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Conference Paper

Flexible Supply Chain Design under Stochastic Catastrophic Risks

Provided in Cooperation with:

Hamburg University of Technology (TUHH), Institute of Business Logistics and General Management

Suggested Citation: Fan, Yingjie; Schwartz, Frank; Voß, Stefan (2014) : Flexible Supply Chain Design under Stochastic Catastrophic Risks, In: Kersten, Wolfgang Blecker, Thorsten Ringle, Christian M. (Ed.): Next Generation Supply Chains: Trends and Opportunities. Proceedings of the Hamburg International Conference of Logistics (HICL), Vol. 18, ISBN 978-3-7375-0339-6, epubli GmbH, Berlin, pp. 379-406

This Version is available at:

<https://hdl.handle.net/10419/209216>

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Flexible Supply Chain Design under Stochastic Catastrophic Risks

Yingjie Fan, Frank Schwartz and Stefan Voß

Abstract

Real-world experiences prove that supply chains may suffer great losses or even complete break downs after catastrophic events. However, extra costs after great disasters are usually not incorporated in the supply chain costs in the existing literature. The aim of this study is to design a flexible cost efficient supply chain, which is able to keep stable supply even if great disasters happen. The supply chain is designed by initially determining the location of production facilities and choosing a transportation mode for each transportation link, and then estimating extra costs after a catastrophe occurs according to the type of the catastrophe and the structure and transportation modes of the supply chain. All variable costs, including supply chain catastrophe costs, operational costs, holding costs and transportation costs are included in the objective function of a two stage stochastic decision model. An algorithm is used to solve the model in order to get an optimal or close to optimal structure of the supply chain. Numerical results are presented. Based on computational experiments we can deduce that postponement is effective to deal with supply chain catastrophic events; slow transportation seems a viable option to leave more time for a supply chain for the adjustment of production planning after catastrophes.

Keywords: supply chain risk management, slow transportation, postponement, catastrophe

1. Introduction

Globalization makes international supply chains more and more versatile but also more complicated. Although humans have all sorts of high-tech nowadays, they are usually still not able to forecast catastrophes. Without rapid response and the right decisions, however, whole supply chains would easily break down if a catastrophe happens on any of its nodes or links. Nokia's huge success compared with Ericsson's great loss after a fire in a fabrication line of Philips on March 17, 2000 is a good example (Chopra and Sodhi, 2004). From then on, researchers pay more attention on risk management and supply chain risks.

For the purpose of developing sustainable supply chains, constructing flexible supply chains is necessary. Flexible supply chains would respond immediately if catastrophic events happen and recover quickly after such events. Flexibility can be defined as the ability to change or react with little penalty in time, effort, cost or performance (Grigore, 2007). From existing literature the characteristics of flexible supply chains could be summarized as follows: the supply chain has the ability to keep its negative impacts as small as possible after a catastrophe, and the whole supply chain is able to recover as soon as possible after a catastrophe happens.

This paper focuses on constructing a flexible supply chain through facility location and transportation mode selection under the risk that catastrophes may occur. The locations of suppliers and final product customer zones are out of our consideration in this paper since those are usually fixed and hardly to be changed. Facility location is a well-established research area (Melo, Nickel and Saldanha-Da-Gama, 2009), but we merely focus on the location of an assembling center. The assembling center and the processing center of a supply chain are often centralized in low labor cost areas or in areas with major resource availability. Usually these locations were chosen in periods when the supply and demand were stable and smooth. The diversified choices of the market as well as the harmfulness of the supply chains in times of crises motivate for thinking about a repositioning of an assembling center close to the

customer zone. A delayed finalizing of a product in this assembling center is called "postponement" (Zinn and Bowersox, 1988), which was mainly considered as a strategy for dealing with demand uncertainty in previous research. The transportation modes (air, water, rail, and road) in each case can be assumed as either fast or slow. The existing literature about slow steaming primarily focuses on freight and environmental factors. None of the previous research regards postponement or slow transportation as a strategy for dealing with supply chain disruption risks. In this paper, we provide theoretical support to the implementation of postponement and slow steaming in reality by analyzing the impacts of postponement and slow transportation to the supply chain's flexibility in an environment where catastrophic events may occur. In addition, this paper sets the pace of using postponement strategies and slow transportation in order to form a flexible supply chain under supply chain disruption risks not only in scientific research, but also in practices.

The subsequent section consists of a brief literature review. A detailed problem description is provided in the third section in order to introduce the model's background. Assumptions, the objective function as well as the constraints, and an algorithm for solving the model are presented in Section 4. Computational experiments are given in Section 5 in order to demonstrate the effectiveness of our model. The paper finishes with the conclusion in the sixth section.

2. Literature review

Supply chain risks can be classified into various levels including: operational risks and disruption risks (Tang, 2006). Operational risks refer to inherent uncertainties such as uncertain customer demand, uncertain supply and uncertain costs; disruption risks refer to major disruptions caused by natural and man-made disasters. A typology of risk sources, consisting of environmental factors, industrial factors, organizational factors, problem-specific factors and decision-maker related factors is presented in (Rao and Goldsby, 2009). Relevant literature about supply chain risk management

(SCRM) is collected and classified, e.g., in (Tang, 2006), (Kouvelis, Chambers and Wang, 2006), and (Dadfar, Schwartz and Voß, 2012). Although many qualitative analyses and quantitative models of SCRM exist, most quantitative models for managing supply chain risks focus on operational risks. In contrast, disruption risks are usually disregarded (Tang, 2006). Many researches in the academic literature focus upon single agent problems even though the nature of supply chain management (SCM) almost always involves multiple parties (Kouvelis, Chambers and Wang, 2006). Six risk management strategies with respect to environmental conditions and three moderators are presented in (Manuj and Mentzer, 2008). SCRM, as a nascent research area, has three research “gaps” (Sodhi, Son and Tang, 2012): no uniform definition of SCRM, lack of corresponding research on response to supply chain risk incidents, and a shortage of empirical research in the area of SCRM. Although a huge amount of literature exists about risk management, a good portion of it only focuses on demand fluctuations. Rather few papers point out how to cope with catastrophic events. (Woodruff and Voß, 2006) present a first attempt to deploy a progressive hedging algorithm on the supply chain production planning problem with big bang scenarios. This problem is the focus of this paper.

Postponement was introduced in the marketing literature in the 1950s and can be traced back to the 1920s in practice. Five types of postponement strategies are defined and tested in (Zinn and Bowersox, 1988). Researchers on qualitative as well as quantitative analyses of postponement strategies followed this paper, such as (Van Hoek, Vos and Commandeur, 1999), (Pagh and Cooper, 1998), (Waller, Dabholkar and Gentry, 2000), and (Guericke, Koberstein, Schwartz and Voß, 2012). The relationship between postponement and product customization is analyzed thoroughly in (Waller, Dabholkar and Gentry, 2000), who also reveal that an accelerated production decreases total costs. More specifically regarding the focus of this paper, a two-stage stochastic mixed integer linear programming model is built to solve supply chain production and distribution network design problems (Guericke et al.,

2012). Advantages of postponement are shown by means of experimental results.

In order to take advantage of improved fuel economy and reduced operating costs, slow steaming was proposed (Perakis and Papadakis, 1987). It is the practice of operating a ship or a fleet of ships at a speed less than their original operating speed. Slow steaming is believed to be a low bunker consumption and environmental friendly way of shipping (Wang and Meng, 2012), whereas fast shipping is preferred by shipping companies and customers due to the extended traveling time and the increased tied-up capital of slow steaming (Meyer, Stahlbock and Voß, 2012), (Psaraftis and Kontovas, 2013).

Lean, agile and so-called leagile strategies are discussed in (Ben Naylor, Naim and Berry, 1999), (Christopher and Towill, 2000), (Mason-Jones, Naylor and Towill, 2000) and (Goldsby, Griffis and Roath, 2006). The two paradigms of lean and agile are complementary within a supply chain strategy. The decision whether to realize an agile capability or a lean manufacturing structure depends upon the location of the supply chain's members (Ben Naylor, Naim and Berry, 1999). The lean paradigm claims that "fat" has to be eliminated, while the agile paradigm must be "nimble" since lost sales are gone forever. Both agility and leanness require minimum total lead-times, and lean supply upstream and agile supply downstream are bringing both paradigms together in a beneficial way (Christopher and Towill, 2000).

It is a matter of common knowledge in the supply chain research that supply chains usually benefit from short lead times. Short cycle times and supply chain flexibility are believed to go hand in hand (Stewart, 1995). The total value to the customers ought to be an inverse proportion to the lead times in a supply chain (Johansson, Machugh, Pendlebury and Wheeler, 1993). Lead time is identified as one of the most important measures to quantify the value of a product from the customer's view (Gunasekaran, Patel and McGaughey, 2004). However, some researchers postulate that safety lead times are useful under supply uncertainties. Literature on safety lead times and safety stocks can be found in (Dolgui, Ammar, Hnaien and Louly, 2013). A framework for studying uncertainty

in MRP systems which incorporates a simulation approach is presented in (Whybark and Williams, 1976). The simulation study indicates that providing safety lead times is the preferred technique under timing uncertainty, and providing safety stocks is beneficial under quantity uncertainty. Numerical experiments in (Hegedus and Hopp, 2001) indicate that optimal safety lead times increase in both supplier variability and system utilization. A simulation study in (Van Kampen, Van Donk and van der Zee, 2010) demonstrates that providing lead times is more effective with supply variability, but providing safety stocks is more effective with uncertainties in demand. In case of uncertainties of both supply and demand, providing safety lead times is more effective than providing an equivalent level of safety stocks. Considering the complexity of the design process of global supply chain networks, algorithms are proposed especially for this problem class. One method combines an accelerated Benders decomposition algorithm with a sample average approximation (SAA) to quickly solve large-scale stochastic supply chain design problems (Santoso, Ahmed, Goetschalckx and Shapiro, 2005).

3. Problem description

Fast transportation and zero inventory policies are adopted by lots of companies to accelerate capital turnover speed and reduce holding costs. Because of the lower labor costs, developing countries like China and India are the center of the world's factory. However, global distributed supply chains become more complicated and rather fragile especially if catastrophic disasters happen. The traditional approach to keep a certain quantity of buffer inventories, which is an effective way to cope with normal fluctuations of customer demand, is not valid to cope with natural catastrophe risks of global supply chains. The reason for this is that most natural catastrophes are hard to forecast, and their fluctuations exceed the time and inventory redundancies that may be provided in order to effectively deal with these catastrophes.

3.1 Supply chain structure

Often there are markets close to the area of origin as well as foreign markets which are far from original suppliers. In this paper we focus on the latter case (see Figure 1).

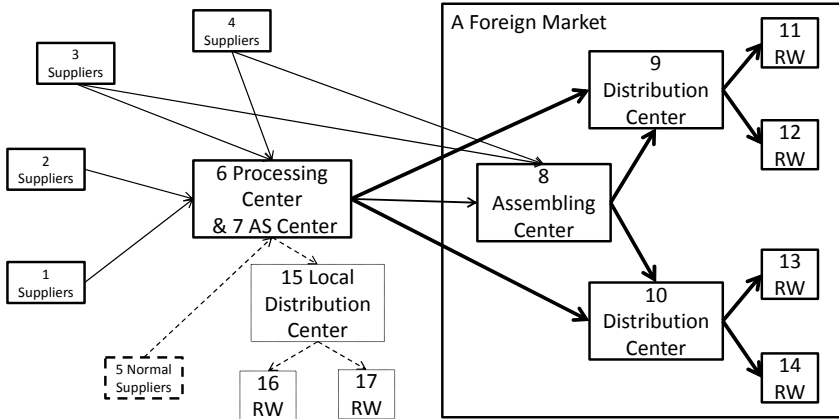


Fig. 1: Global supply chain with focus on one foreign market area

There are two ways of delivering products to foreign markets: delivering final products from the origin area, or delivering semi-finished products from the origin area and assembling them to final products in assembling centers which are close to the foreign markets. The first way results in lower labor costs and higher delivery costs; the second way, which represents a postponement strategy, results in higher labor costs and lower delivery costs. The delivery time could be short (by air transport) with a higher transportation fee and a shorter capital holding period, or long (by sea transport) with a lower transportation fee and a longer capital holding period. Our supply chain (SC) model takes into account stochastic catastrophic risks (on a node) and selects both the appropriate assembling center for a foreign market and the appropriate transportation mode for each transportation link.

3.2 Available time recovering from a catastrophe

In the following, the available time for recovering a SC from a catastrophe is determined. This time ought to be so long that the material flow does not become tardy at the subsequent node(s) of the disrupted node.

Suppose that the transportation time from node i to node j is $Trans_{i,j}$ and the booking period (order lead time) of node j from node i is $T_{i,j}$. If the order and transportation processes of an item are continuous, the available time before the tardiness of a subsequent node equals the transportation time from a destroyed node i to the next node $Trans_{i,j}$. Otherwise, if the order and transportation processes are discrete, the available time, if node i is destroyed and before tardiness occurs at node j , can be written according to:

$$\left\lfloor \frac{Trans_{i,j}}{T_{i,j}} \right\rfloor \times T_{i,j} \leq Available\ Time \leq \left\{ \left\lfloor \frac{Trans_{i,j}}{T_{i,j}} \right\rfloor + 1 \right\} \times T_{i,j} \quad (1)$$

$\lfloor x \rfloor$: maximum integer not bigger than x The larger $Trans_{i,j}$, the longer is the available time for recovering the SC. If the available time is sufficiently long and the emergency plan is sufficiently efficient, negative impacts are kept away from the final retailers, or even from the subsequent node of the disruption. Otherwise, it becomes more unlikely to avoid unmet demands if the available time is short. It can be deduced from (1) that a SC acts more flexibly by using slow transportation. On the contrary, slow transportation is harmful especially for perishable or stylish products which are subject to rapid obsolescence. According to this awareness, the transportation mode for these product types should be as fast as possible, or the distance between the suppliers and the customer zones should be as close as possible.

Many companies keep high levels of inventories and fast transport modes simultaneously in order to avoid unmet final demands if disruptions happen. This policy is costly and may be ineffective. Excess inventories may be useful in case of catastrophes only if they are always on a high level at each node of the SC. As a catastrophe is an unexpected event and time, location and extent of damage are not known in advance, keeping high levels of inventory all the

time and using fast transport modes increases inventory costs as well as transportation costs considerably.

4. Model description

A mathematical model is built in order to verify whether the whole SC becomes more flexible in case of a catastrophe by using slow transportation modes in the SC. Our model consists of a flexible SC structure. In a first step, the location of each crucial node of the SC is chosen. In a second step, transportation modes for each connection are determined by the model in order to obtain an optimal or near optimal solution. The impact on a SC after a catastrophe varies dependent on its structure and the current transportation mode. A flexible SC is able to mitigate the impact of a stochastic catastrophe, resulting in minimal SC losses. Optimal solutions can be obtained by using exact methods for small instances; approximate solutions are obtained by metaheuristics for larger instances. The solution process of the model should be designed in a fashion that a solution after a catastrophe can be quickly calculated.

4.1 Assumptions

According to Figure 1, we focus on the foreign market. Products can be finalized in a local combined processing and assembling center or in an assembling center in the area of the foreign market. Considered nodes in the model are crucial nodes incorporating the suppliers of crucial materials/components, operational nodes (processing, assembling and distribution centers), and retailers. Each crucial node has at least one partner, who has a similar or the same function and could act as a substitute if a catastrophe happens on the original node. All catastrophic scenarios refer to these crucial nodes.

The following additional assumptions are made within our model. External help is charged with extra costs. These come from overtime work at the external site and extra transportation costs due to the farther distances from the external site to the downstream nodes of the SC. Stock outs of final products result in

penalties. There is no backorder for unmet demands of the final products. Final demands are assumed to be constant. The whole SC follows the make-to-order principle. Stock-keeping does not take place in the nodes of the SC. Existing inventories are in transit inventories. Holding costs are related to the costs of the goods in transit. Slow transportation takes more time and is less costly than fast transportation on the same link. Assembling centers having shorter distances to a foreign market are assumed to have higher labor costs, and vice versa. If the assembling center in a foreign area is destroyed, the products can be finalized at the internal partner, the combined processing and assembling center, which means that assembling costs actually may decrease. Finally, within the considered time horizon no more than one catastrophic event occurs.

4.2 Model formulation

We consider a SC network $Net = (N, Conn)$ where N is the set of nodes and $Conn$ is the set of arcs between the nodes. Below a formulation of the developed model is given.

Sets:

- N : Set of nodes
- S : Set of suppliers, $S \subset N$
- RW : Set of retailers/wholesalers, $RW \subset N$
- AS : Set of assembling centers, $AS \subset N$
- PA : Set of processing & assembling centers, $PA \subset N$
- DC : Set of distribution centers, $DC \subset N$
- OP : $OP = AS \cup PA \cup DC$, $OP \subset N$
- P : Set of products
- P_i : Set of products $P_i \subset P$ at node $i \in N$
- $Conn$: Set of transportation links between the nodes in the SC
- Up_i : Set of nodes $g \in N$ which satisfies $(g, i) \in Conn$
- $Down_i$: Set of nodes $j \in N$ which satisfies $(i, j) \in Conn$
- $MChain_{p_i}$: Set of product p_i 's potential generation processes, $p_i \in P, i \in N$

Parameters:

T : Time horizon

$OC_{p,i}$: Operational cost coefficient at node $i \in N$ per unit $p_i \in P_i$

$PC_{p,i}$: Purchasing cost coefficient per unit of product $p \in P$ from the supplier
 $i \in S$

$Cf_{p,i,j}$: Fast transportation cost coefficient per unit of product $p \in P$ from node
 i to node j , $(i,j) \in Conn$

$Cs_{p,i,j}$: Slow transportation cost coefficient per unit of product $p \in P$ between
nodes i and j , $(i,j) \in Conn$

$C_{p,i,j}$: Transportation costs of product $p \in P$ between nodes i and j ,
 $(i,j) \in Conn$

$Tf_{p,i,j}$: Time for fast transportation of product $p_i \in P_i$ between nodes i and j ,
 $(i,j) \in Conn$

$Ts_{p,i,j}$: Time for slow transportation of product $p_i \in P_i$ between nodes i and j ,
 $(i,j) \in Conn$

$T_{p,i,j}$: Transportation time for product $p \in P$ between nodes i and j ,
 $(i,j) \in Conn$

$q_{i,j}(p_i, p_j)$: Number of products $p_i \in P_i$ needed to make one unit of product
 $p_j \in P_j$, $(i,j) \in Conn$

h : Per period cost coefficient of lock up capital

$V(p, i)$: Accumulated costs per unit of product $p \in P$ after being finished at
node $i \in OP \cup RW$, or per unit purchasing price for $i \in S$

$D(i, p)$: Demand per period of product $p \in P_i$ at node $i \in RW$

$A(p)$: Per unit penalty cost coefficient for unmet demand of the final product
 $p \in P$

$At(p, i)$: Time period of stockout of product $p \in P_i$ at node $i \in N$

RT : (SC) Reconstruction time after a catastrophic event occurs

k : Index of catastrophic scenarios, $k = 1, \dots, K$

- $T_{ex1}(i)$: Transportation time to an alternative node after a catastrophe happened at node $i \in N$
- $C_{ex1}(p)$: Transportation costs per unit of product $p \in P_i$ to an alternative node after a catastrophe happened at node $i \in N$
- $T_{ex2}(i)$: Transportation time from an alternative node after a catastrophe happened at node $i \in N$
- $C_{ex2}(p)$: Transportation costs per unit of product $p \in P_i$ from an alternative node after a catastrophe happened at node $i \in N$
- r : Probability that a catastrophe happens within the time horizon T
- α : Correction factor of OC_i in case of a catastrophe at node $i \in N$
- $CR(k)$: SC costs during the reconstruction time of the catastrophic scenario k
- ECR : Expected SC costs during the reconstruction phase of a catastrophe
- TCN : Annual SC costs without any catastrophe
- TCR : Expected annual SC costs if a catastrophe happens within the time horizon T
- ATC : Minimal annual expected SC costs

Decision variables:

- y_i : Node $i \in N$ is part of the SC, if $y_i = 1$, otherwise $y_i = 0$
- $yf_{p,i,j}$: Selection of a fast transportation mode for product $p \in P$ between node i and node j , if $yf_{p,i,j} = 1$, otherwise $yf_{p,i,j} = 0$, $(i, j) \in Conn$
- $ys_{p,i,j}$: Selection of a slow transportation mode for product $p \in P$ between node i and node j , if $ys_{p,i,j} = 1$, otherwise $ys_{p,i,j} = 0$, $(i, j) \in Conn$

Objective function:

$$ATC = \min\{(1 - r) * TCN + r * TCR\} \quad (2)$$

S.t.:

Annual SC costs without any catastrophe:

$$TCN = \sum_{\substack{i \in RW \\ p \in P_i}} V(p, i) * D(i, p) * T \quad (3)$$

Annual SC costs in case of a catastrophe:

$$TCR = \sum_{\substack{i \in RW \\ p \in P_i}} V(p, i) * D(i, p) * [T - RT] + ECR \quad (4)$$

Expected SC costs during the reconstruction time of a catastrophe:

$$ECR = \sum_{k=1}^K CR(k)/K \quad (5)$$

SC costs during RT of the catastrophic scenario k :

$$CR(k) = \sum_{\substack{i \in RW \\ p \in P_i}} \{ A(p) * D(i, p) * At(p, i) \\ + V(p, i) * D(i, p) * (RT - At(p, i)) \}, \forall k = 1 \dots K \quad (6)$$

Costs at supply nodes:

$$V(p, i) = PC_{p,i}, \forall i \in S, p \in P | y_i = 1 \quad (7)$$

Costs at all nodes except supply nodes:

$$V(p_j, j) = \\ \sum_{(i,j) \in Conn} \sum_{p_i \in P_i} \{ V(p_i, i) * q_{i,j}(p_i, p_j) + C_{p_i,i,j} * q_{i,j}(p_i, p_j) + h * V(p_i, i) * \\ q_{i,j}(p_i, p_j) * T_{p_i,i,j} \} + OC_{p_j,j}, \forall j \in OP \cup RW, p_j \in P_j | y_j = 1 \quad (8)$$

Transportation costs:

$$C_{p_i,i,j} = yf_{p_i,i,j} * Cf_{p_i,i,j} + ys_{p_i,i,j} * Cs_{p_i,i,j}, \forall p_i \in P_i, (i, j) \in Conn \quad (9)$$

Transportation time:

$$T_{p_i,i,j} = yf_{p_i,i,j} * Tf_{p_i,i,j} + ys_{p_i,i,j} * Ts_{p_i,i,j}, \forall p_i \in P_i, (i, j) \in Conn \quad (10)$$

Controlling the transportation modes:

$$yf_{p_i,i,j} + ys_{p_i,i,j} \leq y_i \leq 1, \quad yf_{p_i,i,j} + ys_{p_i,i,j} \leq y_j \leq 1, \\ \forall p_i \in P_i, (i, j) \in Conn \quad (11)$$

Variable definition and nonnegativity constraints:

$$y_i \in \{0, 1\} \forall i \in N, y_{p,i,j}^f, y_{p,i,j}^s \in \{0, 1\}, \forall p \in P, (i, j) \in Conn \quad (12)$$

The objective function (2) specifies the minimal annual expected costs of the considered SC. Annual SC costs in the standard case without a catastrophic event are obtained from (3). The annual SC costs in case of a catastrophe in (4) consists of two parts: the second part calculates the SC costs during the reconstruction period of the catastrophe, which is deduced from (5) and (6); the first part quantifies the SC costs during the rest of the period if no negative effects from any catastrophe exist. Note that $V(p, i)$ in (3) and (4) is calculated by (7) and (8) with the values of $C_{p,i,j}$ and $T_{p,i,j}$ determined in (9) and (10). Constraint (11) secures that transportation between two nodes only happens if both nodes are available. Furthermore, it is secured by (11) that a selected transportation mode can be either fast or slow. (12) constitutes appropriate variables to be binary.

SC costs during a period without catastrophes can be calculated according to (3) with known binary values of $y_{p,i,j}^f$ and $y_{p,i,j}^s$. A period with a catastrophic event can be regarded as a three-phase process, which includes a possible stock out phase, an acceleration phase, and a temporary stable phase. The SC may suffer a short time span with unmet final demands (first phase). In this case, a temporary production and transportation planning occurs in order to accelerate production and transportation processes and meet the final demands as much as possible. This approach represents the acceleration phase and can be operated with internal or external help. A temporary stable status can be achieved in the third phase by determining an appropriate transportation mode based on the new formed structure with internal or external help if the recovery time is sufficiently long. The potential difference between plans of the last two phases is that transportation modes may differ. But since the time span to recover from a catastrophe is usually difficult to forecast, the accelerating plan is typically used in the third phase of a catastrophe, too. For a

particular catastrophic scenario k ($k = 1 \dots K$), $CR(k)$ can be deduced in this way. Below this approach is explained in more detail.

First of all, costs and time consumptions will be changed in the SC after a catastrophe occurs at node $i \in S \cup AS \cup PA$. The tardiness time for product $p \in P_j$ at node j , $At(p, j)$, $\forall (i, j) \in Conn$, can be calculated. The operational cost coefficients $OC_{p,i}$ are changed for nodes $i \in OP \cup RW$, $p \in P_i$, or the purchasing cost coefficients $PC_{p,i}$ are changed for $i \in S$, $p \in P_i$. Transportation fees and transportation times are also changed due to the new route from/to the alternative node.

In case of $i \in PA$ for each $p \in P_i$ calculate:

$$OC_{p,i} \leftarrow OC_{p,i} * (1 + \alpha)$$

Other values will be changed as follows:

For all $(g, i) \in Conn$, $(i, j) \in Conn$ calculate:

$$At(p, j) = T_{ex1}(i) + T_{ex2}(i) - T_{p,i,j}$$

$$T_{p,g,i} \leftarrow T_{ex1}(i), \quad C_{p,g,i} \leftarrow C_{ex1}(p)$$

$$T_{p,i,j} \leftarrow T_{ex2}(i), \quad C_{p,i,j} \leftarrow C_{ex2}(p)$$

In case of $i \in S$ for each $p \in P_i$ calculate:

$$PC_{p,i} \leftarrow PC_{p,i} * (1 + \alpha)$$

Other values will be changed as follows:

For all $(i, j) \in Conn$ and $p \in P_i$ calculate:

$$At(p, j) = T_{ex2}(i) - T_{p,i,j}$$

$$T_{p,i,j} \leftarrow T_{ex2}(i), \quad C_{p,i,j} \leftarrow C_{ex2}(p)$$

In case of $i \in AS$ and an alternative node $i' \in PA$ for each $p \in P_i$ calculate:

$$OC_{p,i} \leftarrow OC_{p,i'} * (1 + \alpha)$$

Other values will be changed as follows:

For all $(g, i') \in Conn$, $(i', j) \in Conn$ calculate:

$$At(p, j) = \max \{0, T_{p,g,i'} + T_{p,i',j} - T_{p,i,j}\}$$

$$T_{p,g,i} \leftarrow T_{p,g,i'}, \quad C_{p,g,i} \leftarrow C_{p,g,i'}$$

$$T_{p,i,j} \leftarrow T_{p,i',j}, \quad C_{p,i,j} \leftarrow C_{p,i',j}$$

Secondly, accelerate the transportation on all transportation links $(g, m) \in Conn$ when $At(p_g, g) > 0$ and check the values at node $m \in N$ which are on the downstream side of the destroyed node.

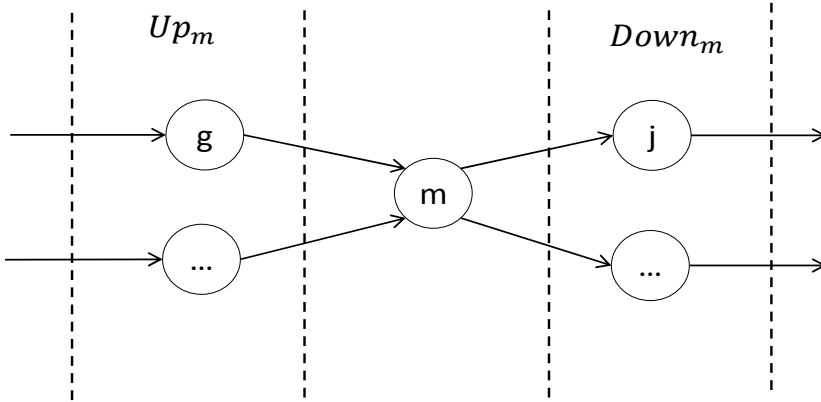


Fig. 2: Upstream and downstream node set

For each downstream node $m \in N, p_m \in P_m$ and $g \in Up_m, p_g \in P_g$ calculate:

If $At(p_g, g) > 0$

$$At(p_m, m) \leftarrow \max_{p_g \in MChain_{p_m}} \{0, At(p_g, g) - (T_{p_g, g, m} - Tf_{p_g, g, m})\}$$

$$T_{p_g, g, m} \leftarrow Tf_{p_g, g, m}, C_{p_g, g, m} \leftarrow Cf_{p_g, g, m}$$

$$yf_{p_g, g, m} \leftarrow 1, \quad ys_{p_g, g, m} \leftarrow 0$$

The tardiness time of each final product can be calculated for each retailer/wholesaler node. Obtain $V(p_m, m)$ through the iteration of (8) for all downstream nodes of the destroyed node m , and then deduce TCR through (4). Eventually, the objective function value will be calculated through (2).

4.3 Algorithm

An algorithm in order to calculate the objective function value consists of the following steps:

Step 1: Fix values of binary variables y_j and get the connection set $Conn$

Step 2: Fix values of binary variables $yf_{p,i,j}$ and $ys_{p,i,j}$ for each transportation link $(i,j) \in Conn$

Step 3: Assume the case that no catastrophe occurs. Calculate the annual total costs T_{CN} , which can be obtained through (3) and (8)

Step 4: Get T_{CR} in case of a catastrophe

Step 5: The objective function value based on the determined SC structure and transportation modes according to Steps 1 and 2 is acquired.

Small scale problems could be optimized by an exhaustive search. Meta-heuristics or PH (progressive hedging) could be used for large scale problems.

5. Computational Experiments

In this section the experimental design as well as computational results are presented. Suppliers include both crucial and normal suppliers. A final product could be finished in an assembling center, which is located close to the foreign market, or in the combined processing and assembling center, which is located close to the origin suppliers. All products should be processed in a processing center and an assembling center. Final products are sent to distribution centers/warehouse centers at first, and then they are distributed to local retailers. We do not consider the type of a catastrophe in our experiments; we only care about its location. A catastrophe could happen in an experiment at one of the crucial suppliers, at the processing center, or at the assembling center. If one of the crucial suppliers breaks down, an alternative partner of the destroyed supplier will provide the same components or similar components with higher purchasing costs and higher transportation fees.

If a processing center is damaged by a catastrophe, all products will be sent to an alternative processing center. The processing costs at this alternative processing center, the transportation time as well as the transportation fees are increased due to overtime working costs and longer distances from and to the alternative processing center. Final products can be assembled at a combined

processing and assembling center which represents a common policy for the majority of companies, or at an assembling center, which is established close to the foreign market. With respect to this assembling center we suppose that it operates with increased assembling costs. If the assembling center is destroyed, the final products can be assembled at the combined processing and assembling center with lower assembling costs. Note that a totally destroyed center for combined processing and assembling consequently leads to an interruption of both manufacturing and assembling activities at this site.

The SC in our experiments incorporates 14 nodes (see Figure 1). The assembling center could be located at nodes 7 or 8, which represents the first stage decision. Transportation links are fixed after the location of the assembling center is determined. The second stage variables determine the transportation mode for each link. The optimal annual SC costs are calculated after the first and second stage decisions are made. We use an exhaustive search to try all possibilities of all variable values in order to find the optimal solution. Motivated by the huge negative impacts from catastrophes that may happen at upstream nodes of the SC, six catastrophic scenarios with respect to six crucial nodes are considered in our experiments: four crucial suppliers, the combined processing and assembling center, and the foreign assembling center. Since catastrophes happen randomly, we assume that these six nodes have the same possibility to get destroyed. For the transportation links holds that the transit times in the slow mode are assumed to be nine times longer than in the fast mode, and similarly, that transportation fees in the fast mode are assumed to be nine times higher than in the slow mode.

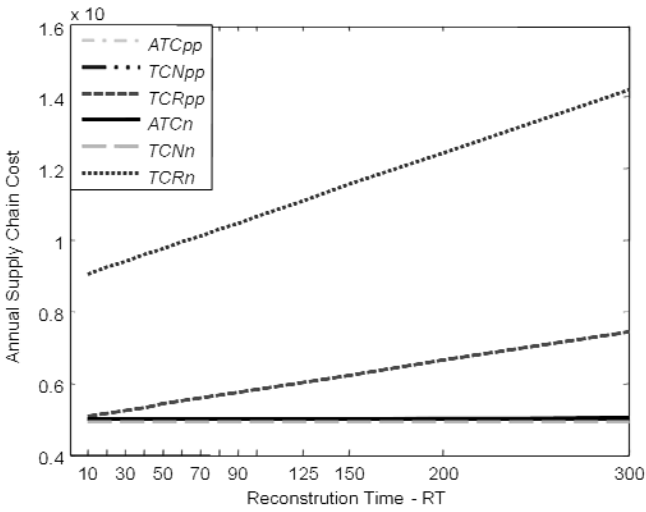
We performed three analyses for two problem instances P1 and P2 in each case: In the first analysis, we determined optimal annual SC costs depending on different reconstruction times RT , which may be within the parameters of 10 days and 300 days (see Figures 3 a and b). In the second analysis, we identified optimal annual SC costs depending on different holding costs (see Figures 4 a and b), and in a third analysis, the optimal annual SC costs were calculated depending on different tardiness cost coefficients (see Figures 5 a

and b). The problem instances P1 and P2 equal in each analysis regarding their SC structure, but differ significantly regarding several parameter values. For example, in the first analysis, in P2 the distances are longer than in P1, and in the second and the third analysis, in P2 diverse cost coefficients like purchasing or production cost coefficients are higher than in P1.

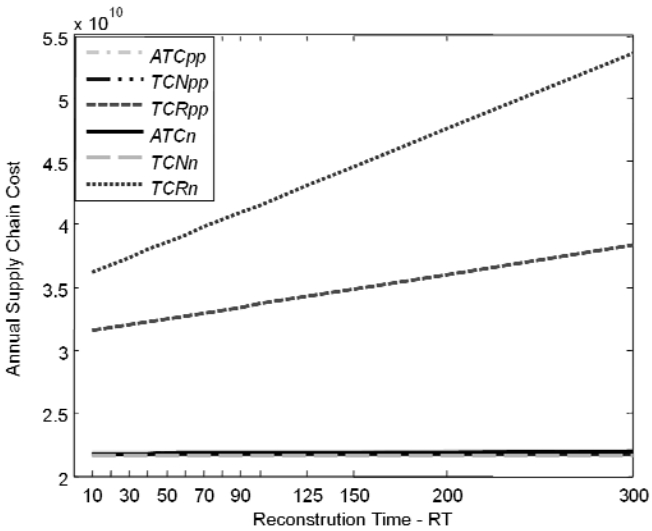
In Figures 3, 4 and 5, six different types of annual SC costs are illustrated: ATC_{pp} and ATC_n , which can be calculated from (2), are the expected annual SC costs in case of using or not using postponement, respectively. The probability r that a catastrophe occurs within the considered time horizon is assumed to be 1%. The holding cost coefficient h is assumed to be 0.01. TCN_{pp} and TCN_n , which can be obtained from (3), are the annual SC costs with and without applying postponement if no catastrophe occurs. TCR_{pp} and TCR_n , which can be received from (4), are the corresponding costs if a catastrophe occurs within the time horizon.

All solutions are generated by Matlab R2013a on a Windows PC (i5-3570 Core, 3.40 GHz, 8.00 GB RAM, Windows 7 Enterprise). The solution time for a group of six SC costs with each value of RT/holding cost coefficients/tardiness cost coefficients are between 69 s (seconds) and 79 s. The average time used for each group of SC costs of P1 and P2 in the first analysis are 71.27 s and 74.99 s, respectively; these times are 72.16 s and 74.86 s in the second analysis, and 71.59 s and 71.77 s, respectively, in the third analysis. The output times of P1 and P2 in the first analysis are below one second in all cases. The numerical results of the first analysis are presented in Figure 3.

Figure 3 reveals that if no catastrophe happens within the considered time horizon T , the annual SC costs do not vary a lot. However, if a catastrophe happens in the considered time horizon, the annual costs increase dramatically, particularly if the implementation of a postponement strategy is not taken into account. TCR_n in the figure of problem instance P2 (see Figure 3 b) increases faster than in problem instance P1 (see Figure 3 a).



(a) P1



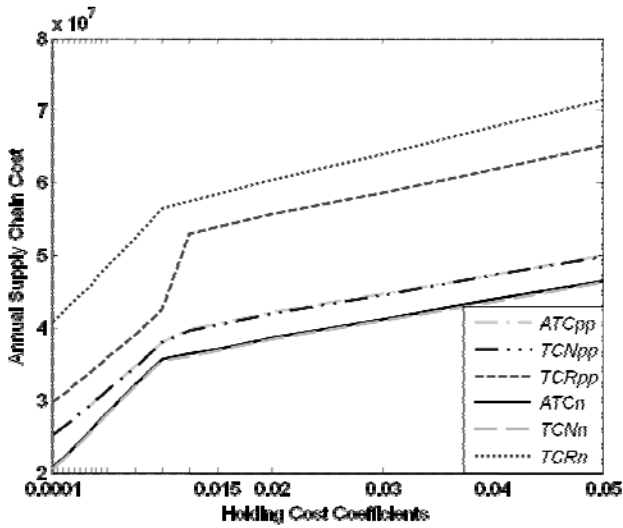
(b) P2

Fig. 3: Annual SC costs for P1 and P2 depending on the reconstruction time

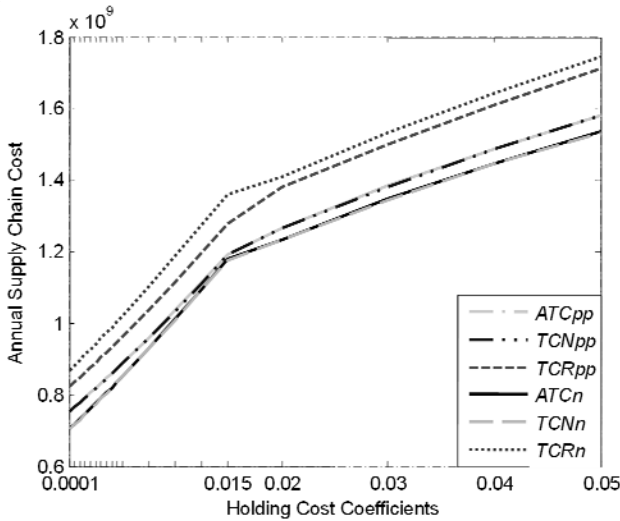
The optimal solution if postponement is taken into account predominantly uses slow transportation. Only one link from one of the distribution centers to one of the retailers uses fast transportation. The optimal solution if postponement strategies are not taken into account determines a slow transportation mode for the links from the suppliers to the combined processing and assembling center. For the remaining links a fast transportation mode is selected. The optimal solutions in our first analysis provide for both SC structures (with and without postponement), that slow transportation modes are selected for transportation links originating from suppliers, and fast transportation modes are selected for links outgoing from processing centers.

In Figure 4, the numerical results of the second analysis are displayed. The cause of the inflection points at the holding cost coefficients around 0.01 in Figure 4 a and 0.15 in Figure 4 b is that at these values a change of the transportation mode takes place. We can deduce that the decision of transportation modes rely on the holding cost coefficients. Optimal solutions of both structures (with and without postponement) use slow transportation if the holding cost coefficients are very low (below 0.0075). More and more links use a fast transportation mode if the holding cost coefficients increase and all links use a fast transportation mode if the holding cost coefficients are above 0.03.

As mentioned above, purchasing costs in P2 are decuple of P1. The structure with postponed assembling performs better for lower purchasing costs. This is constituted by the fact that the optimal transportation modes in SCs with implemented postponement strategies always choose slow transportation for some links. If the purchasing costs increase, the holding costs of cargo which traverses the SC on links with the slow transportation mode increase very fast. From this point of view, we can conclude that postponement and slow transportation are more beneficial if the purchasing costs of the required components are lower.

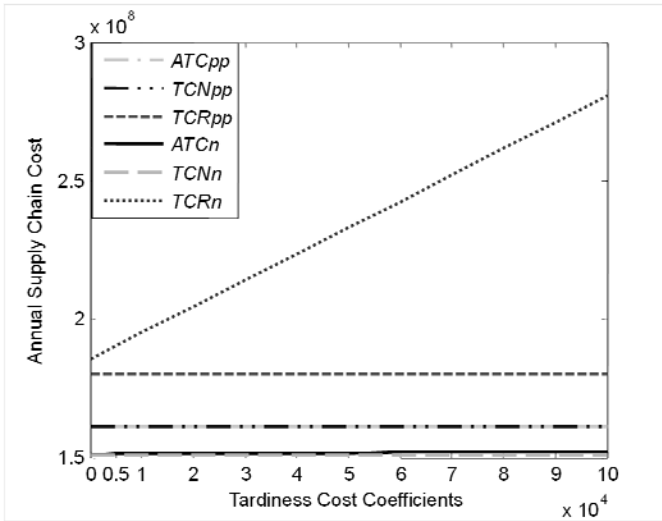


(a) P1

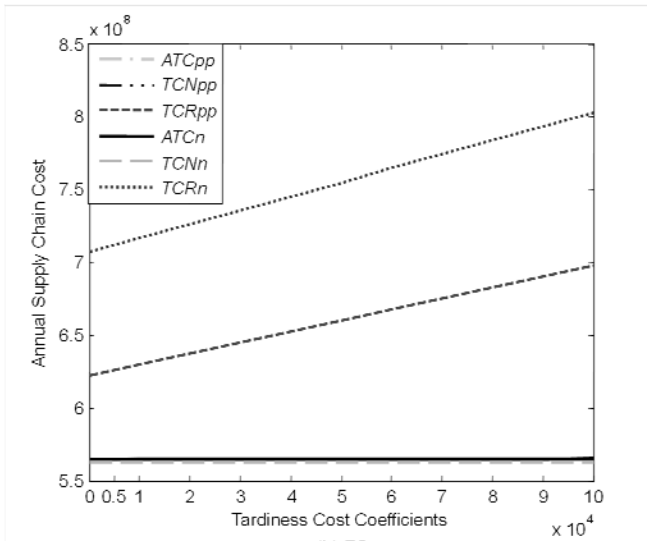


(b) P2

Fig. 4: Annual SC costs for P1 and P2 depending on holding cost coefficients



(a) P1



(b) P2

Fig. 5: Annual SC costs for P1 and P2 depending on tardiness costs

Figure 5 visualizes the numerical results of the third analysis. In the third analysis, the purchasing costs of instance P2 are also decouple of instance P1. It can be seen from Figure 5 that in case of lower purchasing costs (see instance P1), a variation of tardiness cost coefficients has no impact on TCR_{pp} , but a considerable impact on TCR_n . The reason is also that the transportation modes are different. Five links are slow transportation modes with the implementation of postponement strategies in P1, but only one slow transportation mode is adopted for the structure without using postponement strategies. The optimal solutions of both structures with and without the implementation of postponement in P2 consist of seven links using fast transportation and five links (from suppliers to the processing center or the assembling center) using slow transportation. When purchasing costs are higher, more links adopt fast transportation with the implementation of postponement. More fast transportation links reduce the flexibility of the SC, which is the reason why TCR_{pp} in P2 is not as stable as in P1.

6. Conclusion

This paper deals with the idea to incorporate postponement as a strategy to operate supply chains in case of disturbances. In case of catastrophic events our results allow for deducing some important insights. Postponement strategies are advantageous if the probability of a catastrophic incident in a SC is high. If postponement strategies are not considered, costs are higher if a catastrophe happens at a node of the SC, especially if the reconstruction time of the destroyed node is long. Slow transportation is preferred if capital holding costs are extremely low, and fast transportation modes are preferred if holding costs are higher. Increasing tardiness costs have no negative effects if no catastrophe occurs, but the annual SC costs increase extremely if a catastrophe happens. Annual SC costs increase a little faster with rising transportation link distances if postponement strategies are not taken into account than in the case that postponement strategies are considered.

If no catastrophe occurs, optimal solutions with or without an implementation of postponement strategies do not differ very much. But if a catastrophe happens at any SC node, the SC costs without the implementation of a postponement strategy increase dramatically. One important aspect is that postponement strategies come along with slow transportation. This does not mean that slow transportation should be used for all transportation links in a SC, but for a few of them – especially for the transportation links from the original suppliers. Slow transportation is not selected in this context due to the cheaper transportation fees, but due to the fact that transportation links with slow transportation modes consist of the capability to accelerate the product flows. Finally, this results in a more flexible supply chain. Moreover, this paper also provides the theoretical basis for companies to choose the transportation mode for each transportation link. It also gives the insight that slow steaming, as a typical slow transportation mode, not only benefits the natural environments, but also benefits the whole SC.

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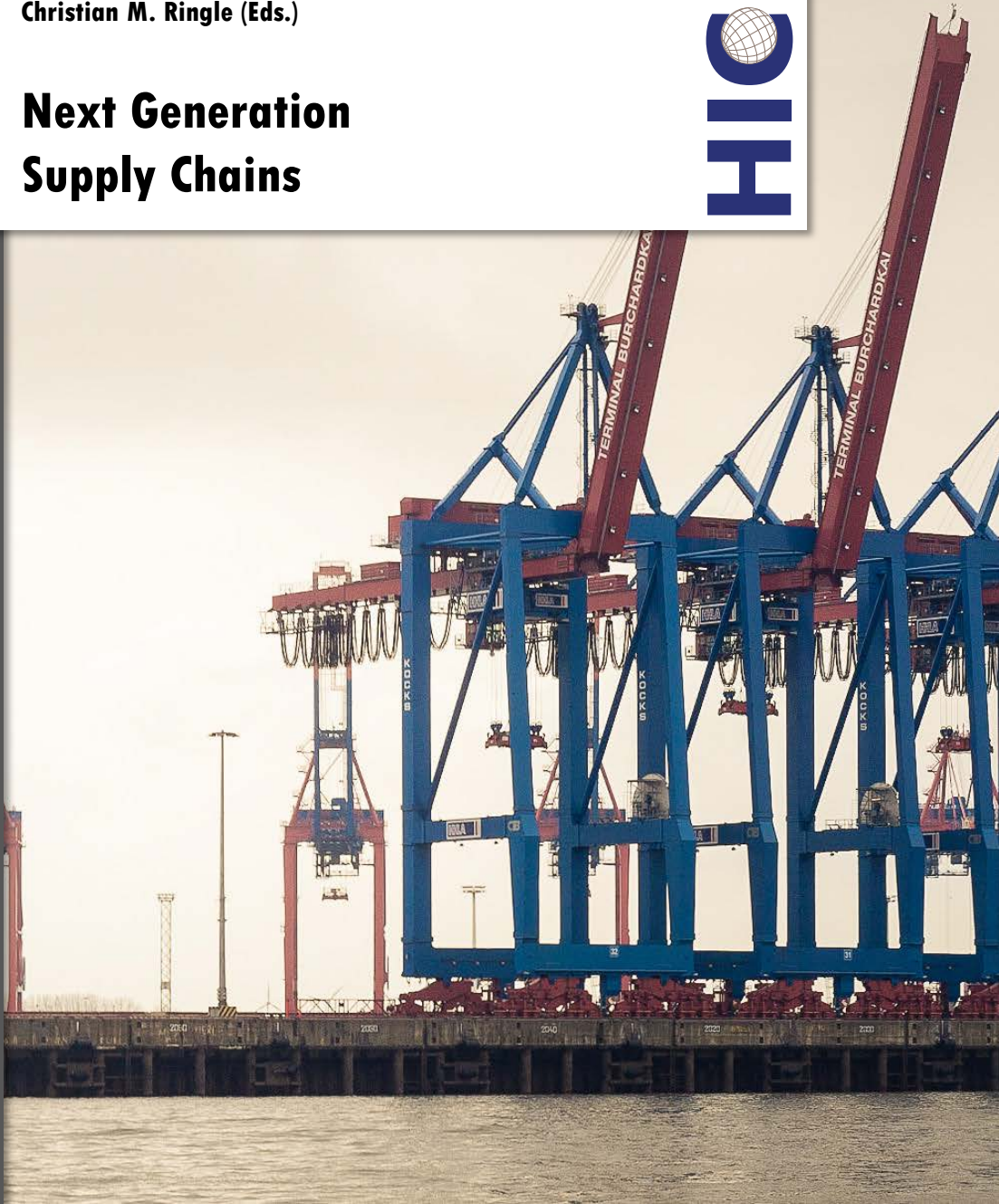
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**Wolfgang Kersten, Thorsten Blecker and
Christian M. Ringle (Eds.)**

Next Generation Supply Chains



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Prof. Dr. Thorsten Blecker
Prof. Dr. Christian M. Ringle
(Editors)

Next Generation Supply Chains

Trends and Opportunities

Edition 1st pdf edition, August 2014
Publisher epubli GmbH, Berlin, www.epubli.de
Editors Wolfgang Kersten, Thorsten Blecker and Christian M. Ringle

Coverdesign Frederik Duchâteau, Moritz Petersen
Coverphoto Viktor Rosenfeld / [flic.kr/p/e7ujk3](https://www.flickr.com/photos/7ujk3/) (CC BY-SA 2.0)

ISBN 978-3-7375-0339-6

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Preface

Today's business environment is undergoing significant changes. Demand patterns constantly claim for greener products from more sustainable supply chains. Handling these customer needs, embedded in a sophisticated and complex supply chain environment, are putting the players under a constant pressure: Ecological and social issues arise additionally to challenges like technology management and efficiency enhancement. Concurrently each of these holds incredible opportunities to separate from competitors, yet also increases chain complexity and risks.

This book addresses the hot spots of discussion for future supply chain solutions. It contains manuscripts by international authors providing comprehensive insights into topics like sustainability, supply chain risk management and provides future outlooks to the field of supply chain management. All manuscripts contribute to theory development and verification in their respective area of research.

We would like to thank the authors for their excellent contributions, which advance the logistics research progress. Without their support and hard work, the creation of this volume would not have been possible. We would also like to thank Sara Kheiravar, Tabea Tressin, Matthias Ehni and Niels Hackius for their efforts to prepare, structure and finalize this book.

Hamburg, August 2014

Prof. Dr. Dr. h. c. Wolfgang Kersten
Prof. Dr. Thorsten Blecker
Prof. Dr. Christian Ringle

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About HICL

Since 2006 the annual conference Hamburg International Conference of Logistics (HICL) at Hamburg University of Technology (TUHH) is dedicated to facilitate the exchange of ideas and contribute to the improved understanding and practice of Logistics and SCM. HICL creates a creative environment which attracts researchers, practitioners, and industry thinkers from all around the world.



Innovation is increasingly considered as an enabler of business competitive advantage. More and more organizations focus on satisfying their consumer's demand of innovative and qualitative products and services by applying both technology-supported and non technology-supported innovative methods in their supply chain practices. Due to its very characteristic i.e. novelty, innovation is double-edged sword; capturing value from innovative methods in supply chain practices has been one of the important topics among practitioners as well as researchers of the field.

This volume, edited by Thorsten Blecker, Wolfgang Kersten and Christian Ringle, provides valuable insights into:

- Innovative and technology-based solutions
- Supply chain security management
- Cooperation and performance practices in supply chain management

ISBN: 978-3-7375-0339-6