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A supply chain design approach considering environmentally sensitive customers: the case of a German manufacturing SME

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A supply chain design approach considering environmentally sensitive customers: the case of a German manufacturing SME

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Sustainable business development is one of the main topics of research and management in recent years. Since the environmental pillar is a part of the sustainability concept, companies are forced to (re-)design their supply chain according to environmental issues. Both government and other stakeholders, e.g. non-governmental organisations and customers, pay a lot of attention on a company's environmental performance. Hence there is a risk of losing reputation if a company does not comply with environmental norms. We focus on the impact of customers' requirements regarding the environmental performance of a product on strategic supply chain design decisions of the manufacturer of the product. Thus, we consider the case of a German manufacturing company and present a mixed-integer linear programming supply chain design model with a demand function that is influenced by sustainability requirements. The company is assumed to be able to improve the environmental performance of the products sold and affect the customer demand positively by designing an environmentally conscious supply chain.

Keywords: sustainable manufacturing; supply chain design; mixed-integer linear programming; case study

1. Introduction

Sustainability has become more and more critical for companies (Kleindorfer, Singhal, and Van Wassenhove 2005; Srivastava 2007). 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' (WCED 1987). 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 (Elkington 1999) and the fact that value-creating processes are increasingly located all over the world lead to supply chain planning situations with increased complexity. 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 (Ageron, Gunasekaran, and Spalanzani 2012). In addition to governments, non-governmental organisations put more and more pressure on companies. Nowadays publications in the media claiming undue social or environmental behaviour of a company could damage 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 (Rao 2002). However, 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 environmental-friendly product as well as potentially higher demands on sustainable products is important (Rao 2002). To achieve a higher environmental product performance, companies are forced to check all relevant supply chain processes for potential improvements.

Supply chain design is the basis for all other supply chain planning levels (Ivanov 2010). 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 suppliers and facilities from a procurement point of view as well as facilities and customers from a distributional perspective (Santoso et al. 2005). 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

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operational decisions (Aronsson and Brodin 2006). The number and locations of supply chain nodes (e.g. suppliers, facilities, warehouses and distribution hubs) as well as the distance between them determine the environmental impact of logistic processes. Furthermore, the type of products has a significant impact on carbon equivalent emissions of both transportation and inventory processes (Jaegler and Burlat 2014). 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, improves the environmental performance, so does the installation of pollution prevention technologies (Klassen and Whybark 1999). By allocating eco-friendly production technologies at the production facilities and by increasing the utilisation ratio of these facilities, the environmental performance could be influenced positively. When considering 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 (ISO 14000, GRI), can be used to verify an environmental responsible behaviour of potential suppliers. Appropriate methods, as e.g. an AHP-QFD approach (Dai and Blackhurst 2012), have already been presented in literature. Only companies which implement green practices on the entire supply chain stay competitive as case studies of Apple and Coca-Cola illustrated (Kumar, Teichman and Timpernagel 2012). However, planning integration of upstream and downstream supply chain actors leads to different suggestions regarding investment and supply chain structure changes (Vachon and Klassen 2007).

In this research, we consider customer integration and capture the mentioned sustainability requirements of customers by integrating a sustainability-dependent demand function into a mixed-integer linear programming supply chain design model. In this way, investments in environmentally conscious production processes can not only lead to a higher environmental performance, but also to an improvement of economic results (Ashford 1993). To evaluate this relationship, we focus on the environmental dimension of sustainability and consider the case of a German manufacturing SME. To the best of our knowledge, this is the first research that focuses on the interrelations of customers' environmental requirements and supply chain design decisions. Accordingly, the presented model can be used as a decision support approach for redesigning a supply chain according to environmental objectives motivated by customer requirements

The rest of the paper is organised as follows: In the next section, we review the relevant literature and discuss the different approaches of integrating environmental issues in supply chain design models. In addition it is elucidated, why customers' sustainability requirements can be interpreted as a motivation to redesign a supply chain. The presentation of a supply chain design model, which considers an environmentally sensitive demand function, is the topic of Section 3. In addition, we describe and analyse the results of a case-based numerical example, from which we derive further management implications. Finally, in Section 4, the conclusions of the paper are drawn.

2. Literature review

2.1 *Sustainability-oriented supply chain design models*

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 with qualitative approaches such as concepts or frameworks (Seuring and Müller 2008). 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 focuses explicitly just on strategic supply chain design approaches that use optimisation techniques in order to find a supply chain configuration. Therefore, neither tactical supply chain planning models, which for instance consider only transportation and routing decision (e.g. Validi, Bhattarcharya, and Byrne 2014a, 2014b, 2014c) nor simulation models are considered in the review. In addition, only models are integrated into the review pool that captures at least two sustainability pillars in the model coefficients. More general literature reviews on modelling approaches can be found in Seuring (2013), Brandenburg et al. (2014) and Farahani et al. (2014).

A multi-objective mixed-integer linear programming model which maximises net present value and minimises environmental impact is developed by Hugo and Pistikopoulos (2005). The environmental impact is measured according to the three categories, such as human health, ecosystem quality and resource. Frota Neto et al. (2008) developed an optimisation approach for sustainable supply chain planning with minimisation of both environmental impact and total costs as objectives. 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 analyse the impact of changing upper emission bounds on total logistic costs. A stochastic mixed-integer non-linear programme for the maximisation of the net present value and minimisation of the environmental impact is presented by Guillén-Gosálbez and Grossmann (2009). Environmental impact is assessed via different impact categories, which are aggregated afterwards. Another green supply chain optimisation approach is presented by Tsai and Hung (2009). 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 Wakolbinger (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 maximisation of net returns, minimisation of emissions as well as the minimisation of risk, covering organisational, environmental and network-related risks as objective functions. 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. Nagurney and Nagurney (2010) propose a multi-criteria optimisation approach for strategic sustainable supply chain design with totals costs and carbon emissions as objectives. Chaabane, Ramudhin, and Paquet (2012a) propose a multi-objective optimisation model that is solved using the ε-constraint method. Minimisation 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. Chaabane, Ramudhin, and Paquet (2012b) 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 maximisation of total cost and minimisation of total greenhouse gases. A multi-objective optimisation approach is proposed by Wang, Lai, and Shi (2011). The two objective functions measure total cost and total carbon emissions in the supply chain. Elhedhli and Merrick (2012) consider carbon emissions by integrating environmental cost into the total cost function. Assuming a concave relationship between vehicle weight and carbon emissions the mixed-integer model is non-linear. Pinto-Varela, Barbosa-Póvoa, and Novais (2011) apply symmetric fuzzy linear programming to maximise profit and to minimise environmental impact as well. 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. The ε-constraint method is used by You et al. (2012) to capture the trade-off 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. To design a closed-loop supply chain according to both economic and environmental objectives, Altmann and Bogaschewsky (2014) propose a robust, multi-objective optimisation model. Both objective functions, discounted total costs as the financial objective and carbon equivalents as the environmental objective, are minimised. 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. 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). Also, Soysal, Bloemhof-Ruwaard, 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. 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.

As the literature review illustrates, the selection of appropriate environmental-based performance indicators that measure the overall environmental supply chain performance can be used as model objectives, and therefore, is heterogeneous. Bhattacharya et al. (2014) presented a fuzzy-ANP-based balance scorecard approach to measure green supply chain performance. Using such an approach, companies are able to consolidate multiple sustainability measures in a singular indicator that helps to compare different decision options. However, Hassini, Surti, and Searcy (2012) reviewed the sustainable performance measures used in the literature and proposed to use composite indicators. 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. According to many models reviewed in this section, 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).

As a result of the literature review above and to the best of our knowledge, it can be summarised 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 identifying appropriate supply chain design decision in the case of customer pressure regarding environmentally conscious products.

2.2 *Environmentally sensitive customer demand*

Besides governmental regulations and pressure from non-governmental organisations, customer's requirements are one of the major drivers for the adoption of green supply chain management practices (Zhu, Sarkis, and Geng 2005). This is of enhanced significance for globally active companies, since environmental requirements of customers differ from country to country (Christmann and Taylor 2001). 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. 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 between environmentally conscious production and customers' buying decisions. One reason can be found in the impact of environmentally consciousness on a business's reputation and customer's goodwill (Schiebel and Pöchtrager 2003). Ateş et al. (2012) analysed the relationship of customers' pressure and environmental investments and found evidence for a positive correlation. Since a reduction in the demand is an effective instrument of customers to show companies how they can turn pressure into action, companies are enforced to pursue a proactive environmental strategy. This assumption is also supported by Ehrgott et al. (2011) who reasoned based on innovation management arguments that customers would not purchase products any more that are not characterised by a certain innovative, in this context sustainable features. As Tate, Ellram, and Kirchoff (2010) showed, customers are up to claim companies to keep a certain level of environmental impact regarding goods that they buy. Focusing on demand functions, Glock, Jaber, and Searcy (2012) assumed that customers' demand is negatively correlated with the environmental impact of a product. Finally, Georgiadis and Vlachos (2004) considered the environmentally consciousness of products in the demand function and assumed that a green image of products, determined by the reuse degree, has a positive impact on the demand.

Summarising the literature, it can be assumed that the relationship between the environmental performance of a product and the demand function is customer specific. Therefore, we integrate a customer-specific demand function into the modelling approach, which depends on the sustainable performance of the ordered product.

3. Model description

3.1 *Case-based problem description and assumptions*

The considered supply chain design problem is motivated by a real-world case of a German manufacturing SME. We consider a product-specific subproblem of a company that produces security equipment for chemical processing facilities based in Germany. Based on sales studies, this company identified that their customers are sensitive to the high environmental impact of the offered products. Accordingly, the company was motivated to analyse what kind of supply chain design changes should be done in order to reach a higher demand. The considered alternative supply chain configurations are shown in Figure 1. As illustrated, the value network can be characterised by a three echelon supply chain with

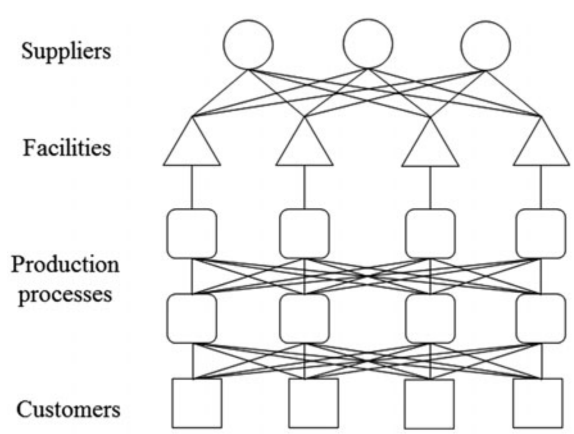

Figure 1. Supply chain structure.

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.

The environmental impact is considered on all three levels: suppliers, production and distribution. To increase the environmental performance, the decision-maker can instal environmental-friendly resources (e.g. machines). In addition, logistical processes could be minimised 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. 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 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 product, 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. In the quality context, Castillo-Villar, Smith, and Simonton (2012) stated that supply chain design decisions influence product quality. 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 2. We assume a piecewise linear function. The various levels characterise 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. Nevertheless, e.g. decreasing in 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.

The demand function can be written as:

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

The demand level of the product depends 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 customers' requirements, the formulation of the demand function is customer specific. We, therefore, modified the demand

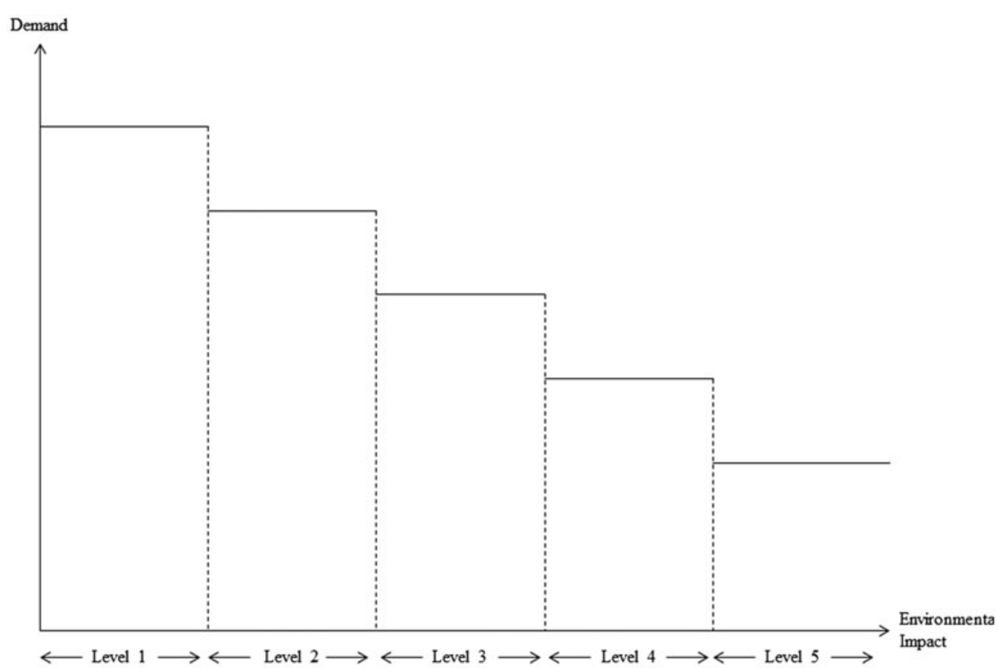

Figure 2. Illustration of the demand function.

function proposed by Banker, Khosla, and Sinha (1998) who mentioned the relationship between demand and the quality of a product. As mentioned above, we use carbon equivalents to measure the environmental impact which we interpret as a quality characteristic. 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 (Glock, Jaber, and Searcy 2012). To analyse production characteristics in detail, we modelled a multi-process production environment. In addition, the long-term planning environment of supply chain design decisions is considered. Therefore, 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 and 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.

Table 1 shows the notations used in the proposed model.

3.2 *Model presentation*

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

$$\text{Max} \sum_{t \in T} \frac{fcf_t}{(1+DR)^t} + \frac{tv}{(1+DR)^T} \tag{2}$$

It maximises the discounted free cash flow to the firm and the time-adjusted terminal value. Since supply chain configurations influence the weighted average costs of capital that are normally used in the free cash flow valuation method (Koller, Goedhart, and Wessels 2010; Longinidis and Georgiadis 2013), we select a fixed discount rate for time adjustment according to Hugo and Pistikopoulos (2005) and Guillén-Gosálbez and Grossmann (2009).

$$fcf_t = \sum_{f \in F} \left(1 - tax_{ft}\right) \cdot ebitda_{ft} + tax_{ft} \cdot dep_{ft} - Invest_t, \qquad \forall t \in T \tag{3}$$

The free cash flow consists of the tax-adjusted ebitda, tax advantages of depreciations less capital expenditures. Equation (4) is just for visual simplification and shows the elements of ebitda calculation:

$$\begin{aligned} ebitda_{ft} = & \sum_{c \in C} \sum_{p \in P} \sum_{l \in L} TP_{fcplt} PP_{cpt} - fix_{ft} x_{ft} - cf_{ft} rx_{ft} - \sum_{r \in R} fixR_{frt} y_{frt} - \sum_{r \in R} cr_{frt} ry_{frt} - \sum_{c \in C} \sum_{p \in P} \sum_{r \in R} \sum_{q \in Q^*} PA_{fcprqt} PC_{fprqt} \\ & - \sum_{g \in F} \sum_{c \in C} \sum_{p \in P} \sum_{r \in R} \sum_{q \in Q} \sum_{l \in L} TAIP_{fgcprqlt} PC_{fprqt} - \sum_{g \in F} \sum_{c \in C} \sum_{p \in P} \sum_{r \in R} \sum_{q \in Q} \sum_{l \in L} TAIP_{fgcprqlt} TCIP_{fgprqlt} \\ & - \sum_{c \in C} \sum_{p \in P} \sum_{l \in L} TP_{fcplt} TCP_{fcplt} - \sum_{s \in S} \sum_{c \in C} \sum_{m \in M} \sum_{l \in L} SA_{sfcmlt} (SC_{smt} + TSC_{sfmlt}) - \zeta_{ft} EC_{ft} \end{aligned} \tag{4}$$

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 (4) considers cost for exceeding regulatory environmental impact levels as calculated in constraint (34).

$$dep_{ft} = depF_{ft} x_{ft} + \sum_{r \in R} depR_{frt} y_{frt} \qquad \forall f \in F, t \in T \tag{5}$$

Equation (5) describes the calculation of depreciations on facility and resource level, respectively.

$$tv = \sum_{f \in F} tv_f + \sum_{f \in F} \sum_{r \in R} tv_{fr} \tag{6}$$

Table 1. Summary of notation.

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

(*Continued*)

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 variable that indicates whether 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

The terminal values of the facility location (7) and resource level (8) are calculated by summarising capital expenditures over all periods less depreciations. Equation (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.

$$tv_f = \sum_{\substack{t \in T \\ t=1}} invF_{ft}x_{ft} + \sum_{\substack{t \in T \\ t>1}} invF_{ft}(x_{ft} - x_{ft-1}) - \sum_{t \in T} depF_{ft}x_{ft} \qquad \forall f \in F \tag{7}$$

$$tv_{fr} = \sum_{\substack{t \in T \\ t=1}} invR_{frt}y_{frt} + \sum_{\substack{t \in T \\ t>1}} invR_{frt}(y_{frt} - y_{frt-1}) - \sum_{t \in T} depR_{frt}y_{frt} \qquad \forall f \in F, r \in R \tag{8}$$

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 in Equations (9) and (10).

$$tv_f \leq BigMx_{ft} \qquad \forall f \in F, t = T \tag{9}$$

$$tv_{fr} \leq BigMy_{frt} \qquad \forall f \in F, r \in R,\ t = T \tag{10}$$

Equation (11) illustrates the calculation of capital expenditures on the facility and resource stage for each period.

$$Invest_t = \begin{cases} \sum_{f \in F} invF_{ft}x_{ft} + \sum_{f \in F}\sum_{r \in R} invR_{frt}y_{frt} & \forall t = 1 \\ \sum_{f \in F} invF_{ft}(x_{ft} - x_{ft-1}) + \sum_{f \in F}\sum_{r \in R} invR_{frt}(y_{frt} - y_{frt-1}) & \forall t > 1 \end{cases} \tag{11}$$

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, (12) equals (1). Thus, ω_{cptb} is binary, and (13) ensures that only one demand level is selected.

$$D_{cpt} = \sum_{b \in B} \omega_{cptb} d(\Pi)_{bcpt} \qquad \forall c \in C, p \in P, t \in T \tag{12}$$

$$\sum_{b \in B} \omega_{cptb} = 1 \qquad \forall c \in C, p \in P, t \in T \tag{13}$$

$$\sum_{f \in F}\sum_{l \in L} TP_{fcplt} = D_{cpt} \qquad \forall c \in C, p \in P, t \in T \tag{14}$$

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:

$$\sum_{l \in L} TP_{fcplt} = \sum_{r \in R^q} \sum_{q \in Q^{p*}} PA_{fcprqt} \qquad \forall f \in F, c \in C, p \in P, t \in T \tag{15}$$

Intercompany flows of intermediate products are considered in the following constraints. Constraint (16) ensures the supply of intermediate products that are inputs into the production of final product p:

$$\sum_{r \in R^q} \sum_{q \in Q^{p*}} PA_{fcprqt} ExIn_{oq} = \sum_{g \in F} \sum_{l \in L} \sum_{r \in R} TAIP_{gfcprolt} \qquad \forall f \in F, c \in C, p \in P, t \in T, o \in Q \tag{16}$$

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

$$\sum_{e \in F} \sum_{p \in P} \sum_{r \in R} \sum_{q \in Q} \sum_{l \in L} TAIP_{fecprqlt} BoM_{rqm} + \sum_{p \in P} \sum_{r \in R} \sum_{q \in Q^{p*}} PA_{fcprqt} BoM_{rqm} = \sum_{s \in S} \sum_{l \in L} SA_{sfcmlt} \qquad \forall f \in F, c \in C, m \in M, t \in T \tag{17}$$

Production capacity considerations are described by the following inequality:

$$\sum_{e \in F} \sum_{c \in C} \sum_{p \in P} \sum_{q \in Q} \sum_{l \in L} \beta_{prq} TAIP_{fecprqlt} + \sum_{c \in C} \sum_{p \in P} \sum_{q \in Q^{p*}} \beta_{prq} PA_{fcprqt} \leq CapR_{frt} y_{frt} \qquad \forall f \in F, r \in R, t \in T \tag{18}$$

Thus, capacities on the facility level are unrestricted, inequality (19) links flow variable TAIP with the binary variable x_{ft}:

$$\sum_{e \in F} \sum_{c \in C} \sum_{p \in P} \sum_{r \in R} \sum_{q \in Q} \sum_{l \in L} TAIP_{fecprqlt} + \sum_{c \in C} \sum_{p \in P} \sum_{r \in R^q} \sum_{q \in Q^{p*}} PA_{fcprqt} \leq BigM x_{ft} \qquad \forall f \in F, t \in T \tag{19}$$

A production resource can only be installed at opened facilities:

$$y_{frt} \leq x_{ft} \qquad \forall f \in F, r \in R, t \in T \tag{20}$$

Inequalities (21)–(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.

$$0 \geq -x_{ft-1} + rx_{ft} \qquad \forall f \in F, t > 1 \in T \tag{21}$$

$$0 \geq -(1 - x_{ft}) + rx_{ft} \qquad \forall f \in F, t > 1 \in T \tag{22}$$

$$1 \geq x_{ft-1} + (1 - x_{ft}) - rx_{ft} \qquad \forall f \in F, t > 1 \in T \tag{23}$$

$$0 \geq -y_{frt-1} + ry_{frt} \qquad \forall f \in F, r \in R, t > 1 \in T \tag{24}$$

$$0 \geq -(1 - y_{frt}) + ry_{frt} \qquad \forall f \in F, r \in R, t > 1 \in T \tag{25}$$

$$1 \geq y_{frt-1} + (1 - y_{frt}) - ry_{frt} \qquad \forall f \in F, r \in R, t > 1 \in T \tag{26}$$

Environmental impact modelling

According to the formulation of Equation (1), it is necessary to calculate the environmental emissions in a customer and product-specific way for each period, evoking 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.

$$\Pi_{cpt} = \sum_{s\in S}\sum_{f\in F}\sum_{m\in M}\sum_{l\in L} EPS_{sfmlt} SA_{sfcmlt} + \sum_{f\in F}\sum_{e\in F}\sum_{q\in Q^p}\sum_{r\in R^q}\sum_{l\in L} EPI_{feprqlt} TAIP_{fecprqlt} + \sum_{f\in F}\sum_{r\in R}\sum_{q\in Q} EPP_{fprqt} PA_{fcprqt}$$
$$+ \sum_{f\in F}\sum_{l\in L} EPC_{fcplt} TP_{fcplt} \qquad \forall c\in C, p\in P, t\in T \tag{27}$$

The environmental performance, calculated in (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 (1)). Therefore, binary variable ω_{cptb} is introduced, which is both customer and product specific, and which determines the relevant bound (28)–(32).

$$EPB_{cptb} \leq UB_{cptb}\omega_{cptb} \qquad \forall c\in C, p\in P, t\in T, b\in B \tag{28}$$

$$EPB_{cptb} \geq LB_{cptb}\omega_{cptb} \qquad \forall c\in C, p\in P, t\in T, b=1 \tag{29}$$

$$EPB_{cptb} > UB_{cptb-1}\omega_{cptb} \qquad \forall c\in C, p\in P, t\in T, b>1 \tag{30}$$

$$\sum_{b\in B} EPB_{cptb} = \Pi_{cpt} \qquad \forall c\in C, p\in P, t\in T, b\in B \tag{31}$$

$$\sum_{b\in B} \omega_{cptb} = 1 \qquad \forall c\in C, p\in P, t\in T, b\in B \tag{32}$$

In addition to the customer-specific environmental performance on the product level, constraint (33) measures the environmental impact per facility, which is used in (34) to ensure that the level of environmental impact complies with the legal environmental impact level at each facility.

$$\xi_{ft} = \sum_{p\in P}\sum_{q\in Q^p}\sum_{r\in R^q} EPP_{fprqt} PA_{fcprqt} + \sum_{p\in P}\sum_{e\in F}\sum_{q\in Q^p}\sum_{r\in R^q}\sum_{l\in L} EPI_{feprqlt} TAIP_{fecprqlt} \qquad \forall f\in F, t\in T \tag{33}$$

$$\xi_{ft} + \zeta_{ft} \leq LIL_{ft} \qquad \forall f\in F, t\in T \tag{34}$$

In constraint (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 (4). The opening decision variable x_{ft} is binary:

$$x_{ft} \in \{0,1\} \qquad \forall f\in F, t\in T \tag{35}$$

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

$$y_{frt} \in \{0,1\} \qquad \forall f\in F, r\in R, t\in T \tag{36}$$

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

$$\omega_{cptb} \in \{0, 1\} \qquad \forall c \in C, p \in P, t \in T, b \in B \tag{37}$$

The other decisions variables are non-negative (38):

$$\begin{gathered} SA_{sfcmlt} PA_{fcprqt}, TAIP_{fecprqlt}, TAIP_{gfcprolt}, TP_{fcplt}, \zeta_{ft} \geq 0 \\ \forall c \in C, e \in E, f \in F, g \in G, l \in L, m \in M, o \in O, p \in P, r \in R, t \in T \end{gathered} \tag{38}$$

3.3 *Solution procedure*

As mentioned above, the model is developed as a mixed-integer linear programming model. Consequently, we can apply a standard solver (IBM ILOG CPlex or LINGO by LINDO Systems) to solve the model. Particularly for the application of the model in SME cases, this is an important issue, since the companies normally do not have both skilled specialists and systems that can be used to solve more complex models.

3.4 *Numerical example*

3.4.1 *Case description*

In this section, we first present the relevant numerical data for the considered case. Further, the supply chain design solution is illustrated to evaluate the model proposed above and to highlight managerial implications. On the supplier level, five suppliers are considered. Each supplier has a specific production capacity of the five materials, which are used in one of the three production processes. The three production processes can be executed using four different production 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 production abilities regarding the specific production 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 the production of product 1 includes production processes 1 and 2, product 2 also needs production process 3 to be accomplished. Consequently, product 2 is an advanced version of product 1. Customers are aggregated into six customer 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). Hence, 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 2 summarises the information regarding the underlying planning problem.

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 (1) to study the impact of changing production structures with the effect of decreasing environmental impact. According to these assumptions, Tables 3 and 4 illustrate customer-specific demand data and the acceptance levels of environmental impact applied for period 1 in our numerical example.

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 on the supply chain stages provide the decision-maker with various opportunities to influence the environmental impact of the products. Using the proposed model, we support the decision-maker in evaluating an appropriate supply chain design. It should 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 investment decisions in production resources to perform selected processes and intercompany as well as 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 maximised 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, because of higher customer demand due to more environmentally conscious operations.

Table 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

Table 3. Customer's 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 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	100,000	100,000	100,000	100,000	100,000	100,000
2	1	850	2000	175	1500	1000	1000
	2	100,000	100,000	100,000	100,000	100,000	100,000

3.4.2 *Results*

As mentioned in Section 3.3, a linear model is developed. Following this assumption, we can use a standard linear solver engine 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 characterised by the parameters, mentioned in 3.4.1. The optimal discounted free cash flow is 421.220.200 €. The solution recommends the opening of production facility location 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 illustrates this solution. Facility in location 5 is assumed to be the cheapest 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 customer environmental impact requirements of the first demand bound.

Demand scenario

In the second scenario, we analyse variations in customer demand. Therefore, we conduct a sensitivity analysis regarding the first and second demand bounds. By doing this, we simulate situations, in which customers shorten their

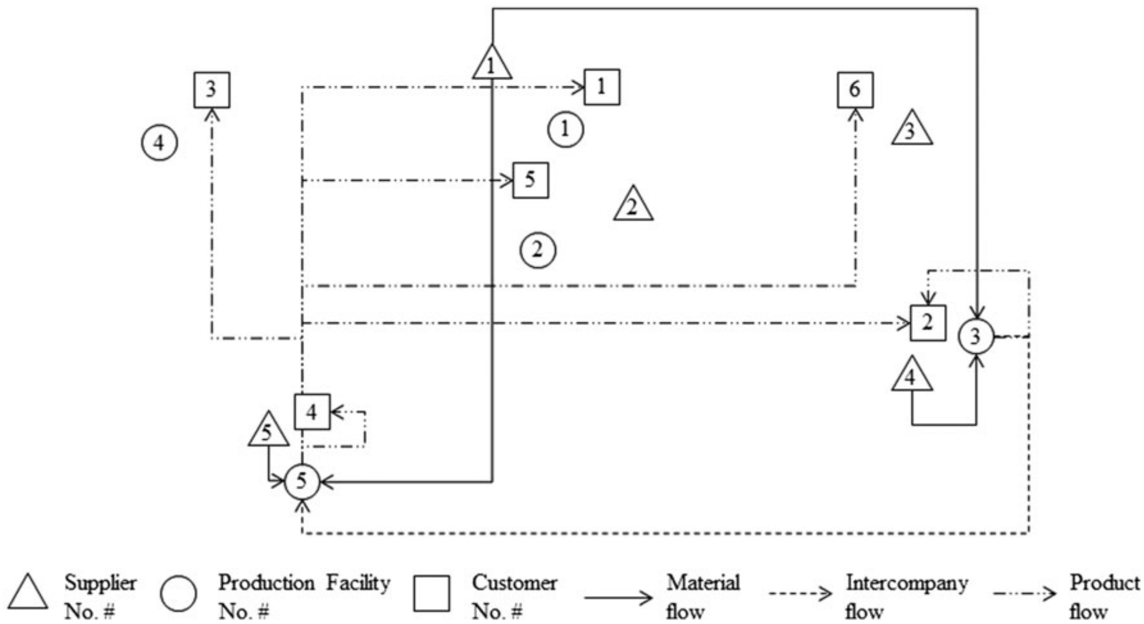

Figure 3. Optimal Supply Chain Design of the initial scenario.

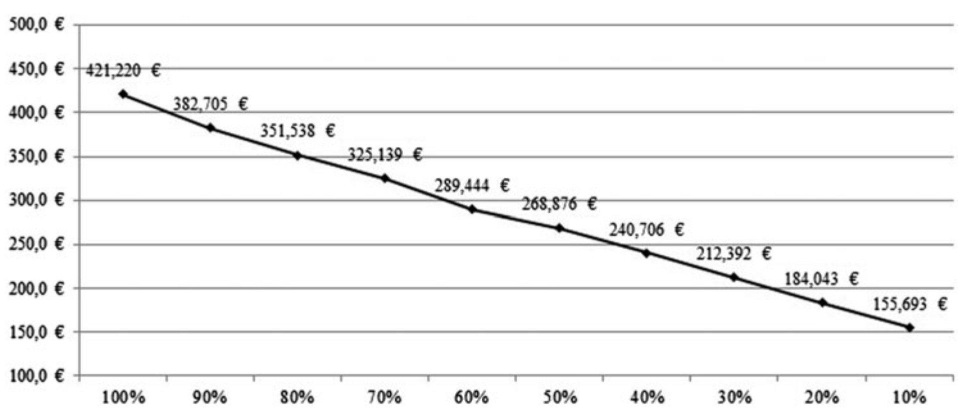

Figure 4. Sensitive analysis of demand bound 2 (Free cash flow in million €).

demand excessively when a certain environmental impact level is reached. Figure 4 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 faster between 100 and 90% as well as between 70 and 60% compared with other areas of the function. Doing a more detailed analysis, we can identify some changes in the supply chain structure.

Table 5 presents the used resources on the production facility level and the customers, which are supplied by the opened facilities.

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

Table 5. Manufacturing structure of products per scenario.

Scenario	Facility	Installed resources	Supply material	Supply intermediate products	Customers	Products
100%	F5	R1[a],R2	S1 (M4) S5 (M1, M2, M3, M4, M5)	F5	C1, C2, C3, C4, C5	P1, P2
90%	F5	R1[a],R2	S1 (M4) S5 (M1, M2, M3, M4, M5)	F5	C1, C2, C3, C4, C5	P1, P2
80%	F3	R1[a],R2	S4 (M1, M2, M3, M4, M5)	F3	C2	P1, P2
	F5	R1[a],R2	S1 (M4) S5 (M1, M2, M3, M4, M5)	F3, F5	C1, C2, C3, C4, C5	P1, P2
70%	F3	R1[a],R2	S4 (M1, M2, M3, M4, M5)	F3	C2	P1, P2
	F5	R1[a],R2	S1 (M4) S5 (M1, M2, M3, M4, M5)	F3, F5	C1, C2, C3, C4, C5	P1, P2
60%	F3	R1[a],R2	S4 (M1, M2, M3, M4, M5)	F3	C2	P1, P2
	F5	R2, R4[a]	S1 (M4) S5 (M1, M2, M3, M4, M5)	F3, F5	C1, C2, C3, C4, C5	P1, P2
50%	F3	R1[a],R2	S4 (M1, M2, M3, M4, M5)	F3	C2	P1, P2
	F5	R2, R4[a]	S1 (M4) S5 (M1, M2, M3, M4, M5)	F3, F5	C1, C2, C3, C4, C5	P1, P2
40%	F3	R1[a],R2	S4 (M1, M2, M3, M4, M5)	F3	C2	P1, P2
	F5	R2, R4[a]	S1 (M4) S5 (M1, M2, M3, M4, M5)	F3, F5	C1, C2, C3, C4, C5	P1, P2
30%	F3	R1[a],R2	S4 (M1, M2, M3, M4, M5)	F3	C2	P1, P2
	F5	R2, R4[a]	S1 (M4) S5 (M1, M2, M3, M4, M5)	F3, F5	C1, C2, C3, C4, C5	P1, P2
20%	F3	R1[a],R2	S4 (M1, M2, M3, M4, M5)	F3	C2	P1, P2
	F5	R2, R4[a]	S1 (M4) S5 (M1, M2, M3, M4, M5)	F3, F5	C1, C2, C3, C4, C5	P1, P2
10%	F3	R1[a],R2	S4 (M1, M2, M3, M4, M5)	F3	C2	P1, P2
	F5	R2, R4[a]	S1 (M4) S5 (M1, M2, M3, M4, M5)	F3, F5	C1, C2, C3, C4, C5	P1, P2

[a]used to produce intermediate products.

customer 2. 54.41% of the demand of customer 2 regarding product 1 is fulfilled 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 installation 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 customers' requirements regarding the environmental impact of a product. As a major result, it can be summarised that the more sensitive the customers are, the merrier a decentralised production allocation is advisable. In the case, customers are highly sensitive to environmental impact, supply chain design decisions may result suboptimal, if a decision-maker does not explicitly consider the customer-specific demand behaviour in the planning approach.

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 organisations, customer requirements force companies to reconsider their supply chain design. To provide a decision supporting approach for a German manufacturing SME, this paper has presented a multi-echelon, multi-product supply chain design model which considers both economic and environmental impacts of value-adding activities in the supply chain. Compared with previous literature, our approach particularly focuses on customers' requirements regarding the environmental impact of the delivered products. The major contribution is, therefore, the consideration of the linkage between customers' demand behaviour and supply chain design decisions. To model this relationship, we integrated an environmental impact dependent, piecewise linear, customer-specific demand function based on the assumptions of Glock, Jaber, and Searcy (2012). 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 characterised by individual production costs as well as environmental impact per process. The solution of the case-driven model illustrates that in the case of a significant decrease in customers' demand when the environmental impact increases, a rather decentralised production allocation is advisable.

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, including various products, 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. Finally, the consideration of interrelations of the price and environmental performance of a product in a supply chain design model could be a further research direction. Particularly, the ability to reach a higher price for environmentally conscious products could then be analysed in detail.

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References

Ageron, B., A. Gunasekaran, and A. Spalanzani. 2012. "Sustainable Supply Management: An Empirical Study." *International Journal of Production Economics* 140 (1): 168–182.

Altmann, M., and R. Bogaschewsky. 2014. "An Environmentally Conscious Robust Closed-loop Supply Chain Design." *Journal of Business Economics*. 84 (5): 613–637.

Aronsson, H., and M. H. Brodin. 2006. "The Environmental Impact of Changing Logistics Structures." *The International Journal of Logistics Management* 17 (3): 394–415.

Ashford, N. A. 1993. "Understanding Technological Responses of Industrial Firms to Environmental Problems: Implications for Governmental Policy." In *Environmental Strategies for Industry*, edited by K. Fisher and J. Schot, 277–307. Washington, DC: Island Press.

Ateş, M. K., J. Bloemhof, E. M. van Raaij, and F. Wynstra. 2012. "Proactive Environmental Strategy in a Supply Chain Context: The Mediating Role of Investments." *International Journal of Production Research* 50 (4): 1079–1095.

Banker, R. D., I. Khosla, and K. K. Sinha. 1998. "Quality and Competition." *Management Science* 44 (9): 1179–1192.

Bhattacharya, A., P. Mohapatra, V. Kumar, P. K. Dey, M. Brady, M. K. Tiwari, and S. S. Nudurupati. 2014. "Green Supply Chain Performance Measurement Using Fuzzy ANP-based Balanced Scorecard: A Collaborative Decision-making Approach." *Production Planning & Control: The Management of Operations* 25 (8): 698–714.

Brandenburg, M., K. Govindan, J. Sarkis, and S. Seuring. 2014. "Quantitative Models for Sustainable Supply Chain Management: Developments and Directions." *European Journal of Operational Research* 233 (2): 299–312.

Castillo-Villar, K. K., N. R. Smith, and J. L. Simonton. 2012. "The Impact of the Cost of Quality on Serial Supply-chain Network Design." *International Journal of Production Research* 50 (19): 5544–5566.

Chaabane, A., A. Ramudhin, and M. Paquet. 2012a. "Designing Supply Chains with Sustainability Considerations." *Production Planning and Control* 22 (8): 727–741.

Chaabane, A., A. Ramudhin, and M. Paquet. 2012b. "Design of Sustainable Supply Chains under the Emission Trading Scheme." *International Journal of Production Economics* 135 (1): 37–49.

Christmann, P., and G. Taylor. 2001. "Globalization and the Environment: Determinants of Firm Self-regulation in China." *Journal of International Business Studies* 32 (3): 439–458.

Cruz, J. M. 2008. "Dynamics of Supply Chain Networks with Corporate Social Responsibility through Integrated Environmental Decision-making." *European Journal of Operational Research* 184 (3): 1005–1031.

Cruz, J. M., and D. Matsypura. 2009. "Supply Chain Networks with Corporate Social Responsibility through Integrated Environmental Decision-Making." *International Journal of Production Research* 47 (3): 621–648.

Cruz, J. M., and T. Wakolbinger. 2008. "Multiperiod Effects of Corporate Social Responsibility on Supply Chain Networks, Transaction Costs, Emissions and Risk." *International Journal of Production Economics* 116 (1): 61–74.

Dai, J., and J. Blackhurst. 2012. "A Four-phase AHP–QFD Approach for Supplier Assessment: A Sustainability Perspective." *International Journal of Production Research* 50 (19): 5474–5490.

Devika, K., A. Jafarian, and V. Nourbakhsh. 2014. “Designing a Sustainable Closed-loop Supply Chain Network Based on Triple Bottom Line Approach: A Comparison of Metaheuristics Hybridization Techniques.” *European Journal of Operational Research* 235 (3): 594–615.

Ehrgott, M., F. Reimann, L. Kaufmann, and C. R. Carter. 2011. “Social Sustainability in Selecting Emerging Economy Suppliers.” *Journal of Business Ethics* 98 (1): 99–119.

Elhedhli, S., and R. Merrick. 2012. “Green Supply Chain Network Design to Reduce Carbon Emissions.” *Transportation Research Part D: Transport and Environment* 17 (5): 370–379.

Elkington, J. 1999. *Cannibals with Forks: The Triple-Bottom-Line of 21st Century Business*. Oxford: Capstone Publishing.

Farahani, R. Z., S. Rezapour, T. Drezner, and S. Fallah. 2014. “Competitive Supply Chain Network Design: An Overview of Classifications, Models, Solution Techniques and Applications.” *Omega* 45: 92–118.

Frota Neto, J., J. M. Bloemhof-Ruwaard, J. A. E. E. van Nunen, and E. van Heck. 2008. “Designing and Evaluating Sustainable Logistics Networks.” *International Journal of Production Economics* 111 (2): 195–208.

Georgiadis, P., and D. Vlachos. 2004. “The Effect of Environmental Parameters on Product Recovery.” *European Journal of Operational Research* 157 (2): 449–464.

Glock, C. H., M. H. Jaber, and C. Searcy. 2012. “Sustainability Strategies in an EPQ Model with Price- and Quality-sensitive Demand.” *The International Journal of Logistics Management* 23 (3): 340–359.

Govindan, K., A. Jafarian, R. Khodaverdi, and K. Devika. 2014. “Two-Echelon Multiple-vehicle Location–Routing Problem with Time Windows for Optimization of Sustainable Supply Chain Network of Perishable Food.” *International Journal of Production Economics* 152 (c): 9–28.

Guillén-Gosálbez, G., and I. E. Grossmann. 2009. “Optimal Design and Planning of Sustainable Chemical Supply Chains under Uncertainty.” *AIChE Journal* 55 (1): 99–121.

Hassini, E., C. Surti, and C. Searcy. 2012. “A Literature Review and a Case Study of Sustainable Supply Chains with a Focus on Metrics.” *International Journal of Production Economics* 140 (1): 69–82.

Hugo, A., and E. N. Pistikopoulos. 2005. “Environmentally Conscious Long-Range Planning and Design of Supply Chain Networks.” *Journal of Cleaner Production* 13 (15): 1471–1491.

Ivanov, D. 2010. “An Adaptive Framework for Aligning (Re)planning Decisions on Supply Chain Strategy, Design, Tactics, and Operations.” *International Journal of Production Research* 48 (13): 3999–4017.

Jaegler, A., and P. Burlat. 2014. “What is the Impact of Sustainable Development on the Re-localisation of Manufacturing Enterprises?” *Production Planning and Control* 25 (11): 902–911.

Jayaraman, V., R. Singh, and A. Anandnarayan. 2012. “Impact of Sustainable Manufacturing Practices on Consumer Perception and Revenue Growth: An Emerging Economy Perspective.” *International Journal of Production Research* 50 (5): 1395–1410.

Klassen, R. D., and D. C. Whybark. 1999. “The Impact of Environmental Technologies on Manufacturing Performance.” *Academy of Management Journal* 42 (6): 599–615.

Kleindorfer, P. R., K. Singhal, and L. V. Van Wassenhove. 2005. “Sustainable Operations Management.” *Production and Operations Management* 14 (4): 482–492.

Koller, T., M. Goedhart, and D. Wessels. 2010. *Valuation - Measuring and Managing the Value of Companies*. 5th ed. New York: John Wiley.

Kumar, S., S. Teichman, and T. Timpernagel. 2012. “A Green Supply Chain is a Requirement for Profitability.” *International Journal of Production Research* 50 (5): 1278–1296.

Longinidis, P., and M. C. Georgiadis. 2013. “Managing the Trade-Offs between Financial Performance and Credit Solvency in the Optimal Design of Supply Chain Networks under Economic Uncertainty.” *Computers & Chemical Engineering* 48: 264–279.

Nagurney, A., and L. S. Nagurney. 2010. “Sustainable Supply Chain Network Design: A Multicriteria Perspective.” *International Journal of Sustainable Engineering* 3 (3): 189–197.

Nagurney, A., and F. Toyasaki. 2003. “Supply Chain Supernetworks and Environmental Criteria.” *Transportation Research Part D: Transport and Environment* 8 (3): 185–213.

Pinto-Varela, T., A. P. F. D. Barbosa-Póvoa, and A. Q. Novais. 2011. “Bi-objective Optimization Approach to the Design and Planning of Supply Chains: Economic versus Environmental Performances.” *Computers & Chemical Engineering* 35 (8): 1454–1468.

Pishvaee, M. S., J. Razmi, and S. A. Torabi. 2012. “Robust Possibilistic Programming for Socially Responsible Supply Chain Network Design: A New Approach.” *Fuzzy Sets and Systems* 206 (1): 1–20.

Ramudhin, A., A. Chaabane, M. Kharoune, and M. Paquet. 2008. “Carbon Market Sensitive Green Supply Chain Network Design.” In *Proceedings of Industrial Engineering and Engineering Management 2008*, 1093–1097. Singapore.

Rao, P. 2002. “Greening the Supply Chain: A New Initiative in South East Asia.” *International Journal of Operations and Production Management* 22 (6): 632–655.

Santibañez-Aguilar, J. E., J. B. González-Campos, J. M. Ponce-Ortega, M. Serna-González, and M. M. El-Halwagi. 2014. “Optimal Planning and Site Selection for Distributed Multiproduct Biorefineries Involving Economic, Environmental and Social Objectives.” *Journal of Cleaner Production* 65: 270–294.

Santoso, T., S. Ahmed, M. Goetschalckx, and A. Shapiro. 2005. “A Stochastic Programming Approach for Supply Chain Network Design under Uncertainty.” *European Journal of Operational Research* 167 (1): 96–115.

Schiebel, W., and S. Pöchtrager. 2003. "Corporate Ethics as a Factor for Success – The Measurement Instrument of the University of Agricultural Sciences (BOKU), Vienna." *Supply Chain Management: An International Journal* 8 (2): 116–121.

Seuring, S. 2013. "A Review of Modeling Approaches for Sustainable Supply Chain Management." *Decision Support Systems* 54 (4): 1513–1520.

Seuring, S., and M. Müller. 2008. "From a Literature Review to a Conceptual Framework for Sustainable Supply Chain Management." *Journal of Cleaner Production* 16 (15): 1699–1710.

Soysal, M., J. M. Bloemhof-Ruwaard, and J. G. A. J. van der Vorst. 2014. "Modelling Food Logistics Networks with Emission Considerations: The Case of an International Beef Supply Chain." *International Journal of Production Economics* 152: 57–70.

Srivastava, S. K. 2007. "Green Supply-chain Management: A State-of-the-art Literature Review." *International Journal of Management Reviews* 9 (1): 53–80.

Tate, W. L., L. M. Ellram, and J. F. Kirchoff. 2010. "Corporate Social Responsibility Reports: A Thematic Analysis Related to Supply Chain Management." *Journal of Supply Chain Management* 46 (1): 19–44.

Tsai, W. H., and S. J. Hung. 2009. "A Fuzzy Goal Programming Approach for Green Supply Chain Optimisation under Activity-Based Costing and Performance Evaluation with a Value-Chain Structure." *International Journal of Production Research* 47 (18): 4991–5017.

Vachon, S., and R. D. Klassen. 2007. "Supply Chain Management and Environmental Technologies: The Role of Integration." *International Journal of Production Research* 45 (2): 401–423.

Validi, S., A. Bhattacharya, and P. J. Byrne. 2014a. "Integrated Low-carbon Distribution System for the Demand Side of a Product Distribution Supply Chain: A DoE-Guided MOPSO Optimiser-based Solution Approach." *International Journal of Production Research* 52 (10): 3074–3096.

Validi, S., A. Bhattacharya, and P. J. Byrne. 2014b. "A Case Analysis of a Sustainable Food Supply Chain Distribution System – A Multi-objective Approach." International Journal of Production Economics 152: 71–87.

Validi, S., A. Bhattacharya, and P. J. Byrne. 2014c. "A Solution Method for a Two-layer Sustainable Supply Chain Distribution Model." *Computers & Operations Research*. doi:10.1016/j.cor.2014.06.015.

Wang, F., X. Lai, and N. Shi. 2011. "A Multi-objective Optimization for Green Supply Chain Network Design." *Decision Support Systems* 51 (2): 262–269.

WCED. 1987. *Our Common Future*. New York: Oxford University Press.

You, F., L. Tao, D. J. Graziano, and S. W. Snyder. 2012. "Optimal Design of Sustainable Cellulosic Biofuel Supply Chains: Multiobjective Optimization Coupled with Life Cycle Assessment and Input-Output Analysis." *AIChE Journal* 58 (4): 1157–1180.

Zhu, Q., J. Sarkis, and Y. Geng. 2005. "Green Supply Chain Management in China: Pressures, Practices and Performance." *International Journal of Operations and Production Management* 25 (5): 449–468.