L. N., Sustainable Operations Management, 2005, p. 482; Srivastava, S. K., Green supply-chain management, 2007, p. 53.
[87] WCED, Common Future, 1987.
[88] See Elkington, J., Cannibals, 1997, pp. 69-96.
[89] Cf. Preuss, L., Corporate Greening, 2005, p. 127.
[90] Cf. Ageron, B.; Gunasekaran, A.; Spalanzani, A., Sustainable supply management, 2012, p. 176.
[91] Cf. Rao, P.; Holt, D., green supply chains, 2005, p. 898.

new end-user consumption patterns also enable companies to improve their financial results. In this context, the willingness of customers to pay a higher price for an environmentally friendly product as well as potentially higher demands on sustainable products are important.[92] To capture these requirements, we integrate a sustainability dependent demand function into a supply chain design model. In this way, investments in environmentally conscious production processes, particularly in pollution prevention technologies,[93] can not only lead to a higher environmental performance, but also to an improvement of economic results.[94] To evaluate this relationship, we focus on the environmental dimension of sustainability. Our approach might be of interest for companies, especially those who introduce an environmental management system (e.g. according to EMAS or ISO 14000)[95], to evaluate the potential of changing or substituting production processes.

The rest of the paper is organized as follows: In the next section we discuss the impact of supply chain design on the environmental supply chain performance and customer requirements regarding environmentally conscious products. In section 3 we review the relevant literature and discuss the different approaches of integrating environmental issues in supply chain design models. The presentation of a supply chain design model, which considers an environmentally sensitive demand function, is the topic of section 4. In addition we describe and analyse the results of a numerical example, from which we derive further management implications. Finally, in section 5 the conclusions of the paper are drawn.

3.2 Environmental issues in supply chains

3.2.1 Environmentally conscious supply chain design

Supply chain design, also entitled as supply chain network planning or strategic supply chain planning, is the basis for all other supply chain planning levels.[96] While on the strategic planning level decisions about the infrastructure of the supply chain are made, it is part of the tactical level to plan aggregated flows of materials and products among

[92] Cf. Rao, P.; Holt, D., green supply chains, 2005, p. 906.
[93] Cf. Klassen, R. D., environmental technologies, 2000, p. 130.
[94] Cf. Ashford, N. A., environmental problems, 1993, p. 279.
[95] EMAS is the voluntary European eco-management and audit scheme based on EC Regulation No 1221/2009. For further information see www.emas.de. ISO 14000 addresses a wide range of environmental management issues. Detailed information can be found on http://www.iso.org/iso/home/standards/management-standards/iso14000.htm.
[96] Cf. Ivanov, D., supply chain strategy, 2010, p. 4005.

suppliers and facilities from a procurement point of view as well as facilities and customers from a distributional perspective.[97] In this paper we focus on the strategic supply chain design, as strategic decisions have a larger impact on the environmental performance than tactical and operational decisions.[98] The main impact factors of supply chain design decisions on the environmental supply chain performance are illustrated in Figure 3.1.

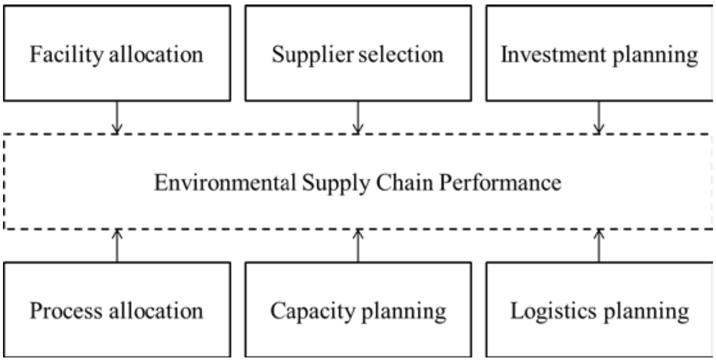

Figure 3.1: Issues of environmental supply chain design

The number and locations supply chain nodes (e.g. suppliers, facilities, warehouses, distribution hubs) as well as the distance between them determine the environmental impact of logistic processes. Thus, the allocation of facilities and the selection of suppliers should be done by considering environmental objectives in addition to financial goals. Furthermore, country-specific environmental regulations need to be considered in the selection process. In addition to the location of the nodes, their accessibility should be taken into account, thus introducing alternative transportation modes, e.g. train or barge, with different environmental characteristics and cost functions.[99] In detail, fuel efficiency and the adoption of environmental management standards can be decision criteria for the selection of logistic service providers.[100] Furthermore, a high level of vehicle capacity utilization, e.g. through consolidation of shipments, might be advisable.[101] By taking a cradle-to-grave-view according to the life cycle assessment approach, not only the processes of the company but also those of the suppliers are relevant for the assessment of the environmental impact of value-creating processes. Hence, environmental supplier selection criteria, for instance environmental management standards[102], can be used to verify an

[97] Cf. Santoso, T. et al., supply chain network design, 2005, p. 96.
[98] Cf. Aronsson, H.; Brodin, M. H., environmental impact, 2006, p. 397.
[99] Cf. McKinnon, A. C., Logistics, 2003, p. 673.
[100] Cf. Carter, C. R.; Jennings, M. M., Logistics social responsibility, 2002, pp. 154-155.
[101] Cf. Harris, I. et al., infrastructure modelling, 2011, p. 320.
[102] E.g. ISO 14000, GRI Reporting Guidelines.

environmental responsible behaviour of potential suppliers. Investment planning, capacity planning as well as the allocation of production processes are closely interlinked. An investment in both, new facilities and production equipment, featured with a higher level of ecological efficiency, improve the environmental performance, so does the installation of pollution prevention technologies.[103] By allocating eco-friendly production technologies at the production facilities and by increasing the utilization ratio of these facilities, the environmental performance could be positively influenced. This emphasizes the importance of capacity planning.

Carbon emissions are only one out of several important issues when addressing environmental as well as sustainability performance. Although different norms and standards (e.g. ISO 14001, GRI) may give some advice, many companies struggle with determining the right performance indicators for their needs.[104] HASSINI, SURTI and SEARCY (2012) reviewed the sustainable performance measures used in the literature and proposed composite indicators.[105] In addition they noticed that the right selection of performance metrics is highly industry specific. Thus we use a more general performance metric to illustrate the relations between supply chain design decisions, environmental performance and customer demand. As most of the previous environmentally conscious supply chain design approaches stated, carbon equivalents are practicable to evaluate the environmental impact of supply chain topics.[106] According to many other models,[107] we use carbon equivalents to describe the environmental performance as they consider the environmental impact of various greenhouse gases. In addition, nowadays carbon emissions data can be gathered from various institutions and databases (e.g. EcoTransIT[108]).

3.2.2 Environmentally sensitive customer demand

Besides governmental regulations and pressure from non-governmental organizations, customer's requirements are one of the major drivers for the adoption of green supply

[103] Cf. Klassen, R. D.; Whybark, D. C., environmental technologies, 1999, p. 610.
[104] Cf. Hervani, A. A.; Helms, M. M.; Sarkis, J., green supply chain management, 2005, p. 341.
[105] See Hassini, E.; Surti, C.; Searcy, C., sustainable supply chains, 2012, pp. 69-82.
[106] Cf. Lee, K.-H., carbon footprint, 2011, p. 961; Sundarakani, B. et al., carbon footprint across the supply chain, 2010, pp. 43.
[107] See the literature review in section 3.3
[108] The database EcoTransIT can be accessed via http://www.ecotransit.org/.

chain management practices.[109] This is of enhanced significance for globally active companies, since environmental requirements of customers differ from country to country.[110] The willingness of customers to pay for environmentally conscious products as well as the assumption that a higher level of sustainability leads to a higher demand are discussed in the literature. Some studies reason that increasing the level of sustainability of a product leads to higher demand, while other studies could not find evidence for this correlation.[111] HAZEN et al. (2012) examined whether the adoption of green reverse logistic processes lead to the willingness of customers to pay more for offered products. They found evidence for the assumption that companies need to improve customer loyalty to realize price premium.[112] JAYARAMAN, SINGH and ANANDNARAYAN (2012) analysed the relationship of sustainable manufacturing practices on customer´s behaviour in India and found evidence for a significant positive correlation.[113] One reason can be found in the impact of environmentally consciousness on a business´s reputation and customer´s goodwill.[114] As TATE et al. (2010) showed, customers are up to claim companies to keep a certain level of environmental impact regarding goods that they buy.[115] On behalf of the GERMAN FEDERAL MINISTRY FOR THE ENVIRONMENT, NATURE CONSERVATION, BUILDING AND NUCLEAR SAFETY, the SINUS INSTITUTE conducted a study analysing the environmental consumer awareness in Germany. As a result it can be noted, that two thirds of the respondents frequently buy products which are produced under environmental friendly conditions.[116]

Summarizing the empirical studies it can be concluded, that the relation of a sustainability-oriented production and a positive effect on customer´s behaviour is only evident for a few countries and thus customer specific. Therefore we integrate a customer specific demand function into the modelling approach, which depends on the sustainable performance of the ordered product.

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[109] Cf. Zhu, Q.; Sarkis, J.; Geng, Y., Green supply chain management, 2005, p. 452.
[110] Cf. Christmann, P.; Taylor, G., Globalization and the Environment, 2001, p. 452.
[111] Cf. Seuring, S.; Müller, M., sustainable supply chain management, 2008, p. 1704; Ageron, B.; Gunasekaran, A.; Spalanzani, A., Sustainable supply Management, 2012, p. 176.
[112] See Hazen, B. T.; Cegielski, C.; Hanna, J. B., green supply chain management, 2012, pp. 417-434.
[113] See Jayaraman, V.; Singh, R.; Anandnarayan, A., sustainable manufacturing practices, 2012, pp. 1395-1410.
[114] Cf. Schiebel, W.; Pochtrager, S., Corporate ethics, 2003, p. 117.
[115] Cf. Tate, W. L. et al., supply chain management, 2010, p. 36.
[116] See BMU, Umweltbewusstsein in Deutschland, 2010.

3.3 Literature review

Although sustainable supply chain management is an emerging field of research and management, reviewing the relevant literature illustrates, that quantitative models are still underrepresented compared to qualitative approaches like concepts or frameworks.[117] While a lot of approaches treat sustainability issues by integrating reverse logistics or closed-loop systems into supply chain models, only a few approaches which consider either environmental or social coefficients can be identified. The following literature review focusses explicitly just on strategic supply chain design approaches that use optimisation techniques in order to find a supply chain configuration. Therefore, neither tactical nor simulation models are considered. In addition, only models are integrated into the review pool that capture at least two sustainability pillars in the model coefficients. More general literature reviews on modelling approaches can be found in SEURING (2013)[118], BRANDENBURG et al. (2014)[119] and FARAHANI et al. (2014)[120].

A multi-objective mixed integer linear programming model which maximizes net present value and minimizes environmental impacts is developed by HUGO and PISTIKOPOULOS (2005). The environmental impact is measured according to the three categories human health, ecosystem quality, and resource depletion.[121] QUARIGUASI FROTA NETO et al. (2008) develop an optimization approach for sustainable supply chain planning with minimization of both environmental impact and total costs as objectives.[122] In addition to forward flows of materials and products, reverse flows of waste are considered. Another approach is proposed by RAMUDHIN et al. (2008). They develop a supply chain design model under carbon trading considerations. Therefore they integrate the environmental impact of strategic supply chain decisions into the cost-oriented objective function. In addition they analyze the impact of changing upper emission bounds on total logistic costs.[123] A stochastic mixed-integer nonlinear program for maximization of the net present value and minimization of the environmental impact is presented by GUILLÉN-GOSÁLBEZ and GROSSMANN (2009).[124] Environmental impact is assessed via different

[117] Cf. Seuring, S.; Müller, M., sustainable supply chain management, 2008, p. 1702.
[118] See Seuring, S., modeling approaches, 2013, pp. 1513-1520.
[119] See Brandenburg, M. et al., sustainable supply chain management, 2014. 299-312.
[120] See Farahani, R. Z. et al., supply chain network design, 2014, pp. 92-118.
[121] See Hugo, A.; Pistikopoulos, E. N., Environmentally conscious long-range planning, 2005, pp. 1471-1491.
[122] See Quariguasi Frota Neto, J. et al., sustainable logistics networks, 2008, pp. 195-208.
[123] See Ramudhin, A. et al., Green Supply Chain Network Design, 2008, pp. 1093-1097.
[124] See Guillen-Gosalbez, G.; Grossmann, I. E.; Sustainable Chemical Supply Chains, 2009, pp. 99-121.

impact categories, which are aggregated afterwards. Another green supply chain optimization approach is presented by TSAI and HUNG (2009).[125] They propose a fuzzy goal programming approach for supplier selection and flow allocation. A case study illustrates the model application. Different objective structures are proposed and applied. Contrary to the other approaches, CRUZ (2008), CRUZ and WALKOBINGER (2008) as well as CRUZ and MATSYPURA (2009) consider not only the environmental dimension but also the social dimension of sustainability. They propose a model with maximization of net returns, minimization of emissions as well as the minimization of risk, covering organizational, environmental and network-related risks as objective functions.[126] NAGURNEY and TOYASAKI (2003) propose a supply chain network model with environmental considerations and analyse the optimality conditions for the different supply chain actors to identify equilibrium prices and product flows.[127] NAGURNEY and NAGURNEY (2010) propose a multi-criteria optimization approach for strategic sustainable supply chain design with with total costs and carbon emissions as objectives.[128] CHAABANE, RAMUDHIN and PAQUET (2011) propose a multi-objective optimization model that is solved using the ε-constraint method. Minimization of total costs and total carbon equivalents are selected as objectives. In addition, the total carbon equivalent emissions are restricted by an upper bound, modelled as a constraint.[129] CHAABANE, RAMUDHIN and PAQUET (2012) deal in their model with forward and reverse flows in a supply chain. In comparison to the above mentioned approach they consider supply chain processes and a multi-period planning horizon. The objectives are maximization of total cost and minimization of total greenhouse gases.[130] A multi-objective optimization approach is proposed by WANG, LAI and SHI (2011). The two objective functions measure total costs and total carbon emissions in the supply chain.[131] ELHEDHLI and MERRICK (2012) consider carbon emissions by integrating environmental costs into the total cost function. Assuming a concave relationship between vehicle weight and carbon emissions the mixed-integer model is non-linear.[132]

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[125] See Tsai, W. H.; Hung, S. J., green supply chain optimization, 2009, pp. 4991-5017.
[126] See Cruz, J. M., supply chain networks, 2008, pp. 1005-1031; Cruz, J. M.; Walkobinger, T., corporate social responsibility, 2008, pp. 61-74 as well as Cruz, J. M.; Matsypura, D., environmental decision-making, 2009, pp. 621-648.
[127] See Nagurney, A.; Toyasaki, F., supply chain supernetworks, 2003, pp. 185-213.
[128] See Nagurney, A.; Nagurney, L. S., Sustainable supply chain design, 2010, pp. 189-197.
[129] See Chaabane, A.; Ramudhin, A.; Paquet, M., Designing supply chains, 2011, pp. 727-741.
[130] See Chaabane, A.; Ramudhin, A.; Paquet, M., sustainable supply chains, 2012, pp. 37-49
[131] See Wang, F.; Lai, X.; Shi, N., green supply chain network design, 2011, pp. 262-269.
[132] See Elhedhli, S.; Merrick, R., Green supply chain network design, 2012, pp. 370-379.

PINTO-VARELA, BARBOSA-PÓVOA and NOVAIS (2011) apply symmetric fuzzy linear programming to maximize profit and to minimize the environmental impact as well.[133] PISHVAEE, RAZMI and TORABI (2012) propose a socially responsible supply chain design model using robust possibilistic programming. To incorporate the social dimension of sustainability they introduce four measures: number of potentially hazardous products, number of lost days caused from work´s damage, amount of produced waste and number of created job opportunities.[134] The ε-constraint method is used by YOU et al. (2012) use the ε-constraint method to capture the tradeoff between total costs and GHG emissions. With a focus on cellulosic biofuels they propose a model for designing and planning a supply chain. They integrate the social dimension of sustainability by assessing the number of accrued local jobs.[135] To design a closed-loop supply chain according to both economic and environmental objectives, ALTMANN and BOGASCHEWSKY (2014) propose a robust, multi-objective optimization model. Both objective functions, discounted total costs as the financial objective and carbon equivalents as the environmental objective, are minimised.[136] Another recent approach for designing a sustainable closed-loop supply chain is presented by DEVIKA, JAFARIAN and NOURBAKHSH (2014). They consider all three sustainability pillars and compare three different metaheuristics to solve the model.[137] GOVINDAN et al. (2014) focus on a food supply chain and present a three stage supply network model including vehicle routing decisions. The two objectives are minimisation of both the total costs and environmental impact (GHG emissions).[138] Also SOYSAL, BLOEMHOF-RUWAARS and VAN DER VORST (2014) consider a food case and develop a logistic network design model with total costs and total CO_2 emissions as objectives.[139] SANTIBAÑEZ-AGUILAR et al. (2014) consider all three sustainability pillars in their approach and present a multi-objective, mixed-integer linear programming model using net profit, environmental impact as well as social impact as objectives.[140]

[133] See Pinto-Varela, T.; Barbosa-Póvoa, A. P. F. D.; Novais, A. Q., planning of supply chains, 2011, pp. 1454-1468.
[134] See Pishvaee, M. S.; Razmi, J.; Torabi, S. A., responsible supply chain network design, 2012, pp. 1-20.
[135] See You, F. et al., Supply Chains, 2012, pp. 1157-1180.
[136] See Altmann, M.; Bogaschewsky, R., supply chain design, 2014, pp. 613-637.
[137] See Devika, K.; Jafarian, A.; Nourbakhsh, V., metaheuristics, 2014, pp. 594-615.
[138] See Govindan, K. et al., supply chain network, 2014, pp. 9-28.
[139] See Soysal, M.; Bloemhof-Ruwaars, J. M.; van der Vorst, J. G. A. J., logistics network, 2014, pp. 57-70
[140] See Santibañez-Aguilar, J. E. et al., Optimal planning, 2014, pp. 270-294.

As a result of our literature review and to the best of our knowledge it can be summarized that no model has been published yet that integrates the relationship of supply chain design decisions and environmentally sensitive customer demand in a quantitative approach. In addition, we did not find supply chain design models which incorporate customer specific environmental impact measurement at the product level. By closing these gaps we want to make a contribution for answering the question, whether it pays to align supply chain design decisions to environmental requirements of customers or not.

3.4 Model description

3.4.1 Problem description and assumptions

The considered alternative supply chain configurations are shown in Figure 3.2. We assume a three echelon supply chain with numerous suppliers, production facilities and customers. To produce a product various production steps have to be processed. The relevant machines can be installed in each production facility. It is not necessary to execute all steps in the same facility, thus intercompany flows are considered.

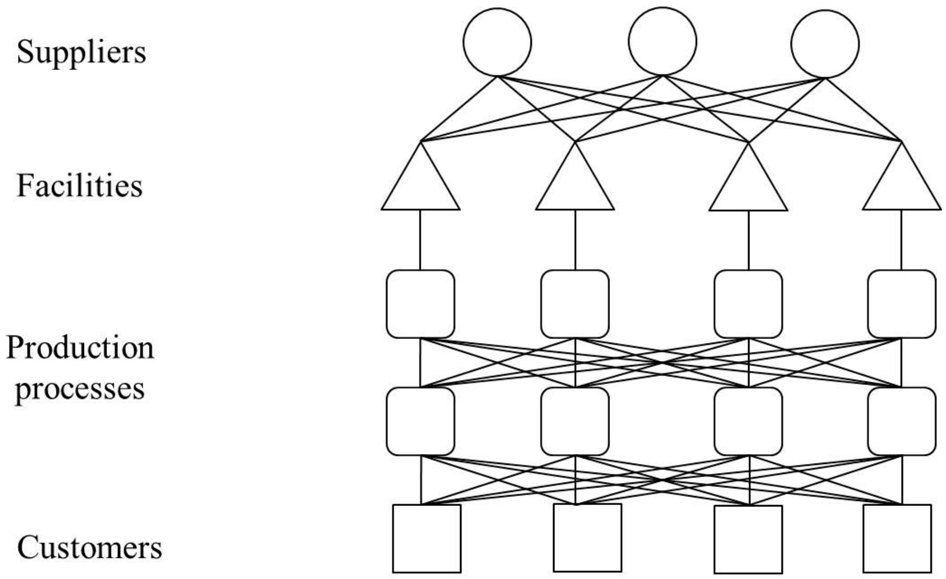

Figure 3.2: Supply chain structure

The environmental impact is considered at all three levels: suppliers, production and distribution. To increase the environmental performance, the decision maker can install environmental friendly resources (e.g. machines). In addition, logistical processes could be minimized by selecting suppliers next to facilities or producing customer demands at facilities close to customers. Simultaneously the decision maker needs to respect maximal permitted emission volumes of the facility, as determined by governmental institutions or by the company itself. Since carbon emissions of opening and closing facilities are not accountable for the environmental performance of a certain product, they are not considered in the model. Obviously, there is a potential trade-off between economic and environmental performance. We capture this trade-off by assuming that customer demand is sensitive to the environmental performance of the value creation process of the products, resulting in a direct impact on the sales volume. As GLOCK, JABER and SEARCY (2012) illustrated, the environmental performance of a product can be treated as a quality characteristic that influences the demand.[141] In the quality context, CASTILLO-VILLAR, SMITH and SIMONTON (2012) stated that supply chain design decisions influence product quality.[142] Transferred to environmental issues, the above mentioned supply chain decisions have an effect on the environmental performance of a product and consequently on customers´ demand. Therefore, we assume a demand function which is decreasing with increasing negative environmental performance. The approximated stepwise form of the function is exemplarily illustrated in Figure 3.3. We assume a piecewise linear function. The various levels characterize the different tolerance levels of customers regarding the environmental impact of the product-specific total demand volume. We focus on a situation in which the demand volume is stable at each demand level. However, e.g. decreasing of customer´s demand at each demand level can easily be integrated. We assume a deterministic planning environment, in which all relevant data is known by the supply chain participants.

[141] Cf. Glock, C. H.; Jaber, M. H.; Searcy, C., Sustainability strategies, 2012, p. 347.
[142] See Castillo-Villar, K. K.; Smith, N. R.; Simonton, J. L., supply-chain network design, 2012, pp. 5544-5566.

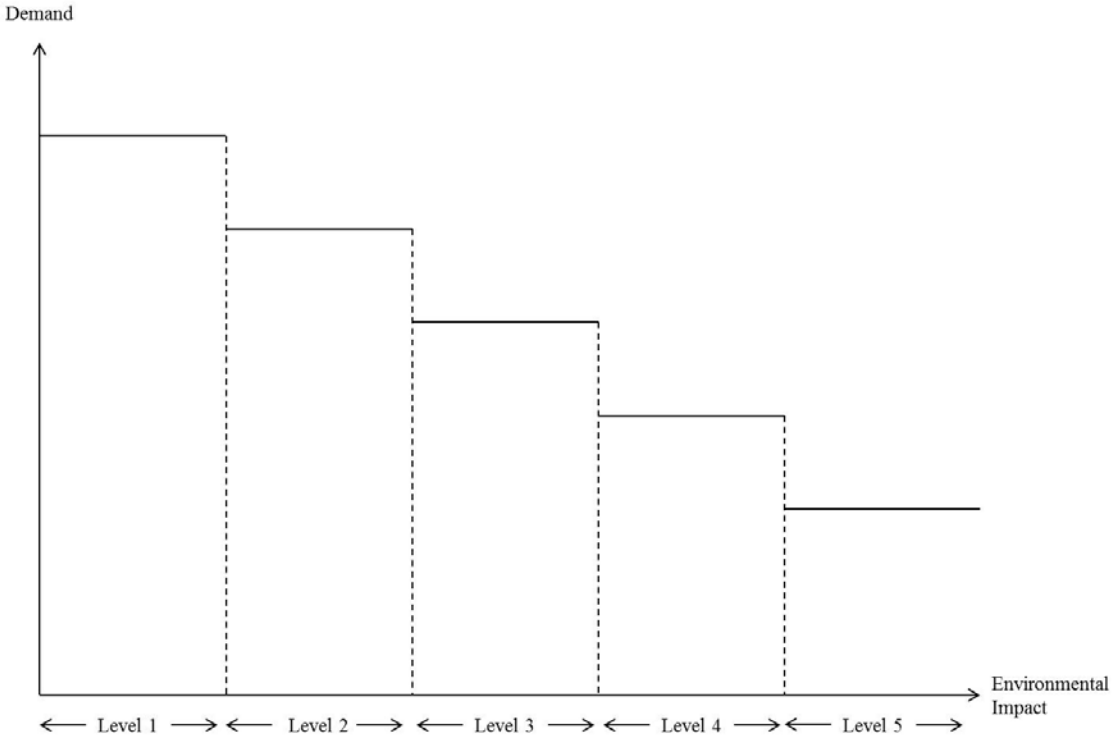

Figure 3.3: Illustration of the demand function

The demand function can be stated as:

$$D_{cpt} = \sum_{b \in B} \omega_{cptb} d(\Pi)_{bcpt}\,, with\ \omega_{cptb} \in [0,1], \sum_{b \in B} \omega_{cptb} = 1\,, \forall c \in C, p \in P, t \in T \tag{3.1}$$

The demand levels of the products depend on the environmental impact during their manufacturing and distribution processes as well as the environmental impact of relevant materials and supply logistics. To model the environmental impact of the relevant supply chain processes, we use life cycle assessment techniques. Since we consider customer´s requirements, the formulation of the demand function is customer specific. As mentioned above, we use carbon equivalents to measure the environmental impact. Particularly the production processes influence the environmental performance of a product. By investing in new production equipment, a company is able to improve the environmental performance of the products. Therefore, we assume a multi-process production environment. To capture the long-term planning environment of supply chains design, we present a multi-period model. Facilities and resources can be closed or uninstalled in the planning periods. The goal of the model is to find the optimal supply chain configuration, including supplier selection, facility location and capacity, resource as well as production allocation. In addition, both selection of logistic modes and flows are determined. The major contribution is the integration of customers´ requirements concerning a product´s environmental performance into the supply chain design context. The complex model helps decision makers to consider the interrelations of strategic procurement, manufacturing and sales topics in the case of environmentally sensitive customers.

The following notations are used in the proposed model:

Table 3.1: Summary of notations

Parameters:	
β_{prq}	Capacity coefficient of process q executed on resource r to produce product p
$BigM$	Sufficient large number
BoM_{rqm}	Bill of materials of process q executed on resource r and material m
$CapR_{frt}$	Capacity of resource r at facility location f in period t
cf_{ft}	Fix costs of closing facility location f in period t
cr_{frt}	Fix costs of uninstalling resource r at facility location f in period t
$d(\Pi)_{cptb}$	Demand volume of demand level b of customer c concerning product p in period t
dep_{ft}	Depreciations at facility location f in period t
DR	Discount rate
EPB_{cptb}	Environmental impact assigned to environmental impact level b of customer c considering product p in period t
EPC_{fcplt}	Environmental impact of delivering product p from facility location f to customer c using logistic mode l in period t
$EPI_{feprqlt}$	Environmental impact of producing an intermediate product of product p on resource r with process q and delivered from facility location f to facility location e using logistic mode l in period t
EPP_{fprqt}	Environmental impact of production of final product p on resource r with process q at facility location f in period t
EPS_{sfmlt}	Environmental impact caused by delivering material m from supplier s to facility location f using logistic mode l in period t
fix_{ft}	Fix costs at facility location f in period t
$fixR_{frt}$	Fix costs of installing resource r at facility location f in period t
LB_{cptb}	Lower bound of environmental impact acceptance level b of customer c regarding product p in period t
PC_{fprqt}	Production costs of final product p produced at facility location f on resource r with process q in period t
PP_{cpt}	Price of product p paid by customer c in period t

SC_{smt}	Costs of material m at supplier s in period t
tax_{ft}	Tax at facility location f in period t
$TCIP_{fgprqlt}$	Production costs of an intermediate product of product p produced at facility location f for further processing at facility location g for customer c on resource r with process q, distributed by logistic mode l in period t
TCP_{fcplt}	Transportation costs of delivering final product p from facility location f to customer c using logistic mode l in period t
TSC_{sfmlt}	Transportation costs of delivering material m from supplier s to facility location f using logistic mode l in period t
UB_{cptb}	Upper bound of environmental impact acceptance level b of customer c regarding product p in period t

Continuous decisions variables

ξ_{ft}	Environmental impact at facility location f in period t
ζ_{ft}	Amount of environmental impact, which does not comply with the legal environmental impact level at facility f in period t
Π_{cpt}	Environmental impact in period t concerning product p ordered by customer c
D_{cpt}	Demand of customer c of product p in period t
$depF_{ft}$	Depreciation at facility location f in period t
$depR_{frt}$	Depreciation at facility location f regarding resource r in period t
$ebitda_{ft}$	Ebitda at facility location f in period t
EC_{ft}	Penalty costs of not complying with the legal environmental impact level at facility location f in period t
fcf_{t}	Free cash flow in period t
$Invest_{t}$	Capital expenditures in period t
$invF_{ft}$	Capital expenditure at facility location f in period t
$invR_{frt}$	Capital expenditure at facility location f regarding resource r in period t
LIL_{ft}	Legal environmental impact level at facility location f in period t
PA_{fcprqt}	Production amount of final product p produced at facility location f for customer c on resource r with process q in period t
$TAIP_{fgcprqlt}$	Production amount of an intermediate product of final product p produced at facility location f for further processing at facility location g for customer c on resource r with process q, distributed by logistic mode l in period t
TP_{fcplt}	Amount of product p delivered from facility location f to customer c using logistic mode l in period t
tv	Terminal value
SA_{sfcmlt}	Amount of material m supplied by supplier s to facility location f to meet the demand of customer c using logistic mode l in period t

Binary decisions variables

ω_{cptb}	Binary variable to determine demand level b of customer c concerning product p in period t
rx_{ft}	Binary variable that indicates whether a facility location f should be closed or not in period t
ry_{frt}	Binary varible that indicates wheter a resource r at facility location f should be uninstalled or not in period t
x_{ft}	Binary variable that indicates whether a facility location f is open or not in period t
y_{frt}	Binary variable that indicates whether a resource r is installed at facility location f or not in period t

3.4.2 Model presentation

First we present the elements of the objective function, which is formulated in the following equation:[143]

$$Max \sum_{t \in T} \frac{fcf_t}{(1+DR)^t} + \frac{tv}{(1+DR)^T} \tag{3.2}$$

It maximizes the discounted free cash flow to the firm and the time-adjusted terminal value.

$$fcf_t = \sum_{f \in F} \left(1 - tax_{ft}\right) \cdot ebitda_{ft} + \sum_{f \in F} tax_{ft} \cdot dep_{ft} - Invest_t, \quad \forall t \in T \tag{3.3}$$

The free cash flow consists of the tax-adjusted ebitda, tax advantages of depreciations less capital expenditures. Equation (3.4) is just for visual simplification and shows the elements of ebitda calculation:

[143] The underlying model is a modified version of Kohler, K., Supply Chain Design, 2008, pp. 119-157.

$$\begin{aligned} ebitda_{ft} = &\sum_{c\in C}\sum_{p\in P}\sum_{t\in T} TP_{fcplt}PP_{cpt} - fix_{ft}x_{ft} - cf_{ft}rx_{ft} - \sum_{r\in R} fixR_{frt}y_{frt} \\ &- \sum_{r\in R} cr_{frt}ry_{frt} - \sum_{c\in C}\sum_{p\in P}\sum_{r\in R}\sum_{q\in Q^*} PA_{fcprqt}PC_{fprqt} \\ &- \sum_{g\in F}\sum_{c\in C}\sum_{p\in P}\sum_{r\in R}\sum_{q\in Q}\sum_{l\in L} TAIP_{fgcprqlt}PC_{fprqt} \\ &- \sum_{g\in F}\sum_{c\in C}\sum_{p\in P}\sum_{r\in R}\sum_{q\in Q}\sum_{l\in L} TAIP_{fgcprqlt}TCIP_{fgprqlt} \\ &- \sum_{c\in C}\sum_{p\in P}\sum_{l\in L} TP_{fcplt}TCP_{fcplt} \\ &- \sum_{s\in S}\sum_{c\in C}\sum_{m\in M}\sum_{l\in L} SA_{sfcmlt}\left(SC_{smt} + TSC_{sfmlt}\right) \\ &- \zeta_{ft}EC_{ft} \quad \forall\, f \in F, t \in T \end{aligned} \tag{3.4}$$

The ebitda calculation consists of the total revenue less the fix costs for opening and closing facilities, installing and reinstalling resources, production costs, transaction costs of intercompany flows for intermediate products as well as delivery and purchasing costs. In addition, the last term of equation (3.4) considers cost for exceeding regulatory environmental impact levels as calculated in constraint (3.34).

$$dep_{ft} = depF_{ft}x_{ft} + \sum_{r\in R} depR_{frt}y_{frt} \quad \forall\, f \in F, t \in T \tag{3.5}$$

Equation (3.5) describes the calculation of depreciations on facility and resource level respectively.

$$tv = \sum_{f\in F} tv_f + \sum_{f\in F}\sum_{r\in R} tv_{fr} \tag{3.6}$$

The terminal values of the facility location (3.7) and resource level (3.8) are calculated by summarizing capital expenditures over all periods less depreciations. Equation (3.6) describes the aggregated terminal value. It is important to note, that we consider a design of a new supply chain. Therefore, initial values on both facility location and resource levels are zero.

$$tv_f = \sum_{\substack{t \in T \\ t=1}} invF_{ft} x_{ft} + \sum_{\substack{t \in T \\ t>1}} invF_{ft}\left(x_{ft} - x_{ft-1}\right) - \sum_{t \in T} depF_{ft} x_{ft} \quad \forall f \in F \tag{3.7}$$

$$tv_{fr} = \sum_{\substack{t \in T \\ t=1}} invR_{frt} y_{frt} + \sum_{\substack{t \in T \\ t>1}} invR_{frt}\left(y_{frt} - y_{frt-1}\right) - \sum_{t \in T} depR_{frt} y_{frt} \quad \forall f \in F, r \in R \tag{3.8}$$

In the context of multi-period models, the calculation of the terminal value should consider structural network changes in different periods. Therefore, only terminal values of those facility locations and resources are integrated into the aggregated terminal value, which are opened in the last period. We ensure this assumption with inequalities (3.9) and (3.10).

$$tv_f \leq BigM x_{ft} \quad \forall f \in F, t = T \tag{3.9}$$

$$tv_{fr} \leq BigM y_{frt} \quad \forall f \in F, r \in R, t = T \tag{3.10}$$

Equation (3.11) illustrates the calculation of capital expenditures on the facility and resource stage for each period.

$$Invest_t = \begin{cases} \sum_{f \in F} invF_{ft} x_{ft} + \sum_{f \in F} \sum_{r \in R} invR_{frt} y_{frt} & \forall\, t = 1 \\ \sum_{f \in F} invF_{ft}\left(x_{ft} - x_{ft-1}\right) + \sum_{f \in F} \sum_{r \in R} invR_{frt}\left(y_{frt} - y_{frt-1}\right) & \forall\, t > 1 \end{cases} \tag{3.11}$$

Constraints:

The sum of product flows of product p shipped from the facilities to customer c is equal to the demand of customer c according to the demand function mentioned above. Therefore (3.12) equals (3.1). Because ω_{cptb} is binary, (3.13) ensures that only one demand level is selected.

$$D_{cpt} = \sum_{b \in B} \omega_{cptb} d(\Pi)_{bcpt} \quad \forall c \in C, p \in P, t \in T \tag{3.12}$$

$$\sum_{b \in B} \omega_{cptb} = 1 \quad \forall c \in C, p \in P, t \in T \tag{3.13}$$

$$\sum_{f \in F} \sum_{l \in L} TP_{fcplt} = D_{cpt} \quad \forall\, c \in C, p \in P, t \in T \tag{3.14}$$

The amount of final product p shipped from one facility to all customers on logistic mode l is equal to the production quantity of the last production process of product p on the according resource:

$$\sum_{l \in L} TP_{fcplt} = \sum_{r \in R^q} \sum_{q \in Q^{p*}} PA_{fcprqt} \quad \forall\, f \in F, c \in C, p \in P, t \in T \tag{3.15}$$

Intercompany flows of intermediate products are considered in the following constraints. Constraint (3.16) ensures the supply of intermediate products, that are inputs into the production of final product p:

$$\sum_{r \in R^q} \sum_{q \in Q^{p*}} PA_{fcprqt}\, ExIn_{oq} = \sum_{g \in F} \sum_{l \in L} \sum_{r \in R} TAIP_{gfcprolt} \quad \forall\, f \in F, c \in C, p \in P, t \in T, o \in Q \tag{3.16}$$

Material flows from suppliers should ensure, that enough material is available for production processes of intermediate and final products:

$$\sum_{e \in F} \sum_{p \in P} \sum_{r \in R} \sum_{q \in Q} \sum_{l \in L} TAIP_{fecprqlt}\, BoM_{rqm} + \sum_{p \in P} \sum_{r \in R} \sum_{q \in Q^{p*}} PA_{fcprqt} BoM_{rqm} = \sum_{s \in S} \sum_{l \in L} SA_{sfcmlt}\, \forall\, f \in F, c \in C, m \in M, t \in T \tag{3.17}$$

Production capacity considerations are described by the following inequality:

$$\sum_{e\in F}\sum_{c\in C}\sum_{p\in P}\sum_{q\in Q}\sum_{l\in L}\beta_{prq}TAIP_{fecprqlt}+\sum_{c\in C}\sum_{p\in P}\sum_{q\in Q^{p*}}\beta_{prq}PA_{fcprqt} \leq CapR_{frt}y_{frt} \quad \forall\, f\in F, r\in R, t\in T \tag{3.18}$$

Thus capacities on the facility level are unrestricted, inequality (3.19) links flow variable TAIP with binary variable x_{ft}:

$$\sum_{e\in F}\sum_{c\in C}\sum_{p\in P}\sum_{r\in R}\sum_{q\in Q}\sum_{l\in L}TAIP_{fecprqlt}+\sum_{c\in C}\sum_{p\in P}\sum_{r\in R^{q}}\sum_{q\in Q^{p*}}PA_{fcprqt} \leq BigMx_{ft} \quad \forall\, f\in F, t\in T \tag{3.19}$$

A production resource can only be installed at opened facilities:

$$y_{frt}\leq x_{ft} \quad \forall\, f\in F, r\in R, t\in T \tag{3.20}$$

Inequalities (3.21) – (3.26) define restructuring constraints for both facility and resource level. In this way, dynamics of opening and closing facility locations as well as installing and reinstalling resources can be considered.

$$0\geq -x_{ft-1}+rx_{ft} \quad \forall f\in F, t>1\in T \tag{3.21}$$

$$0\geq -(1-x_{ft})+rx_{ft} \quad \forall f\in F, t>1\in T \tag{3.22}$$

$$1\geq x_{ft-1}+\left(1-x_{ft}\right)-rx_{ft} \quad \forall f\in F, t>1\in T \tag{3.23}$$

$$0\geq -y_{frt-1}+ry_{frt} \quad \forall f\in F, r\in R, t>1\in T \tag{3.24}$$

$$0\geq -(1-y_{frt})+ry_{frt} \quad \forall f\in F, r\in R, t>1\in T \tag{3.25}$$

$$1\geq y_{frt-1}+\left(1-y_{frt}\right)-ry_{frt} \quad \forall f\in F, r\in R, t>1\in T \tag{3.26}$$

Environmental impact modelling

According to the formulation of equation (3.1) it is necessary to calculate the environmental emissions in a customer- and product-specific way for each period, generating in the value creation process of the products ordered by a customer. Hence, the environmental impact depends on the allocation of supply and production processes and usage of logistic modes.

$$\Pi_{cpt} = \sum_{s\in S}\sum_{f\in F}\sum_{m\in M}\sum_{l\in L} EPS_{sfmlt} SA_{sfcmlt} + \sum_{f\in F}\sum_{e\in F}\sum_{q\in Q^p}\sum_{r\in R^q}\sum_{l\in L} EPI_{feprqlt} TAIP_{fecprqlt} + \sum_{f\in F}\sum_{r\in R}\sum_{q\in Q} EPP_{fprqt}\, PA_{fcprqt} + \sum_{f\in F}\sum_{l\in L} EPC_{fcplt} TP_{fcplt} \quad \forall\, c\in C, p\in P, t\in T \tag{3.27}$$

The environmental performance, calculated in (3.27) contains the emissions of raw materials distributed by suppliers and the according logistic processes. In addition, emissions of the production of intermediate- and final products as well as intercompany and customer specific distribution processes are considered.

After the identification of the relevant environmental impact, it is necessary to link it with the acceptance levels of customers, which are introduced to derive customer´s demand (see equation [3.1]). Therefore, binary variable ω_{cptb} is introduced, which is both customer and product specific and which determines the relevant bound (3.28) - (3.32).

$$EPB_{cptb} \leq UB_{cptb}\omega_{cptb} \qquad \forall\ c\in C, p\in P, t\in T, b\in B \tag{3.28}$$

$$EPB_{cptb} \geq LB_{cptb}\omega_{cptb} \qquad \forall\ c\in C, p\in P, t\in T, b = 1 \tag{3.29}$$

$$EPB_{cptb} > UB_{cptb-1}\omega_{cptb} \qquad \forall\ c\in C, p\in P, t\in T, b > 1 \tag{3.30}$$

$$\sum_{b\in B} EPB_{cptb} = \Pi_{cpt} \qquad \forall\ c\in C, p\in P, t\in T \tag{3.31}$$

$$\sum_{b \in B} \omega_{cptb} = 1 \qquad \forall\ c \in C, p \in P, t \in T \tag{3.32}$$

In addition to the customer specific environmental performance on the product level, constraint (3.33) measures the environmental impact per facility, which is used in (3.34) to ensure that the level of environmental impact complies with the legal environmental impact level at each facility.

$$\xi_{ft} = \sum_{p \in P} \sum_{q \in Q^p} \sum_{r \in R^q} EPP_{fprqt} PA_{fcprqt} + \sum_{p \in P} \sum_{e \in F} \sum_{q \in Q^p} \sum_{r \in R^q} \sum_{l \in L} EPI_{feprqlt} TAIP_{fecprqlt} \qquad \forall\ f \in F, t \in T \tag{3.33}$$

$$\xi_{ft} + \zeta_{ft} \leq LIL_{ft} \qquad \forall\ f \in F, t \in T \tag{3.34}$$

In constraint (3.34) ζ_{ft} represents the amount of carbon equivalents associated with a facility location which exceeds the legal impact level determined by governmental institutions. It is priced with penalty costs and integrated into the ebitda calculation (3.4). The opening decision variable x_{ft} is binary:

$$x_{ft} \in \{0,1\} \quad \forall\, f \in F, t \in T \tag{3.35}$$

The decision variable y_{frt} considering investments in resources is also binary:

$$y_{frt} \in \{0,1\} \quad \forall\, f \in F, r \in R, t \in T \tag{3.36}$$

The decision variable ω_{cptb}, which identifies the customer specific bound for accepting emissions is also binary:

$$\omega_{cptb} \in \{0,1\} \quad \forall c \in C, p \in P, t \in T, b \in B \tag{3.37}$$

The other decisions variables are non-negative (3.38):

$$SA_{sfcmlt} PA_{fcprqt}, TAIP_{fecprqlt}, TAIP_{gfcprolt}, TP_{fcplt}, \zeta_{ft} \geq 0 \quad \forall\, c \in C, e \in E, f \in F, g \in G, l \in L, m \in M, o \in O, p \in P, r \in R, t \in T \tag{3.38}$$

3.4.3 Numerical example

3.4.3.1 Case description

In this section we present a numerical example to evaluate the model proposed above. The supply chain structure is simplified but inspired from a real-world case. We consider a product specific supply chain design subproblem of a medium-sized, mechanical and plant engineering company that produces security equipment for chemical processing facilities based in Germany. On the supplier level, five suppliers are considered. Each supplier has a specific production capacity regarding the five materials, which are used in one of the three production processes of the company. The three production processes can be executed using four different manufacturing resources (e.g. machines) at three potential production facility locations. Each process step results in an intermediate product. Either the processing of these intermediate products is continued at the same facility or they are shipped to other facilities for further processing. The production resources differ in their technical abilities regarding the specific manufacturing processes. The required materials to be used in the various production processes depend on the selected resources and can be derived from the corresponding bill of materials. We consider two products. While production of product 1 includes production processes 1 and 2, product 2 also needs process 3 to be accomplished. Consequently, product 2 is an advanced version of product 1. Customers are aggregated into six clusters with different requirements regarding environmental consciousness of the considered products. Distribution processes between the supply chain nodes can be executed by two different logistic modes (e.g. air and road). Since, supply chain design problems consider a long-term planning horizon, we take three planning periods into account. The free cash flow is discounted using a fixed, company specific discount rate. Depending on each customer, the forecast scenario that will be considered for basic demand in period 2 and 3 takes both decreasing and increasing demand trends into account. Table 3.2 summarizes the information regarding the underlying planning problem.

Table 3.2: Sets of the numerical example

Set	Number
Suppliers	3
Materials	5
Production facilities	5
Production processes	3
Production resources	4
Products	2
Customers	6
Logistic modes	2
Planning periods	3

As mentioned above, the customer demand is negatively correlated to the environmental performance of each product, so the higher the environmental impact, the lower the demand. Therefore, we introduce the concept of demand levels according to equation (3.1), to study the impact of changing production structures with the effect of decreasing environmental impact. According to these assumptions, tables 3.3 and 3.4 illustrate customer specific demand data and the acceptance levels of environmental impact applied for period 1 in our numerical example.

Table 3.3: Customers´ demand (Period 1)

Product	Bound	Customer					
		1	2	3	4	5	6
1	1	1000	1200	500	2000	800	2500
	2	700	720	475	1600	600	2125
2	1	800	2000	200	1500	1200	800
	2	560	1200	190	1200	900	680

Table 3.4: Acceptance levels of environmental impact values (in thousand units)

Product	Bound	Customer					
		1	2	3	4	5	6
1	1	800	1300	300	1500	700	1750
	2	100000	100000	100000	100000	100000	100000
2	1	850	2000	175	1500	1000	1000
	2	100000	100000	100000	100000	100000	100000

All supply chain processes, which are essential to fulfil customer demand, are evaluated in both, an economic and an environmental way. The different decision options at the supply chain stages are ensuring flexibility for the decision maker to influence the environmental impact of the products. Using the proposed model, we support the decision maker in evaluating an appropriate supply chain design. As a result, it could be identified, which supplier has to be selected to deliver an appropriate amount of materials to the opened production facilities according to the production processes assigned to these facilities. In addition, decisions regarding investments connected with manufacturing resources are made. Both, intercompany and customer-oriented network flows are planned. All decisions are made under consideration of customer´s requirements regarding the environmental impact, while the total discounted free cash flow is maximized for a multi-period planning horizon. Hence, we analyse the trade-off between a cost-efficient but environmental damaging supply chain and a higher sales volume, due to higher customer demand resulting from more environmentally conscious operations.

3.4.3.2 Results

As mentioned in section 3.4, a linear model is developed. Following this assumption, we can use a standard linear solver engine (e.g. IBM ILOG CPLEX, LINGO 13.0) to solve the described numerical example using an INTEL i7 2.9 GHz machine with 8 GB RAM under WINDOWS 7 SP 1. To analyse the planning problem we consider two different scenarios.

Initial scenario:

The initial situation is characterized by the parameters as mentioned in 3.4.3.1. The optimal discounted free cash flow is 421.220.200 €. The solution recommends the opening of production facility locations F3 and F5 in all periods. While facility 5 is supplied by suppliers 1 and 5, supplier 1 and 4 deliver the relevant materials to facility 3. To perform production processes, production resources 1 and 2 should be installed in both facilities. In contrast to the production facility in location 5, which only produces intermediate products for self-supply, the production facility in location 3 also supplies the facility in location 5 with a share of the internal intermediate product demand. The final product is delivered to customers from production facility location 5. Only customer 2 is supplied by both production facilities. Figure 3.5 illustrates this solution. The facility in location 5 is assumed to be the less costly production facility location regarding opening investments, fix costs as well as production costs. For all cases the second demand bound of the customers, except demand of customer 4 for product 2, is selected. Therefore we can state that the lower sales volume does not compensate the higher costs, which would be necessary to fulfil customers´ environmental impact requirements as defined by the first demand bound.

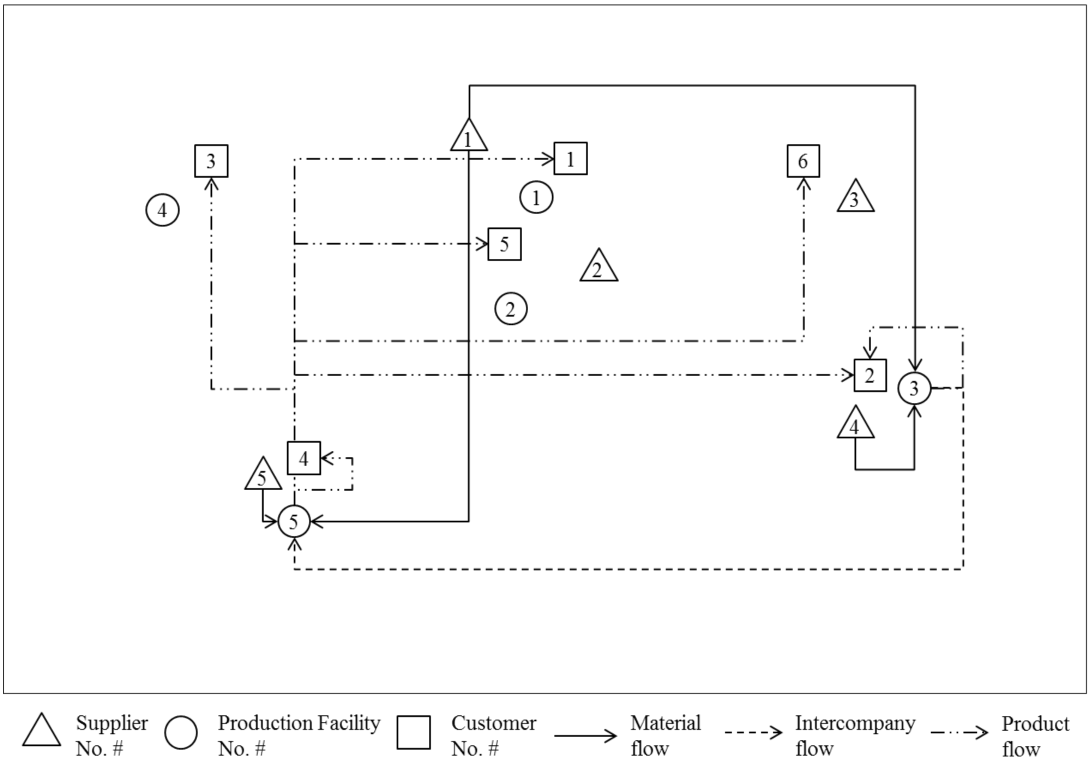

Figure 3.4: Optimal Supply Chain Design of the initial scenario

Demand scenario:

In the second scenario we analyse variations in customer demand. Therefore we conduct a sensitivity analysis regarding the first and second demand bound. By doing this we simulate situations, in which customers shorten their demand excessively when a certain environmental impact level is reached. Figure 3.5 shows the discounted free cash flow as a function of the relative demand of demand bound 2. As it is shown, there is nearly a linear relationship. The function declines steeper between 100% and 90% as well as between 70% and 60% compared to other areas of the function. Doing a more detailed analysis, we can identify some changes in the supply chain structure.

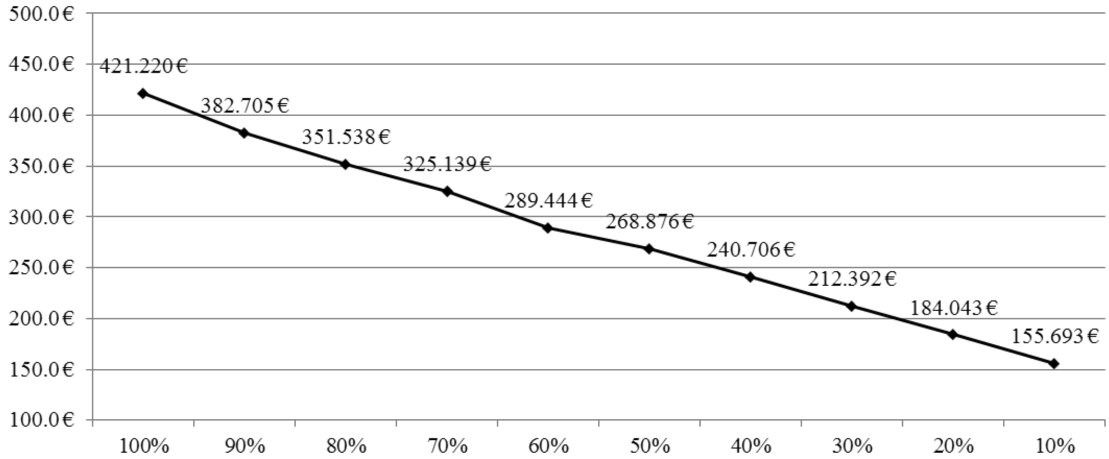

Figure 3.5: Sensitive analysis of demand bound 2 (Free cash flow in million €)

Table 3.5 presents the used resources on the production facility level and the customers, which are supplied by the opened facilities.

Table 3.5: Manufacturing structure of products per scenario[144]

Scenario	Facility	Installed resources	Supply Material	Supply Intermediate Products	Customers	Products
100%	F5	R1*, R2	S1 (M4) S5 (M1, M2, M3, M4, M5)	F5	C1, C2, C3, C4, C5	P1, P2
90%	F5	R1*, R2	S1 (M4) S5 (M1, M2, M3, M4, M5)	F5	C1, C2, C3, C4, C5	P1, P2
80%	F3	R1*, R2	S4 (M1, M2, M3, M4, M5)	F3	C2	P1, P2
	F5	R1*, R2	S1 (M4) S5 (M1, M2, M3, M4, M5)	F3, F5	C1, C2, C3, C4, C5	P1, P2
70%	F3	R1*, R2	S4 (M1, M2, M3, M4, M5)	F3	C2	P1, P2
	F5	R1*, R2	S1 (M4) S5 (M1, M2, M3, M4, M5)	F3, F5	C1, C2, C3, C4, C5	P1, P2

144 * used to produce intermediate products

60%	F3	R1*, R2	S4 (M1, M2, M3, M4, M5)	F3	C2	P1, P2
	F5	R2, R4*	S1 (M4) S5 (M1, M2, M3, M4, M5)	F3, F5	C1, C2, C3, C4, C5	P1, P2
50%	F3	R1*, R2	S4 (M1, M2, M3, M4, M5)	F3	C2	P1, P2
	F5	R2, R4*	S1 (M4) S5 (M1, M2, M3, M4, M5)	F3, F5	C1, C2, C3, C4, C5	P1, P2
40%	F3	R1*, R2	S4 (M1, M2, M3, M4, M5)	F3	C2	P1, P2
	F5	R2, R4*	S1 (M4) S5 (M1, M2, M3, M4, M5)	F3, F5	C1, C2, C3, C4, C5	P1, P2
30%	F3	R1*, R2	S4 (M1, M2, M3, M4, M5)	F3	C2	P1, P2
	F5	R2, R4*	S1 (M4) S5 (M1, M2, M3, M4, M5)	F3, F5	C1, C2, C3, C4, C5	P1, P2
20%	F3	R1*, R2	S4 (M1, M2, M3, M4, M5)	F3	C2	P1, P2
	F5	R2, R4*	S1 (M4) S5 (M1, M2, M3, M4, M5)	F3, F5	C1, C2, C3, C4, C5	P1, P2
10%	F3	R1*, R2	S4 (M1, M2, M3, M4, M5)	F3	C2	P1, P2
	F5	R2, R4*	S1 (M4) S5 (M1, M2, M3, M4, M5)	F3, F5	C1, C2, C3, C4, C5	P1, P2

In a situation, in which the demand values of each demand bound are equal, the whole production would be located at production facility in location 5. Starting with a demand volume relation of the two demand levels of 80% the structure of the supply chain changes. In addition to the facility in location 5, the facility in location 3 is opened up as a second production facility, which performs production processes to create intermediate as well as final products. Simultaneously, a third supply source (S4) is selected to deliver raw materials to the facility in location 3. While the majority of intermediate products is produced at the facility in location 5, a small part of the intermediate products is manufactured at the facility in location 3 for self-supply and for final production at the facility in location 5. In contrast to the facility in location 5, which delivers the final products to all customers, the facility in location 3 only supplies customer 2. 54.41% of the demand of customer 2 regarding product 1 is fulfiled by the facility in location 3 and 45.59% by the facility in location 5. Regarding product 2 the major part is delivered by the facility in location 3 (91.2%) while only 8.7% is shipped from the facility in location 5 to customer 2. Analysing the 70% scenario, only changes in the distribution of demand of customer 2 are identified. 69.17% of product 1 and 91.28% of product 2 are delivered from the facility in location 3. The remaining scenario solutions differ regarding the implementation of resource 4 instead of resource 1 at the facility in location 5. This resource is able to perform processes 1 as well as 2 instead of processes 1 and 3. Demand of customer 2 is mainly fulfilled by the facility in location 3.

It can be identified that there is a strong relationship between supply chain design decisions and customer´s requirements regarding the environmental impact of a product. In case customers are highly sensitive to environmental impact, supply chain design decisions may be suboptimal, if a decision maker does not explicitly consider the customer-specific demand behavior in the planning approach.

3.4.4 Conclusion and future research

Nowadays, integrating sustainable issues in business planning is one of the major targets of company´s decision makers. Besides pressure of governments and non-governmental organizations, customer requirements force companies to reconsider their supply chain design. To provide a decision support approach, this paper has presented a multi-echelon, multi-product supply chain design model, which considers both economic and environmental impact of value adding activities in the supply chain. Compared to previous literature, our approach particularly focuses on customer requirements regarding the environmental impact of the delivered products. Therefore, we integrated an environmental impact dependent, piecewise linear, customer specific demand function. In addition, the production of the final products is divided into single production processes. Each process can be performed at different production resources, which are characterized by individual production costs as well as environmental impact per process. Hence, our model can help decision makers to evaluate discrete investment decisions in production resources in an environmentally conscious supply chain design context. In a numerical example the capabilities of our model has been illustrated.

As a lack of our paper, a complete real-world case is missing. Thus, a possible future extension is to consider a complex real-world case to verify our preliminary results. To deepen the focus on customer requirements regarding the environmental impact of products, we identified an integrated assessment of impact-oriented environmental risks as an interesting research field. Therefore, also the modelling of an additional objective function considering the environmental impact could be useful. By doing so, the trade-off between the economic and the environmental dimension of sustainability could be further investigated. In addition our assumption, that the demand values as well as the limits of each demand bound are deterministic, could be replaced by a stochastic modelling approach. As the literature review illustrates, the majority of modelling approaches in the sustainable supply chain design context uses general environmental performance metrics. Thus, an analysis of the relevant environmental performance measures regarding strategic supply chain design would be another promising field of research. Finally, the consideration of interrelations of the price and environmental performance of a product in a supply chain design model would be of interest.

4 An environmentally conscious robust closed-loop supply chain design[145]

4.1 Introduction

Nowadays, the protection of the environment is getting more and more critical. Besides that we recently see a growing scarcity of many natural resources that seem to become critical for some manufacturing industries. These challenges as well as the increasing awareness of environmental and social issues by both governments and consumers are forcing companies to reconsider and quite often to restructure their supply chain operations or even to alter their business strategies.[146] “This process involves not only an evaluation of the environmental and social impacts of existing products and production processes, but also an assessment of environmental and social liabilities and opportunities throughout the corporate value chain.”[147] Hence, strategic planning activities, especially of multinational companies, are recently influenced by an increasing number of regulations and non-governmental pressures.[148] European Union´s Waste Electrical and Electronic Equipment (WEEE), Restriction on the Use of Hazardous Substances (RoHS) and Ecodesign Requirement for Energy-using Product (EuP) directives are only a few examples.[149]

Besides, not only external pressures from stakeholders such as governments, customers, society, NGOs, competitors and suppliers are drivers for putting more attention to environmental practices in the supply chain management context.[150] According to empirical studies the (re-)design of an environmental supply chain structure is associated with an improvement of economic performance.[151] A well formulated environmental supply

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[145] This chapter is published as Altmann, M.; Bogaschewsky, R., supply chain design, 2014, pp. 613–637.

[146] Cf. Wu, Z.; Pagell, M., sustainable supply chain management, 2011, p. 577; Shukla, A. C.; Deshmukh, S. G.; Kanda, A., Environmentally responsive supply chains, 2009, p. 155; Quariguasi Frota Neto, J. et al., sustainable logistics networks, 2008, p. 195.

[147] Maxwell, J. et al., Green Schemes, 1997, p. 132.

[148] Cf. Zhu, Q.; Sarkis, J.; Lai, K., green supply chain management, 2008, p. 261.

[149] Cf. Quariguasi Frota Neto, J. et al., sustainable supply chains, 2010, p. 4463; Tsai, W.-H.; Hung, S.-J., green supply chain optimisation, 2009, pp. 4991-4992.

[150] Cf. Park-Poaps, H.; Rees, K., Socially Responsible Supply Chain Management, 2010, p. 306; Walker, H., Di Sisto, L.; McBain, D., environmental supply chain management, 2008, p. 73; Zhu, Q.; Sarkis, J., green supply chain practices, 2007, pp. 4337; Handfield, R. B. et al., ‘Green’ value chain, 1997, p. 307; Henriques, I.; Sadorsky, P., environmentally responsive firm, 1996, p. 392.

[151] Cf. Azevedo, S. G.; Carvalho, H.; Cruz, M. V., green practices, 2011, p. 866; Zhu, Q.; Sarkis, J., Lai, K-h., green supply chain management, 2007, pp. 186; Rao, P.; Holt, D., green supply chains, 2005, p. 912; Zhu, Q.; Sarkis, J., green supply chain management, 2004, p. 276.

chain strategy can lead to a number of strategic and competitive benefits, such as better quality, both reduced costs and risks, an improved environmental image, and the enhanced ability to enter new markets.[152] The above mentioned positive effects that might encourage an organization to adopt environment related "best practices" regarding its supply chain help in reaching or securing a competitive advantage.[153] On top of that the availability problem of non-renewable resources (oil, gaz, etc.) and the natural scarcity of some raw materials (e.g. rare earths) often require re-engineering existing supply chains and ask for re-evaluating and possibly alteration of corporate strategies.[154] In this context environmentally conscious supply chain management, e.g. reverse- and closed-loop supply chain management, plays an emerging role.[155]

Following the growing stream of research on environmental issues in supply chain management,[156] we will focus on the environmental dimension of sustainability. In the supply chain context this is often referred to green[157] or environmental[158] supply chain management. While sustainable supply chain management encompasses social, environmental and economic aspects based on the triple-bottom-line approach,[159] environmental supply chain management, defined as “the set of supply chain management policies held, actions taken, and relationships formed in response to concerns related to the natural environment with regard to the design, acquisition, production, distribution, use, reuse, and disposal of the firm’s goods and services“,[160] helps organizations as well as their partners to achieve corporate profit and market share objectives by reducing environmental impacts and risk while improving ecological efficiency.[161]

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[152] Cf. Mefford, R. N., Sustainable Supply Chain, 2011, p. 123; Hervani, A. A.; Helms, M. M.; Sarkis, J., green supply chain management 2005, p. 339; Carter, C. R.; Kale, R.; Grimm, C. M., Environmental purchasing, 2000, p. 224; Wycherley, I., Greening supply chains, 1999, p. 123; Maxwell, J. et al., Green Schemes, 1997, p. 118; Porter, M. E.; van der Linde, C., Environment-Competitiveness, 1995, p. 104.

[153] Cf. Testa, F.; Iraldo, F., Green Supply Chain Management, 2010, p. 953.

[154] Cf. Chaabane, A.; Ramudhin, A.; Paquet, M., sustainable supply chains, 2012 p. 37.

[155] Cf. Srivastava, S. K., Green supply-chain management, 2007, p. 54; Fleischmann, M. et al., Reverse Logistics Network Design, 2004, p. 65.

[156] See Linton, J. D.; Klassen, R.; Jayaraman, V., Sustainable supply chains, 2007, pp. 1075-1082.

[157] See e.g. Vachon, S.; Klassen, R. D., green practices, 2006, pp. 795-821; Zhu, Q.; Sarkis, J., green supply chain management, 2004, pp. 265-289.

[158] See e.g. Beamon, B. M., Environmental and Sustainability Ethics, 2005, pp. 221-234.

[159] Cf. Carter, C. R.; Rogers, D. S., sustainable supply chain management 2008, p. 368; Seuring, S.; Müller, M., sustainable supply chain management, 2008, p. 1700.

[160] Zsidisin, G. A.; Siferd, S. P., Environmental purchasing, 2001, p. 69.

[161] Cf. Azevedo, S. G.; Carvalho, H.; Cruz, M. V., green practices, 2011, p. 866; Zhu, Q.; Sarkis, J.; Lai, K., green supply chain management, 2008, p. 261; Rao, P.; Holt, D., green supply chains, 2005, p. 912.

Supply chain management tasks can be classified into operational, tactical, and strategic. While operational and tactical tasks are characterized by short- and mid-term planning issues, strategic tasks include long-term decisions which normally cannot be modified within a short time or only with high expenses. According to ARONSSON and BRODIN (2006) and HARRIS (2011) long-term environmental supply chain structure planning has an essential effect on the environmental performance,[162] hence a detailed analysis of this planning task is required. Traditionally, strategic supply chain planning or supply chain design models encompass decisions determining the supply chain structure including facility and distribution center locations, choice of transportation modes as well as production processes. Furthermore, these planning activities are normally aligned to financial goals (e.g. profit or net present value maximization) and/or the satisfaction of customer demand subject to quantity and time.[163] As a consequence of the long-term planning environment and the complexity of supply chain design problems, a decision maker is confronted with a high level of uncertainty. In this context it can be assumed that a supply chain planner is risk averse,[164] so the application of the robust optimization concept can be useful. The contribution of this paper is to combine the issues of closed-loop supply chain design, sustainability and robustness.

When broadening the perspective by implying environmental factors it becomes indispensable to define appropriate performance indicators, which have to be included into the objective function. At the same time it is necessary to identify the main influencing factors on the environmental performance of supply chain processes. Consequently, a supply chain design model that covers environmental issues should include decisions regarding purchasing, logistics, production as well as distribution.

In this paper we discuss different impacts of supply chain design decisions on the environmental performance of a supply chain. To illustrate the relationships we propose a robust multi-objective closed-loop supply chain design model which minimizes expected total costs as well as environmental impacts.

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[162] Cf. Aronsson, H.; Brodin, M. H., environmental impact, 2006, p. 397; Harris, I. et al., infrastructure modelling, 2011, p. 313.
[163] Cf. Harrison, T. P., Supply Chain Design, 2001, p. 413.
[164] Cf. Klibi, W.; Martel, A.; Guitoni, A., supply chain networks, 2010, p. 287.

The paper is organized as follows: After an introduction we review the relevant literature and discuss the different approaches. In addition we describe implications of environmental aspects on the supply chain design process in the next section. In Section 3, the importance of capturing uncertainty in supply chain design models is discussed. After that we present an environmentally conscious robust closed-loop supply chain design model in Section 4. The model is evaluated in Section 5 by a case application. Finally, in Section 6 the conclusions of the paper are drawn.

4.2 Environmental aspects in supply chain design

Academic interest in sustainable supply chain management emerged in the last decades.[165] However research intensity in quantitative modeling approaches increased only in the last few years. Most researchers focus either on reverse-loop, or closed-loop modeling, thus focusing on green or sustainable supply chain management.[166] Taking into account a more specific perspective of sustainable supply chain design, where sustainability is not only modeled by reverse logistic flows, the number of publications to be found decreases further.[167] Only a few authors consider environmental parameters in their models.

KRIKKE et al. (2003) introduced a modeling approach for both, product design and supply chain design in a closed-loop context. Centralized versus decentralized network structures as well as alternative product designs are analyzed by applying the model in a refrigerator case.[168] To support the task of long-range planning of environmentally conscious supply chains HUGO and PISTIKOPOULOS (2005) developed a multi-objective mixed integer linear programming model, that maximizes the net present value and minimizes the environmental impact (according to Eco-indicator 99).[169] QUARIGUASI FROTA NETO et al. (2008) proposed a multi-objective optimization approach for sustainable supply chain planning. Environmental impacts are assessed through a three-step process (assessment,

[165] Cf. Seuring, S.; Müller, M., sustainable supply chain management, 2008, pp. 1701.
[166] See e.g. Lee, D. H.; Dong, M.; Bian, W., sustainable logistic network, 2010, pp. 159-166; Sheu, J. B.; Chou, Y. H.; Hu, C. C., green-supply chain management, 2005, pp. 287-313.
[167] Cf. Lee, D. H.; Dong, M.; Bian, W., sustainable logistic network, 2010, p. 159.
[168] See Krikke, H.; Bloemhof-Ruwaard, J.; van Wassenhove, L. N., closed-loop supply chain design, 2003, pp. 3689-3719.
[169] See Hugo, A.; Pistikopoulos, E. N., Environmentally conscious long-range planning, 2005, pp. 1471-1491.

normalization and weighting). Cost minimization as well as environmental impact minimization are objectives of the programming model, whereas the pareto approach is applied to solve the multi-objective programming problem. The authors illustrated their approach by a case study based on the situation of the European pulp and paper industry.[170] RAMUDHIN et al. (2008) developed a supply chain design model under carbon trading considerations through integration of the environmental impact of strategic supply chain decision in carbon dioxide equivalents.[171] GUILLÉN-GOSÁLBEZ and GROSSMANN (2009) take uncertainty into account and formulated a bi-criterion stochastic mixed-integer non-linear program that maximizes net present value and minimizes environmental impact, thus assuming that LCA-data follows a normal probability distribution.[172] Another approach for green supply chain optimization is presented by TSAI and HUNG (2009). They proposed a fuzzy goal programming approach for supplier selection and flow allocation. They suggested that the activity-based approach is suitable for cost and performance evaluation.[173] CRUZ and MATSYPURA (2009) introduced a model which includes the maximization of net returns, the minimization of emissions as well as the minimization of risk regarding organizational risk, environmental risk and network-related risk. They include different supply chain actors, thus taking a supply chain system optimization approach.[174] MELE et al. (2009) developed a bi-objective mixed integer linear programming problem considering environmental supply chain design decisions in the sugarcane industry of Argentina, where environmental impact is determined according to the LCA-approach.[175] Another multi-objective optimization model is proposed by WANG et al. (2011). Their single period model consists of minimizing total cost and environmental influence, represented by carbon dioxide emissions. The tradeoff between the two objectives is demonstrated in a numerical study. The impacts on decision making caused by capacity, supply and changing demands are analyzed as well.[176] Different types of environmental impact, such as solid and liquid waste, greenhouse gas emissions as outputs of production processes in the supply chain are incorporated in the work of CHAABANE, RAMUDHIN and PAQUET (2012). Instead of focusing on one supply chain node where environmental impacts are measured, they analyzed the life cycle of a product. Furthermore, reverse logistic

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[170] See Quariguasi Frota Neto, J. et al., sustainable logistics networks, 2008, pp. 195-208.
[171] See Ramudhin, A. et al., Green Supply Chain Network Design, 2008, pp. 1093-1097.
[172] See Guillen-Gosalbez, G.; Grossmann, I. E.; Sustainable Chemical Supply Chains, 2009, pp. 99-121.
[173] See Tsai, W. H.; Hung, S. J., green supply chain optimization, 2009, pp. 4991-5017.
[174] See Cruz, J. M.; Matsypura, D., environmental decision-making, 2009, pp. 621-648.
[175] See Mele, F. D. et al., Sustainable Supply Chain, 2009, pp. 597-602.
[176] See Wang, F.; Lai, X.; Shi, N., green supply chain network design, 2011, pp. 262-269.

transactions are considered.[177] Opposite to the above mentioned approaches, HARRIS et al. (2011) used a simulation model to analyze the relationship between total logistic costs and environmental impact. They focused on carbon emissions, considering different scenarios regarding infrastructure and different freight vehicle utilization ratios.[178]

As the literature review reveals, according to non-environmentally conscious supply chain design models the majority of green supply chain design models are defined under deterministic assumptions as linear programming models. Environmental impacts across supply chains are basically measured based on LCA principles. One possible modeling approach for the integration of carbon footprints is proposed by SUNDARAKANI et al. (2010).[179]

Environmental aspects in the supply chain context are well studied.[180] Researchers defined different factors that influence the environmental performance of supply chains.[181] These factors, that cannot be influenced to full extent without active participation of suppliers, retailers, clients and final consumers, are e.g. the intensive use of raw materials and natural resources, the escalating production of waste caused by consumer goods and their packaging and the environmental impacts of the transportation of intermediate and consumer goods to their final markets. Environmental management along the supply chain means that all value adding processes are focused on minimizing the total environmental impact.[182] Starting with product design and ending with possible recycling many steps in the value adding process are relevant for measuring the environmental impact along the supply chain.

Figure 4.1 illustrates the architecture of environmentally conscious supply chains and shows that - according to the concept of MENTZNER et al. (2001)[183] - environmental supply chain management is not only of concern for a focal company. It also takes into account inter-organizationally sharing of environmental responsibility.[184]

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177 See Chaabane, A.; Ramudhin, A.; Paquet, M., sustainable supply chains, 2012, pp. 37-49.
178 See Harris, I. et al., infrastructure modelling, 2011, pp. 313-321.
179 See Sundarakani, B. et al., carbon footprints across the supply chain, 2010, pp. 43-50.
180 See e.g. Seuring, S.; Müller, M., sustainable supply chain management, 2008, p. 1702.
181 See e.g. Srivastava, S. M., Green supply-chain management, 2007, pp. 55-56.
182 Cf. Wu, H.-J.; Dunn, S. C., responsible logistics systems, 1995, p. 23.
183 See Mentzner, J. et al., Supply Chain, 2001, p. 19.
184 Cf. Hervani, A. A.; Helms, M. M.; Sarkis, J., green supply chain management, 2005, pp. 336.

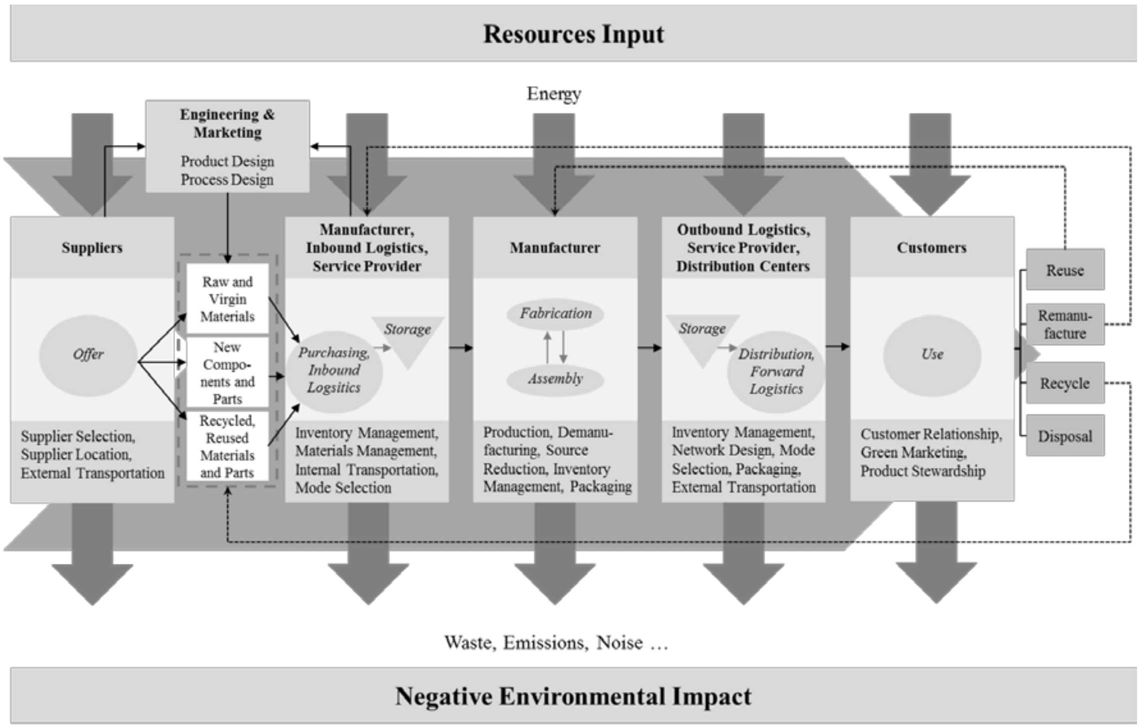

Figure 4.1: Environmentally conscious supply chain architecture[185]

In addition to that, environmental supply chain decisions interact with other business functions like marketing, purchasing, distribution, logistics and operations management. The issues that are involved comprise customer supplier relationship, delivery times, inventory management, product development and purchasing.[186] Relevant supply chain management decisions, which influence the environmental impact, are also drawn such as sourcing and selecting suppliers, assessing supplier's and their environmental performance, modifying and managing processes, reducing packaging and overall waste, developing more eco-friendly products, reducing carbon emissions associated with manufacturing and transportation of goods etc.[187] The wide field of tasks shines a light on the complexity of the associated planning problem. As WU and DUNN (1995) pointed out, strategic network design is one of the most important decisions that influence the environmental performance of the supply chain.[188] Equal to traditional, financially driven

[185] The figure is based on Hervani, A. A.; Helms, M. M.; Sarkis, J., green supply chain management, 2005, p. 335.
[186] Cf. Rao, P., Greening the supply chain, 2002, p. 633.
[187] Cf. Walker, H.; Di Sisto, L.; McBain, D., environmental supply chain management, 2008, p. 69; Vachon, S.; Klassen, R. D., green practices, 2006, p. 812; Beamon, B. M., green supply chain, 1999, p. 337.
[188] Cf. Wu, H.-J.; Dunn, S. C., responsible logistics systems, 1995, p. 29.

supply chain problems, the interrelations between the different supply chain stages have to be considered when designing an environmental supply chain.

The following strategic supply chain design topics have a rather large impact on environmental supply chain performance:

Facility location: The location of a facility determines its geographical distance from suppliers and customers. The shorter the distance, the lower the potential environmental impact of transportation processes. The accessibility of a facility should also be integrated into the decision regarding its location. The possibility to use environmentally conscious transportation modes (e.g. train or barge) could improve the environmental and economic performance.[189] Also country-specific environmental regulations have to be taken into account. Hence, facility location decisions might be more or less strongly influenced by local environmental restrictions, which in turn affect the total environmental impact of a supply chain.

Logistics: Two main factors regarding logistic decisions that influence environmental performance can be differentiated. On the one hand the selection of environmentally conscious transportation modes and vehicles is an important issue. On the other hand fuel efficiency of the vehicle fleet might influence the selection of logistics service providers or on investing in self-owned transportation vehicles.[190] The selection of service providers who have adopted effective environmental practices (i.e., applying an environmental management system that complies with ISO 14001 requirements) can be useful to reduce the environmental impact associated with their activities.[191] In addition, optimal distribution system design improves the environmental performance of logistic processes. The amount of shipments could be reduced through consolidation to various customers.[192] The level of vehicle utilization is another factor influencing the optimum design of supply and distribution networks.[193]

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[189] Cf. McKinnon, A. C., Logistics and the environment, 2003, p. 673.
[190] Cf. Carter, C. R.; Jennings, M. M., Logistics social responsibility, 2002, p. 154.
[191] Cf. Sarkis, J., green supply chain management, 2003, p. 399.
[192] Cf. Kotzab, H., Sustainable supply chain design, 2011, p. 100.
[193] Cf. Harris, I. et al., infrastructure modelling, 2011, p. 320.

Supplier selection: Taken environmental selection criteria into account, e.g. based on the environmental management standard ISO 14000, supplier selection plays a fundamental role especially when applying the LCA-approach, where the environmental impact of a product is measured by a cradle-to-grave analysis. Furthermore the selection of suppliers and supplied (raw-) materials determine the following production steps on the manufacturing level. Thus the environmental performance of raw materials strongly influence the environmental quality of the final product, this topic is of relevance. The production processes of the manufacturers could be environmentally optimized but cannot compensate a highly negative impact on the supplier stage. In addition, the location of the supplier determines the possible transportation modes, influences the transportation distance and hence has an effect on transportation emissions.

Investment planning: Long-term investments in building up new plants or distribution centers as well as in new machines or vehicle fleets can improve the environmental performance when investing in alternatives that show higher levels of ecological efficiency. KLASSEN and WHYBARK (1999) stated investing in pollution prevention technology may have a high impact on the environmental performance.[194]

Production allocation and Capacity planning: The allocation of production capacities along facilities according to customer demands enables a more efficient production and can help reducing transportation processes from other facilities to satisfy customer demand. In addition, allocating manufacturing facilities according to geographical distances to customers helps reducing transportation distances. However, production cost and capacity utilization has to be taken into account as well, so that longer transportation distances might turn out to be preferable.

Inventory planning: As BONNEY and JABER (2011) pointed out, inventory planning decisions influence the environmental performance of a supply chain.[195] However, not all of the options to reduce resource usage or pollution by inventory planning decisions are part of the supply chain design. But fundamental aspects such as warehouse location and rooting decisions are typical supply chain design tasks and they usually have a major impact on economic and environmental performance criteria. According to the supply chain strategy (responsive vs. effective) inventory decisions are influenced by the supplier selection

[194] Cf. Klassen, R. D.; Whybark, D. C., environmental technologies, 1999, p. 610.
[195] Cf. Bonney, M.; Jaber, M. Y., Environmentally responsible inventory models, 2011, p. 48.

and production allocation topics in this way that the inventory level depends on the replenishment time. According to COOPER et al. (1991) decentralized warehousing is a way to reduce environmental impact. The flexibility of a decentralized warehousing concept leads to shorter transportation distances.[196]

To measure the influence of the mentioned topics, appropriate performance indicators need to be identified. On the one hand these indicators can be extracted from sustainable standards and norms such as GLOBAL REPORTING INITIATIVE Standard (GRI) or ISO14001. On the other hand some indicators can be found in the relevant literature.[197] Analyzing Canadian companies ROCA and SEARCY (2012) suggested that the selection of performance indicators depends on the industry, in which the indicators are applied.[198] In addition the decision maker should select the target values according to the requirements of his stakeholders. Most indicators listed in the above mentioned literature are determined by product design decisions. Considering the high aggregation level of strategic supply chain design decisions only a few indicators are appropriate (Table 4.1):

Table 4.1: Environmental performance indicators[199]

	Facility location	Logistics	Supplier selection	Investment planning	Production allocation /Capacity planning	Inventory planning
EN: Location and size of land owned, leased, managed in, or adjacent to, protected areas and areas of high biodiversity value outside protected areas.	▪				▪	
EN: Number of IUCN Red List species and national conservation list species with habitats in areas	▪				▪	

[196] Cf. Cooper, J.; Browne, M.; Peters, M., European logistics, 1991, p. 277.
[197] See. e.g. Olsthoorn, X. et al., Environmental indicators, 2001, pp. 453-463; Krajnc, D.; Glavič, P., sustainable production, 2003, pp. 279-288; Azapagic, A., sustainable development indicators, 2004, pp. 639-662.
[198] Cf. Roca, L. C.; Searcy, C., indicators, 2012, p. 110.
[199] Source: AI: Azapagic, A., sustainable development indicators, 2004, pp. 649; EN: Global Reporting Initiative, Guidelines, 2011, pp. 1-15; KI: Krajnc, D.; Glavič, P., sustainable production, 2003, pp. 283-285; OI: Olsthoorn, X. et al., Environmental indicators, 2001, p. 462.

affected by operations, by level of extinction risk.						
EN: Weight of transported, imported, exported, or treated waste deemed hazardous under the terms of the Basel Convention Annex I, II, III, and VIII, and percentage of transported waste shipped internationally.	▪	▪	▪		▪	
AI: Resource use and availability	▪				▪	
KI: Total energy costs	▪	▪	▪		▪	▪
AI: Total transport distances	▪	▪	▪		▪	
AI: Percentage distance for transport of products to customers and materials from suppliers to facilities by road, rail and water transport	▪	▪	▪		▪	
EN: Materials used by weight or volume			▪			
EN: Percentage of materials used that are recycled input materials			▪	▪		
OI: Environmental investments				▪		
OI: Nuisance				▪		
AI: Product toxity			▪			
EN : Direct energy consumption by primary energy source				▪		
EN: Indirect energy consumption by primary	▪			▪	▪	
EN: Energy saved due to conservation and efficiency improvements				▪		
EN: Water sources significantly affected by withdrawal of water	▪				▪	
EN: Percentage and total volume of water recycled and reused				▪		

EN: Total direct and indirect greenhouse gas emissions by weight			▪	▪		
EN: Other relevant indirect greenhouse gas emissions by weight			▪	▪		
EN: Emissions of ozone-depleting substances by weight			▪	▪		
EN: NO, SO, and other significant air emissions by type and weight			▪	▪		
EN: Total water discharge by quality and destination			▪	▪		
EN: Total weight of waste by type and disposal method			▪	▪		

Assigning the performance indicators to the main supply chain design decisions lead to the assumption that more environmental performance indicators are influenced by facility location, supplier selection, investment planning and process allocation as by logistics and inventory planning, so these decision topics should be focused.

4.3 Supply chain design under uncertainty

As it has been pointed out in the previous section, the management of supply chains encompasses several different decisions that have a high impact on the cost situation and possibly on revenues of the supply chain. Consequently, the overall value of the supply network and its associated enterprises is influenced. Structural supply chain decisions usually have to be made at a certain point of time, thus relying on on-time information and further assumptions. Based on a more or less high level of uncertainty, decisions have to be made that strongly influence the operational settings and capabilities of the entire value network usually for a longer time period. Since forecasts typically become less reliable the longer the planning period, addressing uncertainty is an important element of long-term network planning. Uncertainty in supply chain design may arise for many different reasons such as technical parameters, process specifics or economic factors.[200] According to PEIDRO et al. (2009) they can be classified into three major domains, where uncertainty occurs: “demand”, “process/manufacturing” and “supply”.[201] In the context of sustainability and closed-loop processes emission parameters as well as the amount and quality of redistributed products could be associated with uncertainty. Hence, the values of some of the planning parameters could not be measured with certainty. Different approaches to cope with this uncertainty exist in the literature that can be classified by the way of their mathematical implementation for these uncertain parameters.[202] On the one hand variations of the planning paramaters can be interpreted by ex post analysis using sensitivity or scenario analysis. On the other hand ex ante integration of uncertain parameters into the planning model can be accomplished by applying stochastic programming, fuzzy programming or robust optimization. In contrast to the other above mentioned approaches robust optimization is looking for a solution that is less sensitive to varying input data (solution robustness) and feasible in the possible set of uncertain scenarios (model robustness).[203] As MULVEY, VANDERBEI and ZENIOS (1995) pointed out, stochastic optimization is appropriate for problems under uncertainty where decisions can be adjusted easily as a reaction to changing conditions, while robust optimization is suitable for problems with a high degree of uncertainty, where a risk-averse decision maker is not able to change a decision once it is fixed.[204]

The underlying linear programming model with design variables (x) and control variables (y) has the following structure:

$$Min\,Z = c^T x + d^T y \tag{4.1}$$

$$s.t. Ax = b \tag{4.2}$$

$$Bx + Cy = e \tag{4.3}$$

$$x, y \geq 0 \tag{4.4}$$

[200] Cf. Kallrath, J., Solving Planning and Design Problems, 2005, pp. 351-352.
[201] Cf. Peidro, D. et al. , supply chain planning under uncertainty, 2009, p. 401.
[202] See Sahinidis, N. V., Optimization under uncertainty, 2004, pp. 972-976.
[203] Cf. Mulvey, J. M.; Vanderbei, R. J.; Zenios, S. A., Robust Optimization, 1995, p. 265.
[204] Cf. Mulvey, J. M.; Vanderbei, R. J.; Zenios, S. A., Robust Optimization, 1995, p. 269.

While coefficients of the structural constraint (4.2) are not associated with uncertainty, equation (4.3) denotes the control constraints whose coefficients are subject to noise.

To model the uncertain parameters, MULVEY, VANDERBEI and ZENIOS (1995) introduced a set of scenarios ($s \in \Omega$) as well as the probability of each scenario p_s ($\sum_s p_s = 1$). The model could be infeasible for some scenarios due to parameter uncertainty. In this case δ_s would be unequal to 0 according to (4.7), otherwise the model is feasible and δ_s would take the value 0.[205] To consider the highly uncertain decision environment of supply chain design, we apply the mean/variance formulation, proposed by MULVEY, VANDERBEI and ZENIOS (1995), whereas λ denotes a weighting factor of the variance.[206]

$$Min\, Z = \sum_{s \in \Omega} p_s \xi_s + \lambda \sum_{s \in \Omega} p_s \left(\xi_s - \sum_{s' \in \Omega} p_{s'}\, \xi_{s'} \right)^2 \tag{4.5}$$

$$s.t.\, Ax = b \tag{4.6}$$

$$B_s x + C_s y_s + \delta_s = e_s \tag{4.7}$$

$$x, y_s, \delta_s \geq 0 \tag{4.8}$$

To handle the great computational effort caused by quadratic formulation YU and LI (2000) proposed an alternative formulation to (4.5), which replaces the quadratic formulation of the variance in the objective function with an absolute deviation formulation (9), and in addition a linearized optimization model (4.10) based on LI (1996):[207]

$$Min\, Z = \sum_{s \in \Omega} p_s \xi_s + \lambda \sum_{s \in \Omega} p_s \left| \xi_s - \sum_{s' \in \Omega} p_{s'}\, \xi_{s'} \right| \tag{4.9}$$

$$Min\, Z = \sum_{s \in \Omega} p_s \xi_s + \lambda \sum_{s \in \Omega} p_s \left[\left(\xi_s - \sum_{s' \in \Omega} p_{s'}\, \xi_{s'} \right) + 2\theta_s \right] \tag{4.10}$$

$$s.t.\, Ax = b \tag{4.11}$$

$$B_s x + C_s y_s + \delta_s = e_s \tag{4.12}$$

$$\xi_s - \sum_{s \in \Omega} p_s\, \xi_s + \theta_s \geq 0 \tag{4.13}$$

$$x, y_s, \delta_s \geq 0 \tag{4.14}$$

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[205] Cf. Mulvey, J. M.; Vanderbei, R. J.; Zenios, S. A., Robust Optimization, 1995, p. 265.
[206] Cf. Mulvey, J. M.; Vanderbei, R. J.; Zenios, S. A., Robust Optimization, 1995, p. 267.
[207] Cf. Yu, C.-S.; Li, H.-L., robust optimization, 2000, p. 389. See Li, H. L., goal programming, 1996, pp. 465-469.

In the case of $\xi_s - \sum_{s\in\Omega} p_s \xi_s \geq 0$, then $\theta_s = 0$ and $Z = \sum_{s\in\Omega} p_s\xi_s + \lambda \sum_{s\in\Omega} p_s[(\xi_s - \sum_{s'\in\Omega} p_{s'} \xi_{s'})]$, otherwise if $\xi_s - \sum_{s\in\Omega} p_s \xi_s < 0$, then $\theta_s = \sum_{s\in\Omega} p_s \xi_s - \xi_s$ and $Z = \sum_{s\in\Omega} p_s\xi_s + \lambda \sum_{s\in\Omega} p_s[(\sum_{s'\in\Omega} p_{s'} \xi_{s'} - \xi_s)]$, accordingly it is proofed, that the solutions of (4.10) - (4.14) is identical to that from (4.9).

4.4 Environmentally conscious closed-loop supply chain design

4.4.1 Assumptions and definitions

In the following, we implement the supply chain design topics with a significant impact on environmental performance discussed in Section 4.2 except for inventory management into the environmentally conscious robust closed-loop supply chain design model, which is based on the assumptions listed hereafter:

1) The model is a discrete model. There is a finite number of potential suppliers, production facilities, redistribution centers and disposal facilities.

2) The planning horizon covers several periods (e.g. years).

3) The model covers the strategic planning activities for one product. Nevertheless multiple products can be modeled.

4) Capacities of suppliers, production facilities and redistribution centers are restricted.

5) Redistribution center are used both to collect used products and remanufacture or dispose them.

6) Cradle-to-grave emission data of production, transportation, redistribution and remanufacturing processes are assumed to have a linear relationship to the amount of product units.

7) The minimization of discounted costs and carbon emission equivalents are objectives of the model. Nevertheless the objectives are very general, they can be adjusted according to the application case using the performance indicators discussed in section 2 or a combination of them.

8) Uncertainty associated to the values of customer demands and return rates is integrated by using discrete scenarios.

The following notations are used in the model formulation:

Sets and indices

$I = \{1, \ldots, i\}$	set of suppliers
$J = \{1, \ldots, j\}$	set of facilities
$K = \{1, \ldots, k\}$	set of customers
$L = \{1, \ldots, l\}$	set of redistribution centers
$M = \{1, \ldots, m\}$	set of materials
$N = \{1, \ldots, n\}$	set of logistic modes
$S = \{1, \ldots, s\}$	set of scenarios
$T = \{1, \ldots, t\}$	set of periods

Parameters

BoM_m	bill of material
c_{mnijt}	unit purchase costs of raw material m at supplier i for facility j shipped by logistic mode n in period t
CF_{jt}	production capacity of facility j in period t
CR_{lt}	capacity of redistribution center l in period t
CS_{imt}	capacity of supplier i for material m in period t
dcc_{jt}	unit production costs at facility j in period t
dem_{kts}	demand of customer cluster k in period t and scenario s
e_{njkt}	unit distribution costs shipped by logistic mode n from facility j to customer cluster k in period t
ed_{lt}	unit CO2e-value of disposal processes at redistribution center l in period t
em_{nmi}	unit CO2e-value of material m produced by supplier I and shipped by logistic mode n
ep_{jt}	unit CO2e-value of each production unit at facility j in period t
er_{nklt}	unit CO2e-value of redistribution processes shipped by logistic mode n from customer cluster k to redistribution center l in period t
ery_{nljt}	unit CO2e-value of remanufacturing and shipping processes with logistic mode n at/from redistribution center l to facility j in period t

ex_{njkt}	unit CO2e-value of distribution processes from facility j to customer cluster k in period t
f_{jt}	fixed set up costs of facility j in period t
g_{lt}	fixed set up costs of redistribution center l in period t
gn_{nklt}	unit redistribution costs shipped by logistic mode n from customer cluster k to redistribution center l in period t
h_{lt}	unit disposal costs at redistribution center l in period t
o_{nljt}	unit remanufacturing and shipping costs with logistic mode n at/from re-distribution center l to facility j in period t
rf_{jt}	fixed restructuring costs of facility j in period t
rc_{lt}	fixed restructuring costs of redistribution center l in period t
β_t	disposal rate in period t
q_{kts}	redistribution rate of customer cluster k in period t and scenario s
$WACC$	weighted average costs of capital; rate at which periodical costs are discounted
λ_1	weighting factor for solution robustness part in objective function 1
λ_2	weighting factor for solution robustness part in objective function 2
ρ_s	probability of scenario s
ω	weighting factor for model robustness
ϖ	weighting factor for objective functions

<u>Decision variables</u>

x_{jt}	binary variable for opening facility j in period t
y_{lt}	binary variable for opening redistribution center l in period t
rx_{jt}	binary variable for restructuring facility j in period t
ry_{lt}	binary variable for restructuring redistribution center l in period t
a_{njkts}	amount shipped by logistic mode n from facility j to customer cluster k in period t and scenario s
b_{nklts}	amount of used products shipped by logistic mode n from customer cluster k to redistribution center l in period t and scenario s
d_{lts}	amount of used products disposed at redistribution center l in period t and scenario s
p_{jt}	production amount at facility j in period t

ret_{nljts}	amount of used products remanufactured at redistribution center l and shipped by logistic mode n to facility j in period t and scenario s
u_{mnijt}	amount of raw material m shipped by logistic mode n from supplier i to facility j in period t
δ_{kts}	amount of not meeting demand of customer cluster k in period t and scenario
θ_{1s}	deviation for violations of the mean of total costs in scenario s
θ_{2s}	deviation for violations of the mean of total emissions in scenario s

4.4.2 Environmentally conscious closed-loop supply chain design model

Objective function

$$\begin{aligned} Min\ Z_1 = \sum_s \rho_s \Bigg(\sum_t \frac{1}{(1+WACC)^t} \Bigg(& \sum_j f_{jt} x_{jt} + \sum_l g_{lt} y_{lt} \\ & + \sum_j rf_{jt} rx_{jt} + \sum_l rc_{lt} ry_{lt} + \sum_m \sum_n \sum_i \sum_j c_{mnijt} u_{mnijt} \\ & + \sum_j dcc_{jt} p_{jt} + \sum_n \sum_j \sum_k e_{njkt} a_{njkts} \\ & + \sum_n \sum_k \sum_l gn_{nklt} b_{nklts} + \sum_l h_{lt} d_{lts} \\ & + \sum_n \sum_l \sum_j o_{nljt} ret_{nljts} \Bigg) \Bigg) \\ & + \lambda_1 \sum_s \rho_s \left[(\tau_s) - \sum_{s'} \rho_{s'} (\tau_{s'}) + 2\theta_{1s} \right] + \omega \sum_s \rho_s \sum_k \sum_t \delta_{kts} \end{aligned} \tag{4.15}$$

Objective function (4.15) minimizes the robust financial objective. It is the sum of the mean value of the discounted total costs regarding supply chain decisions for each scenario and includes the fixed costs of building up and closing facilities and redistribution center, supply and production costs as well as distribution, redistribution and disposal costs, the weighted linearized variance and a weighted term measuring the model robustness.

$$Min\ Z_2 = \sum_s \rho_s \left(\sum_m \sum_n \sum_i \sum_j \sum_t em_{mni} u_{mnijt} + \sum_j \sum_t ep_{jt} p_{jt} + \sum_n \sum_j \sum_k \sum_t ex_{njkt} a_{njkts} + \sum_n \sum_k \sum_l \sum_t er_{nklt} b_{nklts} + \sum_l \sum_t ed_{lt} d_{lts} + \sum_n \sum_l \sum_j \sum_t ery_{nljt} ret_{nljts} \right) + \lambda_2 \sum_s \rho_s \left[(\varphi_s) - \sum_{s'} \rho_{s'} (\varphi_{s'}) + 2\theta_{2s} \right] + \omega \sum_s \rho_s \sum_k \sum_t \delta_{kts} \tag{4.16}$$

The second objective function (4.16) describes the environmental impact calculated by CO_{2eq}. It is equally structured and includes the emissions caused by procurement, production, distribution, redistribution, remanufacturing and disposal processes, the weighted variance and the model robustness term. τ_s in (4.15) and φ_s in (4.16) are defined for formulation convenience and represent the total cost and total emissions respectively for each scenario.

Constraints

$$(\tau_s) - \sum_s \rho_s (\tau_s) + \theta_{1s} \geq 0, \quad \forall s \tag{4.17}$$

$$(\varphi_s) - \sum_s \rho_s (\varphi_s) + \theta_{2s} \geq 0, \quad \forall s \tag{4.18}$$

In order to use the approach proposed in (4.10) - (4.14) constraints (4.17) - (4.18) are auxiliary constraints for linearization.

$$\sum_n \sum_j a_{njkts} + \delta_{kts} = dem_{kts}, \quad \forall k, t, s \tag{4.19}$$

Constraint (4.19) is a control constraint and determines the product flows shipped from facilities to customers. It should be equal to the demand of customer k in each period and scenario.

$$p_{jt} = \sum_n \sum_k a_{njkts}, \quad \forall j, t = 1, s \tag{4.20}$$

In period 1 the sum of products shipped from one facility to all customers is equal to the production quantity of the facility.

$$p_{jt} + \sum_n \sum_l ret_{nlj(t-1)s} = \sum_n \sum_k a_{njkts}, \quad \forall j, t > 1, s \tag{4.21}$$

In the following periods the sum of new and remanufactured products defines the amount of distribution.

$$p_{jt} BoM_m = \sum_n \sum_i u_{nmijt}, \quad \forall j, m, t \tag{4.22}$$

The balance constraint of raw material flow and production quantity is derived of the bill of material.

$$\sum_n \sum_j a_{njkts} q_{kts} = \sum_n \sum_l b_{nklts}, \quad \forall k, t, s \tag{4.23}$$

Based on the amount of distributed products and the redistribution rate of q_{kts} the amount of redistributed products can be calculated using equation (4.23).

$$\sum_n ret_{nljts} = \sum_n \sum_k b_{nklts} \beta_t, \quad \forall l, j, t, s \tag{4.24}$$

$$d_{lts} = \sum_n \sum_k b_{nklts}(1 - \beta_t), \quad \forall l, t, s \tag{4.25}$$

With a rate of β_t the redistributed products can be remanufactured (4.24) otherwise they are disposed (4.25).

$$CS_{imt} \geq \sum_n \sum_j u_{mnijt}, \quad \forall i, m, t \tag{4.26}$$

$$CF_{jt} x_{jt} \geq \sum_n \sum_k a_{njkts}, \quad \forall j, t, s \tag{4.27}$$

$$CR_{lt}^{s} y_{lt} \geq \sum_{n} \sum_{k} b_{nklts}, \quad \forall l, t, s \tag{4.28}$$

Constraints (4.26) - (4.28) are capacity constraints regarding suppliers, opened facilities and redistributions centers.

$$0 \geq -x_{j(t-1)} + rx_{jt}, \quad \forall j, t > 1 \tag{4.29}$$

$$0 \geq -(1 - x_{jt}) + rx_{jt}, \quad \forall j, t > 1 \tag{4.30}$$

$$1 \geq x_{j(t-1)} + \left(1 - x_{jt}\right) - rx_{jt}, \quad \forall j, t > 1 \tag{4.31}$$

$$0 \geq -y_{l(t-1)} + ry_{lt}, \quad \forall l, t > 1 \tag{4.32}$$

$$0 \geq -(1 - y_{lt}) + ry_{lt}, \quad \forall l, t > 1 \tag{4.33}$$

$$1 \geq y_{l(t-1)} + (1 - y_{lt}) - ry_{lt}, \quad \forall l, t > 1 \tag{4.34}$$

Constraints (4.29) - (4.34) make sure that only those facilities (4.29) - (4.31) and redistribution centers (4.32) - (4.34) can be closed that were opened in the previous period.

$$x_{jt}, y_{lt}, rx_{jt}, ry_{lt} \in \{0,1\}, \forall j, l, t \tag{4.35}$$

$$a_{njkts}, b_{nklts}, d_{lts}, ret_{nljts}, p_{jt}, u_{mnijt} \geq 0, \forall j, k, l, m, n, s, t \tag{4.36}$$

Constraints (4.35) - (4.36) enforce the binary and positive restrictions on decision variables.

4.4.3 Multi-objective optimization

The model includes two objective functions: (i) minimization of the total costs and (ii) minimization of the environmental impact calculated by CO2e. To combine both objective functions into a single one, we use the weighted metric method also known as L_p-metrics method, which is one of the well discussed methods in MODM literature[208] and it is also used in other robust multi-objective problems. [209] As the financial and environmental objective functions do not have the same scale, we make the new combined objective function Z_3 scale-less.

[208] See Deb, K.., Multi-Objective Optimization, 2005, pp. 60-66; Chankong, V.; Haimes, Y. Y., Multi-objective Decision Making, 1983.

[209] See e.g. Mirzapour Al-e-hashem, S. M. J.; Malekly, H.; Aryanezhad, M. B., robust optimization model, 2011, p. 34.

$$Min\, Z_3 = \left[\varpi \frac{Z_1 - Z_1^*}{Z_1^*} + (1-\varpi)\frac{Z_2 - Z_2^*}{Z_2^*}\right] with\, 0 \leq \varpi \leq 1 \quad (4.37)$$

The proposed model has to be solved separately for each of the objectives to get the optimal values Z_1^* and Z_2^* respectively. The weight ϖ of the two objectives is given by the decision maker and addresses the relevance of environmental aspects compared to cost issues.

4.5 Model application

4.5.1 Problem description

In this section, the proposed model is applied to a simplified numerical example based on parts of a real life case in a mechanical and plant engineering company to illustrate the relationship between supply chain design decisions and environmental performance as well as the capability as a decision support tool for sustainable supply chain design. At the request of the company all data are anonymized. The structure of the analyzed supply chain is illustrated in Figure 4.2. The model is applicable in fundamental supply chain design problems such as integrated facility location planning or product allocation but not useful for detailed decisions, e.g. regarding production process allocation. Although the planning system is quite aggregated, the major results can be generalized.

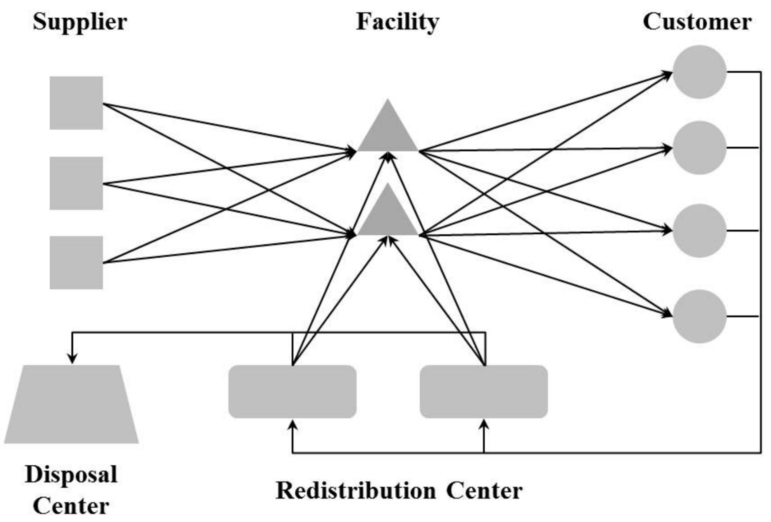

Figure 4.2: Supply Chain Structure

The world-leading company owns two production facilities in Germany and USA, which could be potentially equipped with production machines of the new product. The company formulates a supply, production, distribution and redistribution plan for a new product considering a planning horizon of two years. Raw materials, according to the bill of materials, could be purchased from different suppliers in Germany, USA and India. Finished goods are delivered to the customer clusters according to their aggregated demand, which is subject to uncertainty. In addition, the redistribution rate of used products shipped from the customer zones to potential redistribution centers is uncertain.

The amount of the used products is shipped to one of the two potential redistribution centers and is either remanufactured and shipped back to production facilities or, if remanufacturing is not possible, disposed at regional disposal centers.

Table 4.2: Input data

Period t	Scenario s	Probabilities	Customer k							
			1		2		3		4	
			Dem	Q	Dem	q	Dem	q	Dem	q
1	1	0,25	650	0,25	30	0,1	62	0,15	35	0,2
	2	0,5	745	0,3	55	0,15	79	0,2	58	0,25
	3	0,25	800	0,35	75	0,25	105	0,3	68	0,35
2	1	0,25	610	0,3	40	0,15	75	0,15	40	0,2
	2	0,5	720	0,35	65	0,2	90	0,2	75	0,3
	3	0,25	810	0,4	80	0,25	140	0,35	100	0,35

4.5.2 Results

The model was implemented and solved in Lingo 13.0 using an Intel 2.0 GHz machine with 2 GB RAM under windows 7 SP1. Table 4.3 and Figure 4.3 illustrate the results and show the interrelations of weighting parameter (ϖ) and mean as well as standard deviation values of the two objectives.

As it is shown in Figure 4.3 the expected total costs start to increase and the emissions start to decrease from a weighting of the two objectives of 0.5 as results of the robust model. With a strong overweighting of the environmental goal by the decision maker (ϖ=0.2) the expected total costs increase rapidly with a rate of 22 percent compared to the initial value, where just the economic objective is considered (ϖ=1), caused by a change of the production allocation. At the same time the emissions decrease with a rate of nearly 11 percent. In case of only considering the environmental objective the costs increase further to a relative value of 1.30, but the emissions decrease only slighty. These insights help the decision maker to select a suitable weight (ϖ) according to his individual perspective.

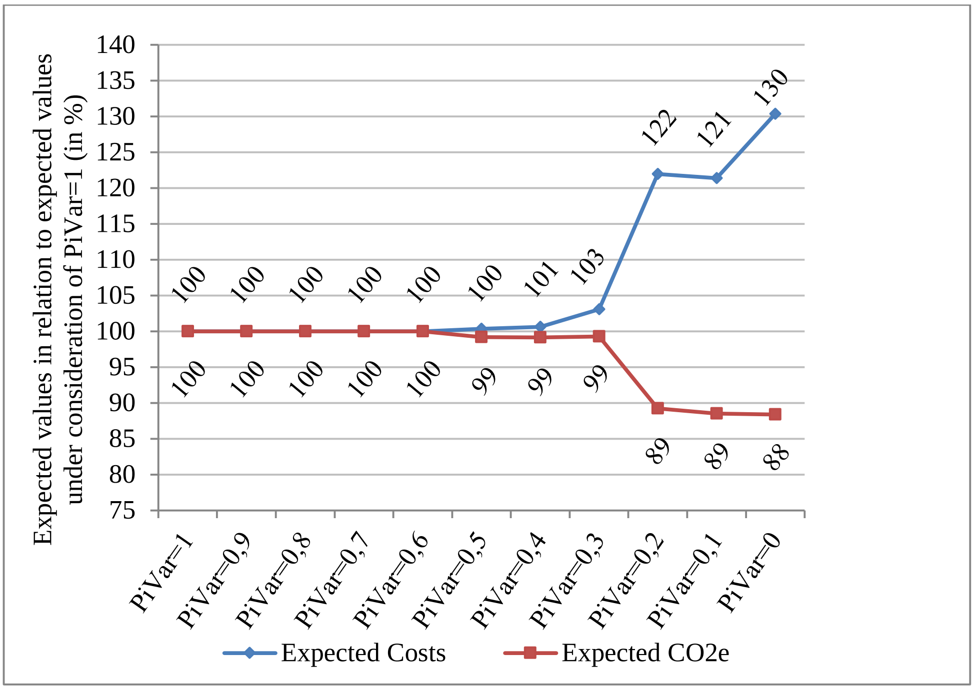

Figure 4.3: Impact of changing the objective weights in percent

In addition to Figure 4.3, Table 4.3 represents the impact of changing ϖ on standard deviation of the objectives. Until $\varpi = 0.5$ it can be stated, that the standard deviation of the expected costs is not changing. A further overweighting of the environmental objective would lead to an increased standard deviation value of 77700.13. The change of standard deviation of the expected emissions is not changing considerably except of $\varpi = 0$.

Table 4.3: Impact of changing the objective weights on mean value and standard deviation

	μ_1	μ_2	σ_1	σ_2
ϖ=1	1109479.00	512005.50	63827.21	23503.15
ϖ=0,9	1109479.00	512005.50	63827.21	23503.15
ϖ=0,8	1109479.00	512005.50	63827.21	23503.15
ϖ=0,7	1109479.00	512005.50	63827.21	23503.15
ϖ=0,6	1109479.00	512005.50	63827.21	23503.15
ϖ=0,5	1113429.00	507933.90	63827.21	23503.15
ϖ=0,4	1116215.00	507597.00	63827.21	23503.15
ϖ=0,3	1143481.00	508275.10	67918.22	23512.24
ϖ=0,2	1353117.00	456951.00	64446.01	23507.04
ϖ=0,1	1346599.00	453238.60	63827.21	23503.15
ϖ=0	1446685.00	452548.10	77700.13	23378.62

In order to identify key decisions, which have a strong influence on environmental supply chain performance, a sensitivity analysis with a deviation of -/+ 25% of emission values of the considered processes is performed. It leads to the result, that particular supply and recycling processes are relevant for the environmental performance while production, logistics and redistribution have only a small impact (Figure 4.4).

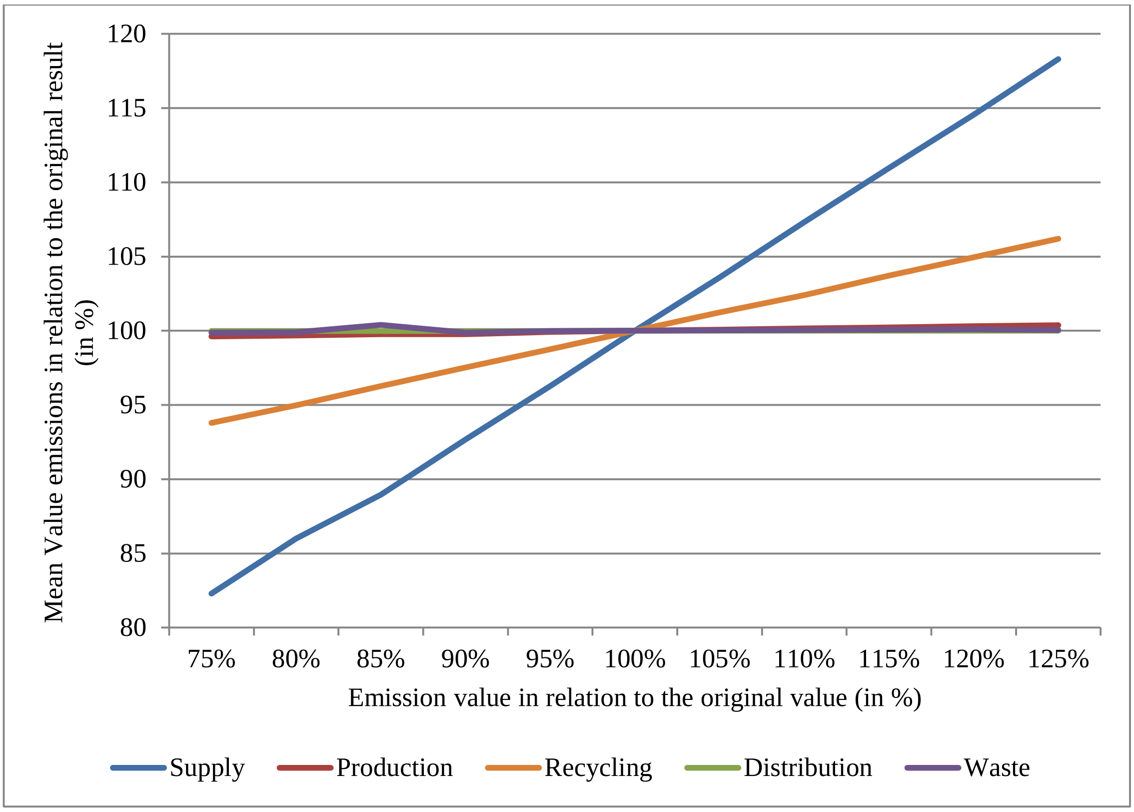

Figure 4.4: Sensitivity analysis

To evaluate the results of the robust model concerning mean values and standard deviation, we compared it to solutions derived from an equivalent deterministic model, which we solved for each of the three scenarios separately.

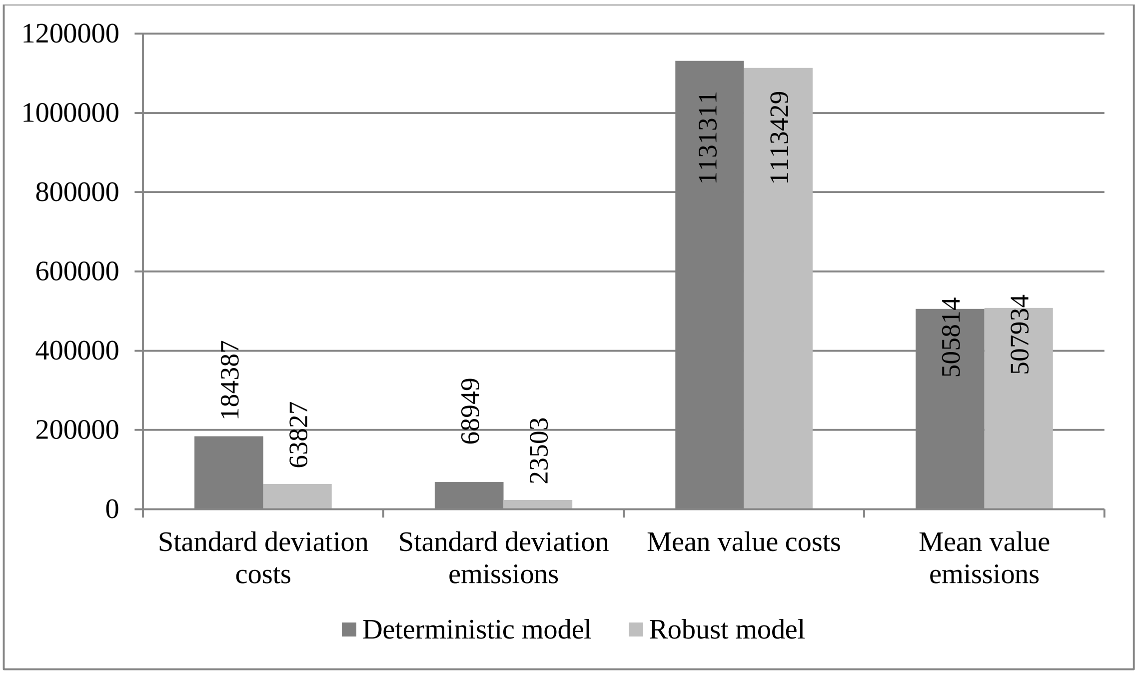

Figure 4.5: Comparison of the robust and deterministic results (ϖ=0.5)

The important finding illustrates the advantage of the robust optimization approach. Compared to the deterministic model, the standard deviation concerning the costs as well as the emissions of the robust solution is only nearly one third of the deterministic one while the mean values are nearly equal. To underline these findings, three more sets with the same upper and lower bounds of the uncertain parameters as in the above mentioned case are analyzed. The sets cover three, five and ten uniformly distributed scenarios, which differ in demand and return rate values (Figure 4.6). With an increasing number of scenarios, the standard deviation values of the deterministic as well as the robust solutions decrease and are still in a ratio of three to one.

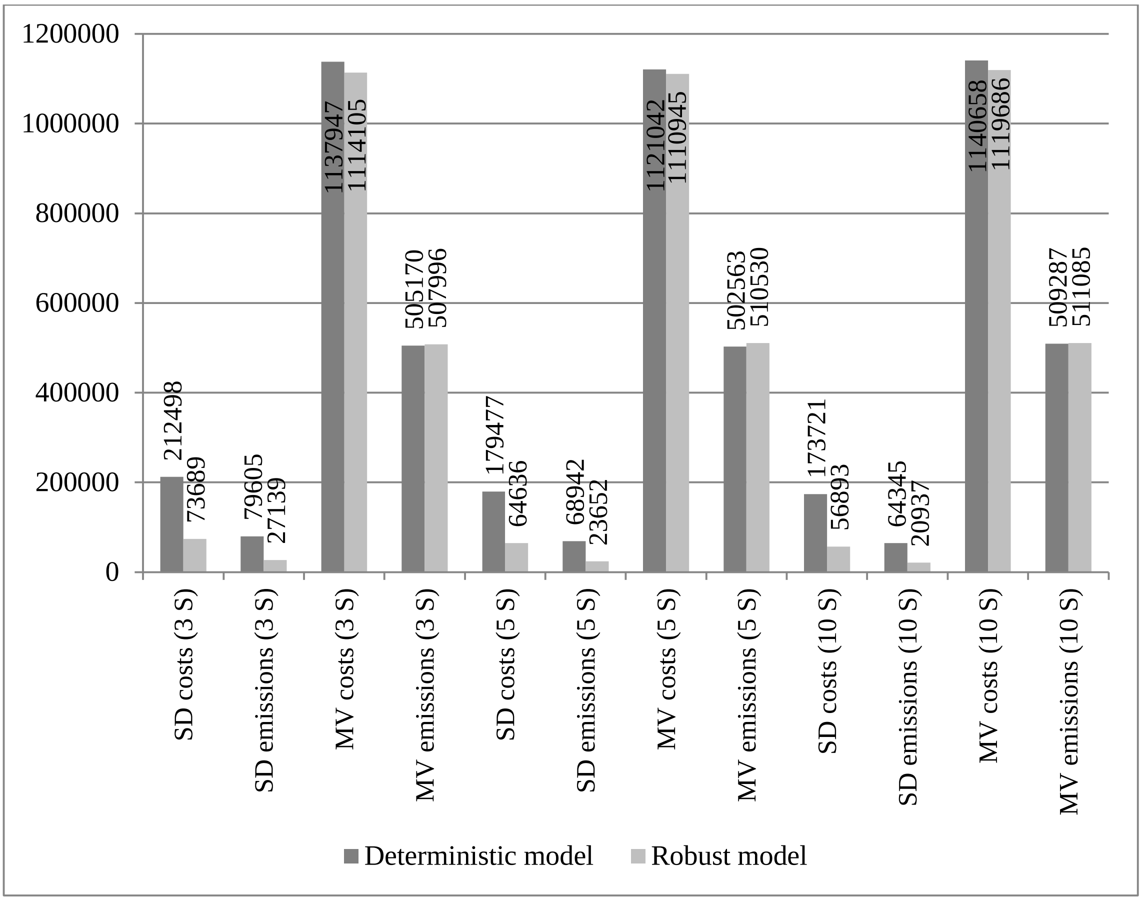

Figure 4.6: Standard deviation of different scenario sets

Although the results depend on the planning data, it can be generally stated that the weighting factor of the objectives has a strong impact on the results.[210] When applying this model, this factor should be determined by using appropriate tools as e.g. the analytic

[210] See Table 4.3.

hierarchy process,[211] especially if the objectives are calculated via combinations of various indicators.[212]

By using the concept of robust optimization the decision maker gets the opportunity to consider uncertainty while planning his supply chain. As shown in the case example the solution robustness measured by variance and standard deviation respectively is increasing significantly. The decision maker achieves a financially and environmentally conscious supply chain design, which is robust to various future scenarios and makes a valuable contribution to a risk-oriented supply chain planning.

4.6 Conclusion and future research

The change of the strategic decision system of a company from an entirely financially driven to a sustainable focused approach is one of the major challenges companies must succeed at these days. Reasons for this development can be found in governmental and non-governmental pressures through regulations, poor levels of information transparency and frequent changes of customer demands. In this paper we discussed several impacts of supply chain design decisions on the environmental performance of a supply chain. In this way we identified six fields, where changes could result in positive environmental effects. To capture a few of these impacts in the decision-making process we further proposed a closed-loop supply chain design model. These models use different performance objectives that may lead to different decisions regarding number, location and capacity of the production, storage, distribution and collection facilities as well as supply and logistic structures between facilities and the corresponding production processes and quantities. In our case this effect is emphasized by not only considering financial but also ecological aspects in the objective function. We use the L_p-metrics method to solve the model considering both minimization of expected total costs and minimization of total CO_2e, which are typically conflicting objectives.

Since strategic supply chain design models consider long-term planning horizons that usually encompass several years, the consideration of uncertainty is an important element

[211] See Saaty, T., Analytic Hierarchy Process, 1980.
[212] See Section 4.2.

of network planning. Instead of applying traditional stochastic programming, we use the concept of robust optimization to find a good solution for any realization of uncertain parameters, what is especially valuable for risk-averse decision makers. Earlier work pointed out, that there is a lack of research in adopting robust optimization in closed-loop supply chain context.[213] To the best of our knowledge, no model has been published yet, that proposes a robust multi-objective closed-loop supply chain design considering environmental as well as financial criteria in the objective function. A simplified numerical study of a four-echelon supply chain illustrates the mentioned relationships and demonstrates the advantage of robust optimization. With the presented approach, companies get a decision support tool for their strategic supply chain planning decisions.

The current study has several limitations. It is noted that the difficulty of obtaining real-world data has limited our model application. Thus we only present preliminary results. Future research could include data from a broader industry case. In order to evaluate the performance of the proposed approach it would be appropriate to extend the case with more suppliers, products and scenarios. Another extension of this research could be a consideration of global economic dynamics (e.g. exchange rates, tariffs, local content regulations). From an environmental point of view the impacts of country-specific emission regulations could be analyzed. The model could also be extended by an integration of tactical and/or operational decisions. Through a simultaneous optimization approach a broader portfolio of impacts on environmental supply chain performance could be considered. Especially inventory decisions would give the opportunity for deeper insights into the interrelations of sustainable supply chain planning.[214] Our assumption that emissions have a linear relationship to the amount of product units is a simplification compared to reality. To achieve more realistic solutions it would be appropriate to integrate emissions as a function of intensity of use of the considered processes.

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[213] Cf. Pishvaee, M. S.; Rabbani, M.; Torabi, S. A., robust optimization, 2011, p. 640.
[214] Cf. Bonney, M.; Jaber, M. Y., Environmentally responsible inventory models, 2011, p. 43.

5 Guidelines for practical application

5.1 Guideline development

In contrast to optimization approaches, there is a lack of guidelines to implement supply chain design decision support tools in practical applications or projects. To close this gap, the following section presents a framework to illustrate the implementation steps of an environmental supply chain design project. Consequently, both classical project management requirements and supply chain management specifications are considered. The framework development is based on the experiences of three practical application projects that are not described in detail in this research project but have been executed during the elaboration of this thesis.

As mentioned in the project management literature, it is of vital relevance, to assure top management support.[215] This is not only important to improve motivation of the project team members and project reputation in the whole company, but also for determining general supply chain goals derived from corporate strategy.[216] This is consistent with IVANOV who sees the definition of supply chain strategies superordinated to supply chain design decisions.[217] Since supply chain design decisions have a strong impact on the structure of a company and particularly redesign projects change fundamental supply chain characteristics that have evolved over time, company-wide acceptance has to be ensured by the project sponsor.[218] However, clashing interests of different groups in the company always exist and should be resolved since they could endanger the success of the project at the execution stage after a supply chain design decision has been made. Referring to this, the above presented models make a significant contribution by enabling decision makers to balance the numerous decision alternatives and their impacts on the overall supply chain and finally to make informed decisions.

In the context of environmentally conscious supply chain configurations with special focus on customers´ requirements, it is necessary to consider both internal and external determinants. Accordingly, a vast number of planning parameters needs to be gathered. As

[215] Cf. Kerzner, H., Project management, 2009, p. 17.
[216] Cf. Smith, A. D.; Offodile, O. F., project management, 2007, p. 177.
[217] Cf. Ivanov, D., supply chain strategy, 2010, p. 4000.
[218] Cf. Kerzner, H., Project management, 2009, p. 384.

it is already true for supply chain design decision support models that are only financially oriented, it is indispensable to have a valid data basis. Otherwise, the solution would be probably of low quality. To ensure good data quality, the relevant functional departments should be able to provide all necessary planning parameters typically by accessing the companies IT systems and databases. Quite often, gathering environmental impact data connected to the focused value creating processes is a rather new task for the employees involved in the project. Consequently, it is advisable in most instances that environmental management specialists are involved in such a project. In addition, the proposed complex planning methods should be operated by a specialist with advanced knowledge regarding operations research and supply chain management. Obviously, data quality, manpower, know-how, and a realistic estimate regarding the needed resources are critical success factors for a supply chain design project. Consequently, the responsible project manager has to act as a bridge between top management and all supply chain management functions that are involved. For this purpose, steering committee meetings at regular intervals should be installed in order to communicate project progress, avoid unrealistic expectations and to ensure project success.

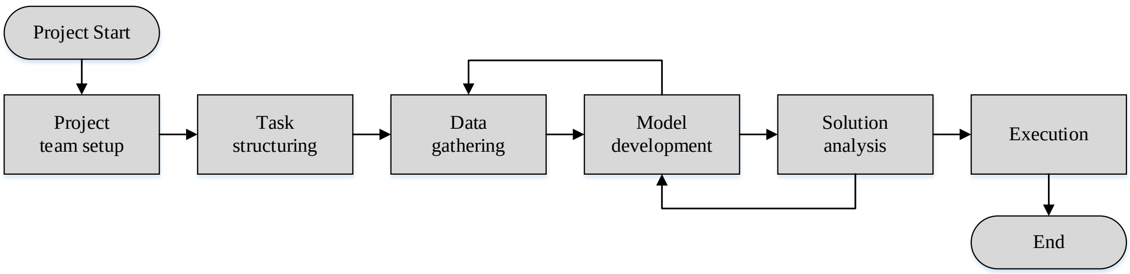

Figure 5.1: Generic supply chain design project chart

The major steps as stated above are shown in the generic supply chain design project chart (Figure 5.1). It can be used as a guideline to set up a supply chain design project with special consideration of economic and environmental issues. Details of the relevant project steps are described in the next section.

5.2 Project steps

Step 1: Project team set-up

Since supply chain design decisions influence almost all business functions of a company, it is necessary to get team members of the main functional areas together in the project team. As mentioned above, top management support could be ensured by a strong project sponsor from the executive level. It is also important to select a competent project manager with advanced experience regarding leadership, planning methods as well as organizing teams. [219] Furthermore, specific knowledge regarding supply chain management and environmental issues is requested. The project manager and the sponsor act as coordinators in the steering committee. [220] In the regular project team, procurement, production, sales as well as the logistics departments should be represented by experts in order to capture all relevant supply chain functions. To ensure that all environmental management topics are considered, a representative from the environmental management department should be part of the team. However, normally such a department is only installed in globally active, big companies. Finally, an employee from the financial department should be involved, since supply chain design decisions are closely interrelated with investment decisions. In addition, an adequate IT infrastructure as well as mathematical programming (modelling) support need to be ensured. Figure 5.2 illustrates the set-up of an environmental supply chain design project team.

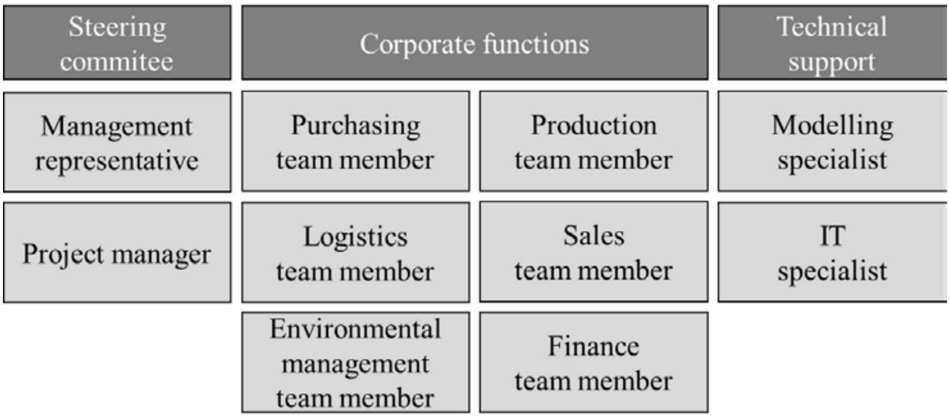

Figure 5.2: Environmental supply chain design project team

It can be assumed that most often project team members and project stakeholders have different motivations and interests that are mainly driven by the impact of the potential supply chain design decision on their own function.[221] Hence, the project manager needs to identify these potential sources for opportunistic behavior and should anticipate e.g.

[219] Cf. Kerzner, H., Project management, 2009, p. 144, p. 149
[220] Cf. Parr, A.; Shanks, G., project implementation, 2000, p. 301.
[221] Cf. Boddy, D.; Patron, R., lessons for project managers, p. 231.

possible risks of manipulation concerning particularly planning data. Making sure that each team member is fully dedicated to give maximum support for reaching the project goals is crucial.

Step 2: Task structuring

In addition to the project team set-up, clear responsibilities need to be assigned.[222] In this way, all project team members know their own as well as the tasks of the others. This is conducive to a structured completion of the various topics and could therefore contribute to an efficient realization of the project.

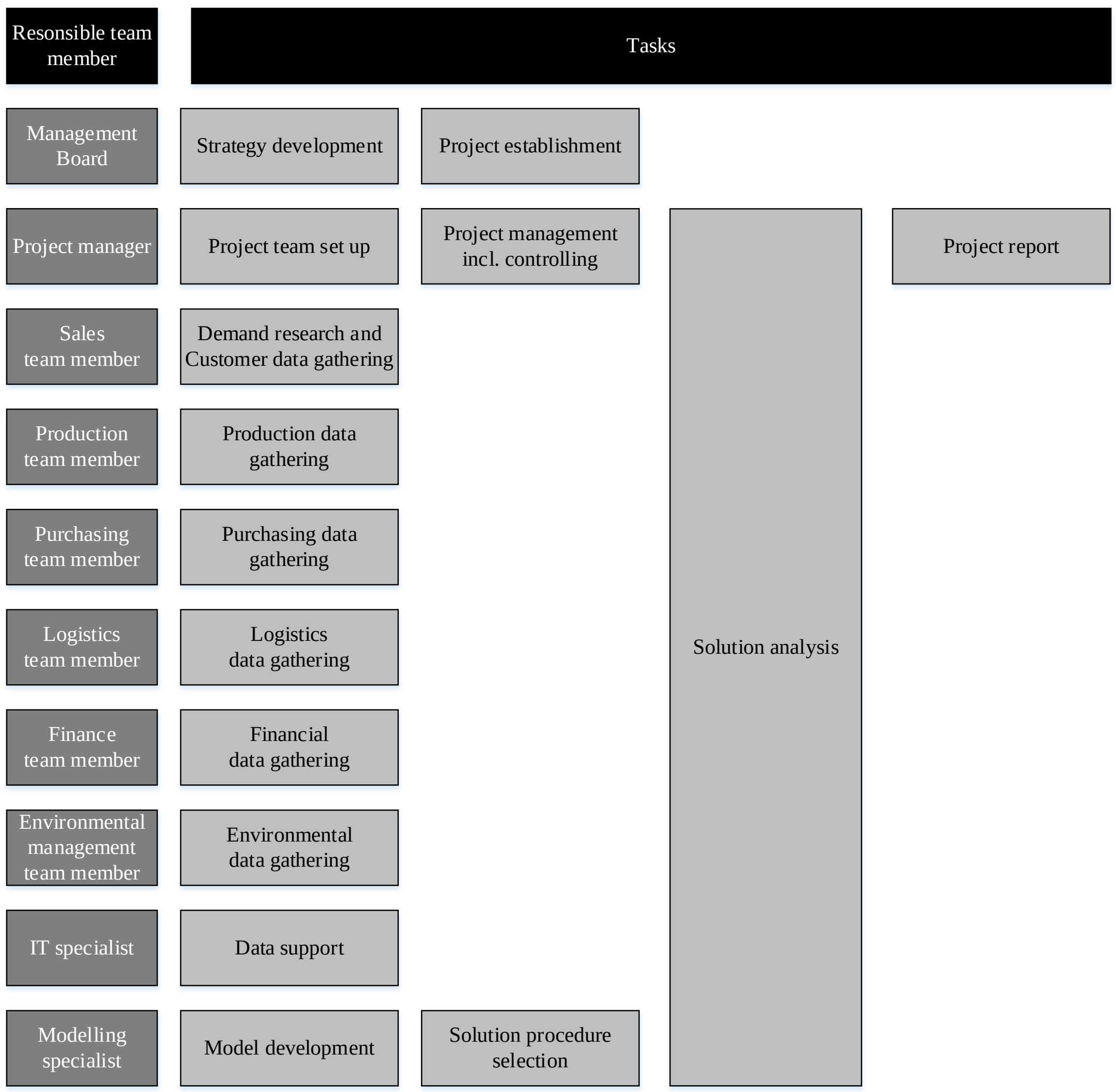

Figure 5.3: Project tasks and responsibilities

[222] Cf. Al-Khouri, A. M., Projects Management, 2012, p. 10.

First of all, it is necessary to identify the goals and opportunities of the sustainable supply chain design project. As mentioned above, various motivations could lead to such a strategic project. Therefore, the requirements of internal and external stakeholders should be analyzed.[223] In addition, barriers need to be identified in order to exclude potential options that cannot be implemented in the supply chain design. Another important issue is the definition of the project objective: Should an existing supply chain be redesigned or should a complete new supply chain be built up? According to the planning situation, the planning environment can be defined.

In the case of redesigning an existing supply chain structure, an analysis of the status quo leads to transparency regarding the interrelations in the considered supply chain. Value stream mapping or other mapping methods are useful tools for supply chain analysis,[224] particularly in the sustainability context.[225] In a further step, alternatives for each element of the existing structure need to be identified. In case of a greenfield project where supply chain characteristics, e.g. for a new product, have to be defined from scratch, potential supply chain design options need to be discussed in the team. Usually, relevant inputs are given by the supply chain strategy and business development objectives as defined by the managerial board. In addition, interrelations to existing supply chains of the company should be analyzed. In this way, potential supply chain design options could become obvious and limitations regarding the degree of freedom of the underlying mathematical model can be defined intuitively.

It is advisable to assign specific tasks to the project team members according to the company function they represent. In contrast to more project-related tasks as project management and controlling that are in the responsibility of the project manager,[226] the other team members are responsible for gathering the data related to their function. Furthermore, IT support members should ensure the technical availability. Finally, modelling specialists are responsible for representing the considered supply chain design problem in an appropriate mathematical model. The entire project team discusses the supply chain design decisions after the model has been solved and define recommended actions for

[223] Cf. Sánchez, A. M., sustainability issues, 2014, p. 3.
[224] Cf. Gardner, J. T.; Cooper, M. C., supply chain mapping, 2003, p. 39.
[225] Cf. Brown, A.; Amundson, J.; Badurdeen, F., Sustainable value stream mapping, 2014, pp. 1-2.
[226] Cf. Ayers, J. B., supply chain project management, 2004, p. 4.

decision execution. The project manager consolidates the developed actions and illustrates the project outcome in a project report. Milestone schedules combined with clear work package definitions are useful to ensure the progress of the project.[227]

Step 3: Data gathering

One of the major challenges in environmentally conscious supply chain design projects is the gathering of valuable planning data. This is vital, since the quality of the planning parameters has significant impact on the solution quality of mathematical models. Hence, it needs to be guaranteed that all relevant planning data are available. In recent times, most planning data can be extracted from Enterprise Resource Planning (ERP) systems. However, particularly in context of sustainability issues, most implemented systems fall short in providing the necessary data. Therefore, alternative data sources have to be identified.

For environmental and social planning data, two basic alternatives are available. First, an individual analysis of potential decision options can be performed. Therefore, the preparation of a sustainability report could be useful.[228] In this way, the environmental and social performance of existing supply chain processes can be identified. Important environmental management and reporting standards that can be used as a guidance, are the GRI G4 SUSTAINABILITY REPORTING GUIDELINES[229] as well as the ISO 14000 guideline family[230]. Similar environmental and social information need to be gathered for the other potential supply chain design options that should be considered as alternatives. Since environmental and social performance figures cannot be measured easily, it is necessary to obtain this information from other sources. On the resource level, the vendors of the machines to be installed as well as machine manufactures can deliver relevant information. Environmental and social data regarding logistical processes can often be gathered from service providers. Furthermore, there are supply chain processes for which the relevant information are not available. In this case, assumptions need to be made which should be close to reality as possible. To support this, data specialists could gather sustainability

[227] Cf. Kerzner, H., Project management, 2009, p. 433.
[228] An example for a very detailed sustainability report, including specific quantifications of relevant parameters, can be found for PUMA AG.
[229] GRI G4 sustainability reporting guidelines are published by the Global Reporting Initiative. Cf. https://www.globalreporting.org/reporting/g4/Pages/default.aspx.
[230] Standards of the ISO 14000 guideline family consider the most important environmental management issues. Cf. http://www.iso.org/iso/home/standards/management-standards/iso14000.htm.

information from accessible databases[231]. As an alternative, benchmark values from other companies can be used, if available. In addition, the project team needs to discuss and analyze the possible assumptions in order to determine a good data set.

After identifying all relevant data sources, the required data structure should be defined according to the requirements of the applied solution procedure. Particularly, data export- as well as import interfaces are determinates. Due to flexibility, database structures are recommended in most cases. Usually, ERP systems as well as mathematical optimization or simulation tools support data exchange via database interfaces.

Step 4: Model development

Parallel to gathering the relevant data, the model can be developed. It should consider all relevant planning decisions. As described above,[232] various decision support methods are available. As we support the usage of optimization models, we would like to introduce the basic principles of creating an appropriate optimization model.[233]

First of all, the modelling specialists should analyze the identified topics and decision options. Since supply chain design problems are highly specific, it is advisable to create a problem-specific optimization model that represents the real world problem to a high degree. In less complex cases it is possible to modify available standard models provided by commercial software packages.

As it is common in mathematical modelling, the modelling specialists need to consider the trade-off between solvability of a model and the quality of representing the underlying problem situation. In this context, it has to be decided if the model should be deterministic or stochastic on the one hand and linear or non-linear on the other. Often, the supply chain design modelling options that are harder to solve, represent the reality more adequately than the options that are easier to solve. Nevertheless, it should be decided by evaluating the loss of quality regarding the solution and therefore the possible loss of money and other performance criteria when deciding on how accurately the model should be defined. However, particularly in the context of long-term supply chain design problems, the application of methods that approximate the reality could be useful, since for the selection

[231] For instance, emission data of transportation processes are accessible on http://ecotransit.org/.
[232] See section 1.3.
[233] See Figure 5.4.

of strategic decision alternatives it is often not necessary to calculate with figures showing several decimal places.

As illustrated in Figure 5.4, the model development phase is normatively pre-defined in all its details but rather a dynamic process. It is advisable to develop a basic model first in order to provide a basis for further discussions in the project team. Particularly, the fundamental interdependencies of the considered topics can be shown and project team members can get in touch with the mode of action regarding mathematical optimization models. With this in mind, the defined problem topics are often reviewed again. Subsequently, the complete model can be developed.

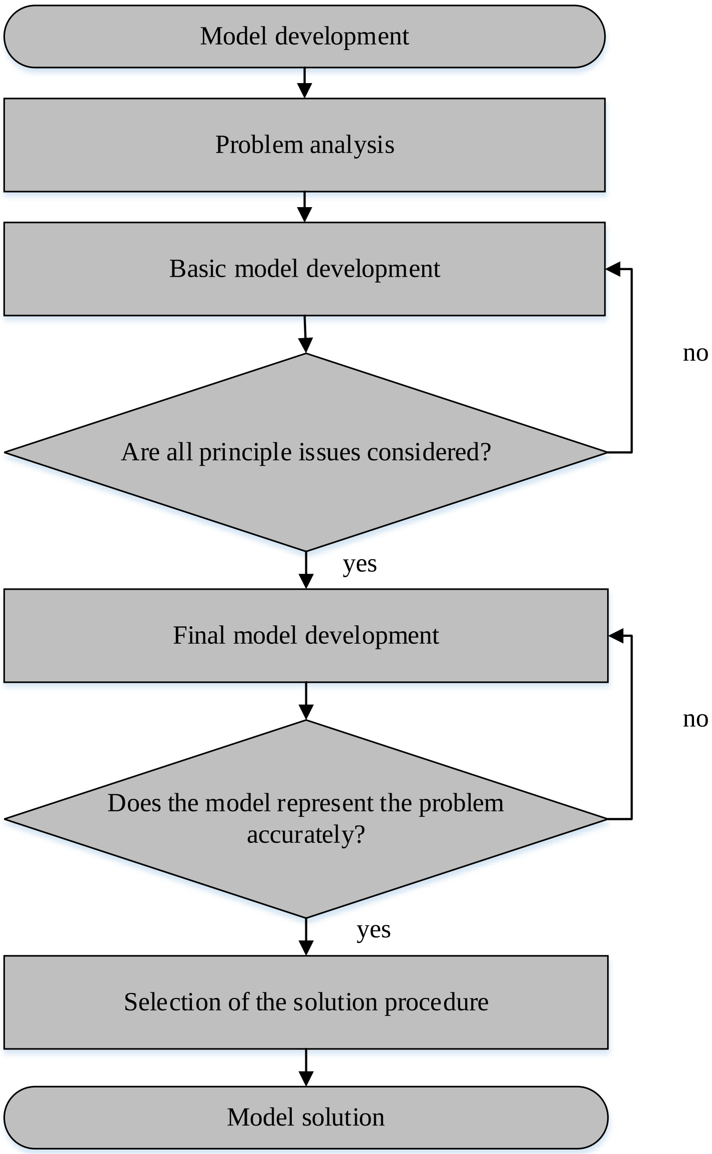

Figure 5.4: Model development process

In a further step, the modelling specialists need to evaluate and select an appropriate mathematical solver software, if the company does not work with a specific supply chain design module as part of their ERP system.[234] For this task, two general options need to be analyzed. First, commercial optimization solvers can be used. Most prominent solvers in the supply chain design context are IBM ILOG CPLEX, FICO XPRESS OPTIMIZATION SUITE AND LINGO of LINDO SYSTEMS, INC.. As a second option, the modelling specialists can develop or modify problem-specific solution algorithms. Although this is the most time-consuming option, developing specific algorithms (e.g. evolutionary algorithms) might be not avoidable for highly complex supply chain design situations that cannot be solved using standard solvers.

After the model has been developed and implemented, the gathered data for the model parameters can be integrated in order to start the solution procedure and generate the optimal supply chain design.

Step 5: Solution analysis

Based on the optimization results, the optimal supply chain design can be analyzed. Therefore it is necessary to present the solution in a breakdown. Often graphical reports, e.g. in the form of a supply chain map, are used to present the relevant decisions.[235] In addition, numerical breakdowns including summarizing charts and figures help to understand the solution. For detailed discussions, the plain solution data can be used.

There are various general issues that should be analyzed in this project step. First of all, it should be discussed whether all relevant factors are included in the solution. According to the experience and attended by the terms of a supply chain design project, modifications of the set of topics, parameters and consequently of the model could become necessary. Furthermore, the project team should analyze impacts of certain parameters on the solution. In this way, the level of robustness of the solution can be identified. As mentioned in section 2.3, the application of the robust optimization approach can help to improve solution robustness. Nevertheless, the application of sensitivity analysis and what-if scenario analysis are advisable. With the help of what-if scenario analysis, pre-defined, possible future scenarios can be analyzed. This method could be useful to evaluate the

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[234] Many ERP-System cover supply chain design problems: e.g. SAP ERP APO Network Designer. Another option is the use of a special supply chain design software, as LLAMASOFT Supply Chain Guru. For a detailed tool catalogue see Funaki, K., Commercial Software, 2009, p. 5.

[235] Cf. Funaki, K., Commercial Software, 2009, p. 12.

impact of specific risk situations on the supply chain design.[236] With the help of sensitivity analysis it is possible to identify parameters that are of high relevance for the robustness of the solution. Therefore, the parameter values are modified in a certain range in order to evaluate regarding the problem variables.[237] Parameters with a high relevance should be monitored in the future. Thus, the presented approach helps to identify relevant factors that should be considered by an appropriate risk management. Consequently, it could be possible that due to strategic risk aspects of superior relevance or because of possible future developments that could not be integrated in the mathematical model the optimal solution regarding the supply chain structure will not be implemented. Instead, the optimal structure might then act as a reference for other design options that discussed by the management board

Particularly, this solution analysis step enables a fact-based decision making process in a complex planning environment. Normally, the project team defines several scenarios in order to test the solution and to get further insights into the interrelations of underlying decisions. In this way, a future-based decision making process can be achieved. However, a backward loop to the upstream project stages is necessary in order to modify both, data and possibly the mathematical model.

Step 6: Execution

Finally, the analyzed and discussed supply chain design decisions need to be prepared in order to clarify the relevant topics for execution. Based on the analyzed model solutions, an implementation action plan can be developed.[238] According to the step "*task structuring*" it is necessary to define the relevant tasks and responsibilities in order to ensure proper decision execution. Since the decision parameters are dynamic, a structured execution is advisable. Otherwise, claims of company-internal stakeholders which are concerned by the decisions could arise and endanger successful implementation. Both a management summary and a project report, prepared by the project manager, can be used as a basis for defining appropriate execution steps.

Accordingly, each company function, represented by a project team member, should take the supply chain design decisions as a basis for further planning topics at the tactical

[236] For an application see e.g. Deniz, E.; Luxhøj, J. T., Supply chain risk management, 2008.
[237] Cf. Kleijnen, J. P. C.; Smits, M. T., supply chain management, 2003, p. 511.
[238] Cf. Crosby, P. A., Network Design, 2004, p. 328.

planning level. This highlights the assumptions of Ivanov regarding the interrelations of the supply chain planning stages.[239]

[239] Cf. Ivanov, D., supply chain strategy, 2010, p. 4000.

6 Final Conclusion

6.1 Summary

The present research aims to develop mathematical approaches for sustainable supply chain design problems. After the relevance of sustainable supply chain design and according research questions were introduced, three different optimization models with various main aspects have been presented. To illustrate how the presented models can be applied in practical problem cases, guidelines for implementing an environmentally supply chain design project were developed. Finally, a conclusion and further research directions complete the thesis.

Sustainability has become a critical topic in all areas of supply chain management. As discussed, drivers for this development can be identified as both internal and external phenomena. Since customers are one of the key stakeholders in supply chain management, we pay special attention to the impact of costumers´ behavior on sustainable supply chain design decisions. In this context, two main research questions were analyzed:

1. *What is the appropriate way to design a supply chain according to environmentally-oriented requirements of customers?*
2. *What is the impact of customer´s behavior regarding both usage and return of products on supply chain design decisions in an environmentally conscious closed-loop supply chain environment?*

The first research question is treated in chapter 2 as well in chapter 3. In the second chapter, an optimization approach was introduced that considered environmental product requirements of customers. Due to the assumption that these requirements have a high impact on the financial performance of companies, we analyzed the impact in a multi-period planning environment. Therefore, we proposed a mixed-integer linear programming model. Uncertainty of product prices and customer requirements were considered by applying robust optimization techniques. A numerical example illustrated the advantages of the proposed approach. As customers´ requirements were modeled in a product-specific way including supply, manufacturing and distribution processes, a decision maker gets the ability to allocate the whole value creation of certain products along the supply chain in a way that customers´ requirements are met. Since we assumed that customers´ environmental requirements are uncertain and hard to forecast, the application of the robust optimization concept led to a supply chain design that is less sensitive to variations of planning parameters. Hence, the risk of a costly redesign of the supply chain could be decreased. Therefore, the presented approach contributes to a risk-oriented sustainable supply chain design. In addition it was presented that a detailed analysis of demand specifications regarding environmental product characteristics seems to be relevant when considering both economic and environmental issues in supply chain design decisions.

To extend the analysis of the first research question, chapter 3 emphasized on environmental friendly customers. It was assumed that the demand function would decrease in case of increasing environmental impacts of an ordered product. According to a state-of-the-art literature review on sustainable supply chain design approaches, no earlier model that addressed this problem could be found. This issue is of high importance for supply chain design decisions, as it is critical for financial performance as well as for decisions regarding the amount of network flows. To represent the planning structure, we introduced a mixed-integer linear programming model. The demand function is modeled via piecewise-linear demand stages. It is assumed that customers determine their demand quantity for the products depending on environmental impacts that occur during the manufacturing and delivery processes. Accordingly, a decision maker, who wants to maximize his sales volume, has the motivation to design an environmentally friendly supply chain in order to meet customers´ requirements. Identically to the model presented in chapter 2, production was considered as a multi-step process. This assumption gives the decision maker the opportunity to allocate production steps in a customer specific way. Particularly, the integration of a customer-specific demand function which decreases with an increasing environmental impact can be identified as a contribution of the approach. A numerical example illustrated the advantages of the proposed model. Performing a sensitivity analysis regarding the demand for each bound, we identified a strong relationship between supply chain design decisions and customers´ requirements regarding the environmental impact of a product. Therefore, it is advisable to integrate both customers´ environmental product requirements and customers´ demand behavior into the model when designing an environmentally conscious supply chain. Without any problems, the robust optimization approach, presented in chapter 2, could be applied to the model of chapter 3. Uncertainty issues could then be considered while solving the model. However, the focus of chapter 3 should be the analysis of the impact of customers´ requirements on strategic supply chain design decisions. Therefore a robust optimization approach was not considered.

The second research question is analyzed in chapter 4. We extended the planning environment and take, in addition to forward network flows, backward flows and corresponding supply chain activities into account. Therefore, we proposed a closed-loop supply chain design model under consideration of two objectives. Besides a financial objective, the environmental performance, measured by carbon equivalents, was taken into account. According to the long-term planning environment of supply chain design decisions as well as the complexity of quantifying and forecasting customers´ requirements and behavior, we considered uncertainty of both the quantity and the quality of returned products. The considered supply chain problem is particularly of interest for decision makers who want to design the supply chain in order to align the network flows either to meet regulatory requirements (e.g. WEEE) or to other externally driven circumstances (e.g. scarcity of raw materials). In accordance to the reasoning in chapter 2 we applied the robust optimization approach to cope with an uncertain planning environment. An anonymized real-world case was used to illustrate the advantages of using robust optimization techniques compared to a deterministic modelling. While the mean values of both objectives differed only slightly from the deterministic model the standard deviation based on the considered planning scenarios decreased by round about two-thirds using robust optimization. As the major contribution, decision makers get the opportunity to design a supply chain that is less sensitive to varying customer driven factors. This is of high interest, as the quality and quantity of returned products influence decisions on the purchasing and production level as well. Hence, the application of robust optimization also helps to reduce fluctuations on these planning stages.

6.2 Future research directions

Even though the presented research provides useful contributions to the field of sustainable supply chain design, further suggestions for future research directions can be presented. The various topics of sustainable supply chain design research, where we identified shortcomings, can be clustered into the following fields:

Production

The first interesting point that should be analyzed in detail is the relationship of capacity utilization and the environmental performance of production processes. Particularly in a supply chain design context, centralization and decentralization decisions are made. Following the assumption that according to economies of scale not only costs decrease while utilization ratio increases, the environmental performance could be improved by modelling an environmental impact function that depends on machine utilization.

In typical, purely financially-oriented supply chain design models, interactions between the strategic, the tactical and the operational planning levels are considered to allow a broader view of supply chain planning topics. However, there is a lack of modelling approaches that consider these relationships in sustainable supply chain design models. In addition to the above mentioned utilization ratio that is highly influenced by tactical supply chain planning issues, inventory decisions play a major role in this context. Hence, as a consequence that production quantities could be produced and stored for later use, utilization ratios could be increased. Furthermore, environmental impacts of inventories need to be considered when assessing the environmental balance. In that case, a broader view on supply chain processes that influence the environmental impact would have to be modeled.

Model objectives

According to the literature reviews presented above, the selection of appropriate model objectives is not analyzed in detail. Although some guidelines are proposed,[240] companies struggle with finding the right sustainability indicators. Particularly in the context of sustainable supply chain design decisions, no research has been published yet that analyzes this question. Since we consider the objective values of relevant approaches, the literature reviews in the present research can be used as a basis for future research in this field. The analysis should capture the impact of supply chain design decisions, the borders of assessment regarding environmental issues as well as the ability to measure real life sustainability data.

[240] See Chapter 4.

Modelling characteristics

As mentioned, supply chain design decision are characterized by a long-term planning environment. Accordingly, these circumstances need to be considered in appropriate planning models. In this context, one of the key requirements is discounting future values. Generally, the weighted average cost of capital (WACC) could be used as a discounting factor. Costs of both equity and debt are considered in this parameter. In recent studies, the impact of an environmentally friendly behavior of companies on the interest rate of debts is discussed. Some of the studies found evidence for a positive correlation. [241] This finding would lead to the assumption that companies, which reduce their environmental impact, would benefit from lower capital costs. Therefore, inventories would become less costly and capital expenditure costs of environmentally friendly manufacturing resources would be amortized earlier. To integrate this relationship in supply chain design decisions, it should be analyzed how the WACC can be described as a function of the environmental impact.

Practical application

Beside the model mentioned in chapter 4, we did not apply the models to large real life enterprise problems. Particularly, this would be of interest to evaluate the advantages or even shortcomings of the models and to identify further ideas of research in order to develop decision supporting models. While the current models have very general characteristics, industry-specific models could be implemented to assess the environmental conditions more realistically. In that case, further attention should be paid to the selection and development of appropriate solution approaches. In recent research papers, metaheuristics as genetic algorithms have been developed and applied in order to cope with the high degree of complexity when considering real-world cases.[242]

[241] Cf. El Ghoul, S. et al., corporate social responsibility, 2011, p. 2400.

[242] See Govindan, K. et al., supply chain network, 2014, pp. 1-20; Devika, K.; Jafarian, A.; Nourbakhsh, V., metaheuristics, 2014, pp. 594-615. For a review on the application of metaheuristics in logistics and supply chain management see Griffis, S. E.; Bell, J. E.; Closs, D. J., Metaheuristics, 2012, pp. 90-106.

Sustainability issues

According to the concept of the triple-bottom-line approach, sustainability consists on an economic, an environmental as well as a social dimension. Following the existing research and due to the difficulties of quantification, we focused on the interrelations of both economic and environmental issues. Hence, the social dimension of sustainability remained largely undiscussed. However, the integration of social issues in sustainable supply chain design models, particularly when analyzing customer impacts, are of high interest. Today customers are aware of unacceptable social conditions in production, e.g. due to child labor. Accordingly, the demand of products which were manufactured under these circumstances decreases as a consequence of damaged reputation.[243] However, not only customers can be identified as drivers to improve social conditions in supply chains, but also companies themselves try to avoid social damages. Consequently, all three sustainability pillars should be considered in future sustainable supply chain design models.

Summarizing the ideas for future research, it can be stated that there are a lot of opportunities for further analysis. However, it should be recognized that supply chain models can not represent all relevant topics simultaneously due to technical restrictions or even restrictions of quantifying the relevant data. In most cases, supply chain design models only consider aggregated data to find a network structure that is specified in detail in the following planning stages.[244] However, once a supply chain design decision is fixed, it has a major impact on the supply chain performance. Thus, practitioners should benefit from using the presented models in order to make environmentally conscious supply chain design decisions based on a systematic approach that covers as many relevant parameters, variables and objectives as possible and that models the major interrelationships and restrictions in the supply chain context. In addition, the research community gains further insights into the sustainable supply chain design problem and can base their research on the contributions of the present thesis.

[243] Cf. Maloni, M. J.; Brown, M. E., Supply Chain, 2006, p. 35; Fabian, T., Supply Chain Management, 2000, p. 29.
[244] See Chapter 2.

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Eidesstattliche Erklärung

Hiermit erkläre ich gemäß § 6 Abs. 2 Nr. 2 der Promotionsordnung der wirtschaftswissenschaftlichen Fakultät der Universität Würzburg vom 19.10.1998, mit drei Satzungsänderungen, dass ich diese Dissertation eigenständig, d.h. insbesondere selbständig und ohne Hilfe eines kommerziellen Promotionsberaters angefertigt habe, und dass ich außer den im Schrifttumsverzeichnis angegebenen Hilfsmitteln keine weiteren benutzt habe und alle Stellen, die aus dem Schrifttum ganz oder annähernd entnommen sind, als solche kenntlich gemacht und einzeln nach ihrer Herkunft unter Bezeichnung der Ausgabe (Auflage und Jahr des Erscheinens), des Bandes und ggf. der Seite des benutzten Werkes nachgewiesen habe.

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