Optimal scope of supply chain network & operations design

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Optimal Scope of Supply Chain Network & Operations Design

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Ning Ma
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Abbreviations

3PL	**3**rd **P**arty **L**ogistics
ANC	**A**utomatic **N**ozzle **C**hanger
BRC	**B**ox **R**obust **C**ounterpart
CTSP	**C**hebyshev **T**raveling **S**alesman **P**roblem
GM	**G**eneral **M**otors
HC	**H**andling **C**lass
LMIP	**L**inearized **M**ixed **I**nteger **P**rogramming
LORA	**L**evel **O**f **R**epair **A**nalysis
MILP	**M**ixed **I**nteger **L**inear **P**rogramming
MILPds	**M**ixed **I**nteger **L**inear **P**rogramming with **d**emand **s**ubstitution
NLMIP	**N**onlinear **L**inear **M**ixed **I**nteger **P**rogramming
OEM	**O**riginal **E**quipment **M**anufacturer
PCB	**P**rinted **C**ircuit **B**oard
PFU	**P**roduction **F**acility **U**nit
RW	**R**egional **W**arehouse
SBR	**S**ubstitution **B**alance **R**atio
SCDP	**S**upply **C**hain **D**ownsizing **P**roblem
SMD	**S**urface **M**ounting **D**evice
SuM	**Su**bstitution **M**atrix
SuMs	**Su**bstitution **M**atrice**s**
TDNP	**T**otal **D**iscounted **N**et **P**rofit
TSP	**T**raveling **S**alesman **P**roblem
WDN	**W**arranty **D**istribution **N**etwork

Symbols

$\mathbb{N}_0$	set of non-negative integer
$\mathbb{R}_+$	set of non-negative real number
$\mathbb{R}_{++}$	set of positive real number
$\mathbb{R}^I_+$	an I-vector composed of non-negative real numbers
$\mathbb{R}^{I\times I}$	an $I \times I$-matrix composed of real numbers
$\mathcal{I}$	the identity matrix

Chapter 1

Introduction

1.1 Supply chain network and operations design

Supply chain networks have increasingly become complex operations, with many players of different size and power, global and dispersed. A variety of factors, ranging from outsourcing, short product-life cycles, rapid technology development, cost structures, tax laws, currency exchange rates, skills and material availability, new market entry and others have driven companies to redesign and reconfigure their supply chain networks and operations continually. The resulting (re-)configuring issues have increased in complexity when markets are volatile; channels of supply are uncertain, production facilities units getting obsolete, and so on.

During the past 20 years, cases of supply chain network and operations design optimization have proven to deliver significant reduction in supply chain costs and improvements in service levels by better aligning supply chain logistics flows with financial strategies. Network optimization incorporates end-to-end supply chain cost, including sourcing, production, warehousing, inventory and transportation. While this is considered a strategic supply chain optimization endeavor, organizations can gain competitive advantage by running supply chain network scenarios, evaluating and proactively implementing changes in response to dynamic business scenarios like new product introduction, changes in demand pattern, addition of new supply sources, changes in tax regimes or currency exchange rates, machine technology changes. Some of these changes are generated internally and others are external.

Traditionally internal changes were known in advance and external ones could be foreseen. However, in the dispersed and disintegrated supply chains of today, where there are many players in different counties, it is hard to make such predictions in time. The rapid changes in political and economic policy, calling into question the relevance/optimality of the current supply networks. In many cases, the impacts of these changes are large enough to drive structural changes. Preparing for such changes is important through use of optimization that incorporates future scenarios.

It is well reported that reaction to each individual change in supply chain environment introduces conflicting optimization objectives and such attention to one change at a time leads to sub-optimal of total supply chain performance. By considering all changes, complexity exceeds the capabilities and insight of even the most knowledgeable and experienced decision makers (see [Goetschalckx and Fleischmann, 2008, p. 120]). As a result, decision support systems are developed based on optimization techniques and have become gradually popular among managers, and motivated a growing number of researches exploring the power of mathematical modeling for assisting the integrated decision-making process in supply chains.

Many of the models developed consider usually a “green field” situation, where the supply chain network and operations is to be designed from scratch. However, considering the dynamic changes in business and mounting pressure due to economic downturns, supply chain managers require re-evaluating the network structure periodically. For successfully maintaining the existing supply chain performance, continuous re-optimization is a necessity, especially in the current financial situation. In the past 15 years economic upheavals have placed extreme pressure on and challenged all transnational supply chains beyond the management capacities in their attempts to deliver continued earnings growth. The slower economic growth of this century and tremendous market volatility is inhibiting revenue increase, whilst pressures from rising materials, manufacturing, and distribution costs exacerbate the inevitable deterioration in profit margins. The consequences are twofold. On the one hand, the continuous reconfiguration needs to include dynamic elements of network and operational decisions. On the other hand, the supply chain management requires a holistic view, i.e. the consideration of all players from the raw material suppliers, to the various production facility units, to transportation and distribution channels, to the final customers.

While the ultimate goal of much up-to-date research is still to maintain operation efficiency, a growing concern shifts to the “effective” configuration (re-design) of the supply chain network and the operations at the same time in order to arrive at a more “robust” solution, resilient to internal/external changes. Key questions that are often raised by managers include:

- Is the current network of operations most effective under the dynamics of the business environment?

- In the case that a more effective network of operations exists, is the reconfiguration of the current network necessary?
- In the case that a transformation of a certain network operation is required, how should the operation be transformed such that it will be robust to future uncertainties?

To answer these questions requires addressing supply chain decisions at three levels: strategic, tactical and operational. At the strategic level, decisions typically link to business and long-term financial strategies and involve investigation of all investments, high capacity change-over lead times, selection of partners, and usually longer horizons. At the tactical level companies focus on adopting measures that focus on competitive needs, such as reducing cost to arrive at a target cost structure for servicing certain markets or releasing capacity for new potential demand. At the operational level the major focus is operational efficiency. Decisions are typically made on a day-to-day basis under the framework defined at strategic and tactical levels.

In order to develop manageable models and realistic solutions, our research focuses on developing a three-stage optimization approach for solving four representative supply chain network design and operational problems, each of which addresses an angle (scope) of decision integration for pursuing effective transformation of supply chain networks and operations. The approach is zoom-in/zoom-out based and allows companies to zoom-out and work with a large number of products-, process- and facility units related investment/divestment options in order to achieve the planned financial obligations, and zoom-in and optimize a production facility unit performance. To be specific, the thesis provides support for the integrated decision making for solving issues from different decision levels (see Figure 1.1). The integration has two dimensions. The first one is horizontal integration, in which we aim at tackling various issues from the same decision level simultaneously. The second one is vertical integration, in which we relate key management issues from different decision levels together. We highlight the development and interrelationships of our research questions as follows:

<u>Horizontal integration of strategic level decisions</u>

Scope 1: Financially Robust and Effective Supply Network with Single Product

The first part of our research looks into a supply chain network downsizing problem of transnational manufacturing companies facing bankruptcy risks. The downsizing of the supply chain network in such cases requires an integrated decision for demand management, facility reallocation (including relocation and selling), and network reconfiguration. In addition, the downsizing process should consider the financial constraints

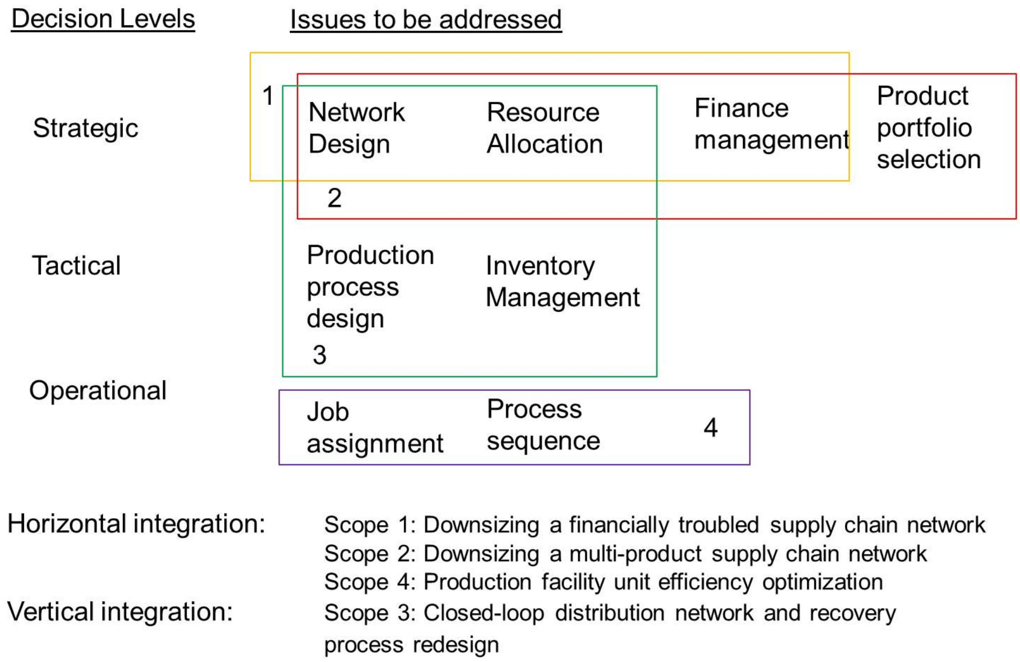


Figure 1.1: Scopes for modeling a supply chain network and operations design

imposed on the company and results in a solution that guarantees the future financial stability while respecting current financial obligations. Therefore, the strategic supply chain network downsizing decisions are integrated with the strategic financial management decisions in a robust optimization model.

Landeghem and Vanmaele [2002] summarized three different types of robust approaches. First, the approach finds the decision policy that yields the most stable outcome, i.e., with low variability of the key performance measures. Second, the approach finds a policy that reduces the number of changes to the plan, while keeping the key performance measures fixed at their target level. Third, the approach finds an aggregated solution which allows the generation of a detailed feasible solution to each possible realization of uncertain parameters. The financial robustness management addressed in the first part of our research demands a new approach to robustness, which is a combination of the first and second above mentioned approaches. The new approach finds a downsizing strategy that (a) yields the most stable future investment returns and (b) always satisfies debt payments even in the worst case scenario, preventing the future downsizing needs.

Scope 2: Financially Robust and Effective Supply Network with Multiple Products

Companies often produce and market more than one product. Although the intention is often to improve profit margin and market share by customer differentiation during the growing years, the extended product lines complicate manufacturing and distribution operations and generate unbearable financial burdens when demand declines. The second part of our research extends the downsizing problem of the first research question to a multi-product case, and also considers product line pruning decisions. While the research question preserves the same financial concerns, the emphasis shifts to study the impact of demand substitution on the optimal combination (portfolio) of product lines. Because of demand substitution, an unsatisfied demand of a product may shift to another product, which suggests a shifted demand after downsizing. When reducing the product lines of a company, the question is which product lines should be discontinued such that the company suffers the least revenue impact or even benefits from the downsizing operation. Therefore, the key for downsizing a multi-product supply chain network is to integrate strategic supply chain network downsizing decisions with strategic product portfolio selection.

Vertical integration of strategic and tactical level decisions

Scope 3: Warranty Distribution Network Re-configuration

Nowadays the repair and warranty services are not only the responsibility of manufacturers, but also became new sources of profit generation and important factors for differentiating their products from others. The desire for reducing operation costs associated with after-sale services and environmental regulations has become the driver for reconfiguring reverse distribution networks. These costs not only relates to the way in which existing network is utilized but also the size and location of inventories. In the third part of this thesis, we look into the reconfiguration of a closed-loop distribution network for warranty service. The closed-loop distribution network is responsible for supplying local service centers with well-functioning (new and refurbished) products, collecting returned products from customers, and performing recovery processes (including inspection, testing, and repair) to returned products if it is necessary. While the recovery of a returned product does not always benefit the company on cost saving, the question is whether the current distribution network and the allocation of recovery processes among distribution centers are optimal. Therefore, the third part of our research focuses on investigating the integration of strategic/tactical closed-loop distribution network reconfiguration with tactical recovery process design.

Horizontal integration of operational level decisions

Scope 4: Production Facility Unit Efficiency

A higher efficiency of day-to-day operations at operational level is achieved by better responsiveness and increased production facility unit throughput. While supply chain downsizing problems have been focusing on the relocation of facilities unit, the fourth part of our research looks into increasing production facility efficiencies. An example from electronic industry is chosen to address the efficiency improvement. The production facility unit is a multi-head surface mounting device (SMD), which is one of the most popular auto-assembly machines for mounting components on printed circuit board (PCB). The mounting process of a PCB often involves placements of a large number of components and frequent adjustments of equipments, which are time consuming. The throughput of a multi-head SMD requires identifying the optimal sequencing of placement operations, which consists of two operational decisions: component and nozzle assignments to placement heads and sequence of component placements. Therefore, as the last part of our research, we investigate the integration of operational component and nozzle assignments to placement heads and operational sequence of component placements.

Figure 1.2 demonstrates the hierarchical structure among research questions. The rest of this chapter is organized as follows. In Section 1.2 through 1.4, we explore the literature related to the research topics and identify the gaps filled by our research questions. Section 1.5 provides an overview of research papers included in this thesis. In the next section, we elaborate on the strategic downsizing of supply chain networks.

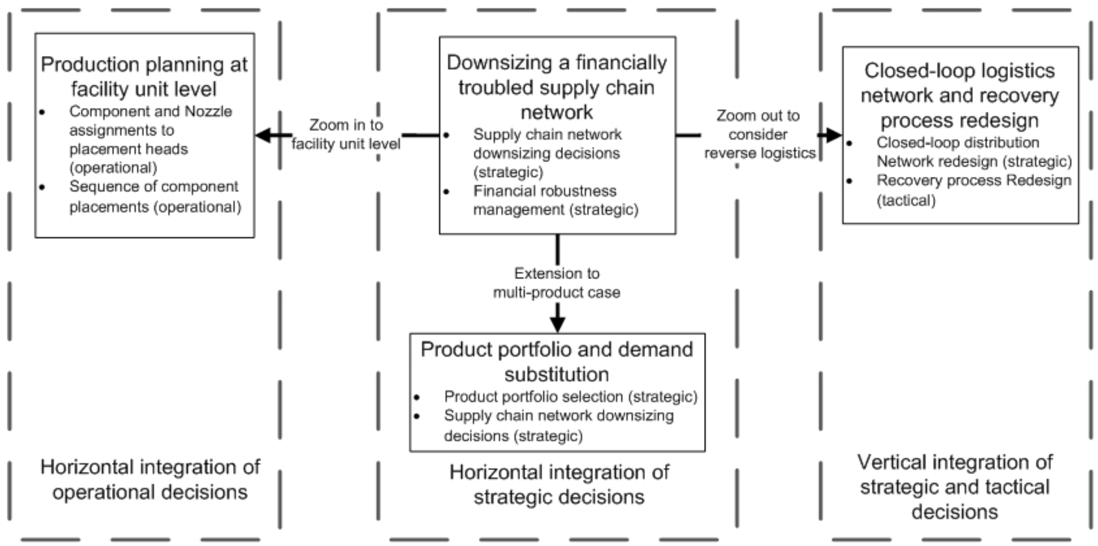


FIGURE 1.2: The hierarchical structure among research questions

1.2 Scope 1 & 2: Strategic downsizing of supply chain networks

Over the past 20 years, we have witnessed a growing trend of downsizing for shed excess capacities and for a more efficient use of resources available to a corporation. As an extreme example, following the recession start in 2008 and a continued market share decline, General Motors filed bankruptcy on July 10, 2009. As parts of the restructuring process, four of its product lines, Hummer, Saab, Pontiac and Saturn, were closed, and some joint ventures like Opel were suspended. Thousands of dealers were cut from the retail network. Plants were shut down or idled, and tens of thousands of people lost their jobs. According to McIntyre [2011,Dec,7], all of the 11 largest downsizing cases happened between 1993-2010.

The downsizing cases often occur in the following situations:

Demand decline due to economic downtrends or new competitors entrance:

- A sales decline caused by national or international economy slowing down unavoidably causes a built up of inventories and or idle production capacities, which results in low profitability.
- Market shares may shrink when new competitors enter into the same industry. This situation can almost never be foreseen. The demand decrease, which comes along with the market share shrinking, causes redundant production capacity and low profitability.

Irrational capacity expansions or take-overs: Many large international enterprises expand capacity by either investing in new manufacturing/distribution operations or by taking over other companies in order to (a) penetrate in certain markets and (b) reinforce their capacity dominance. However, increased sales after capacity expansion may not be realized. These expansions are usually due to over-optimistic sales forecast forcing companies often to take loans to build up capacity or take-over other operations. However, when they finally meet the unexpected sales decline, the newly built capacity brings a large amount of debt rather than profit.

Mergers / Alliances: When companies from the same industry merge or create an alliance, they may decide to share certain production capacities, while the rest of operations will stay intact. By sharing a part of the total capacity may become redundant.

Demand uptrend in part of product range: Companies producing more than one product may sometime experience a demand increase in one product while demand for another product decreases. While a special care is required for the allocation of production capacities of flexible machines among products in order to avoid capacity idleness or redundant productions, dedicated machines often become redundant.

Similar to supply chain design problems, downsizing a supply chain network also needs to address decisions regarding demand management, facility allocation, network design, and financing. As a result, the decision problem of downsizing a supply chain network has not been specially addressed in the literature but rather been considered simply as a result of the supply chain network design problem. In the following, we first review representative literature on the supply chain network (re-)design problems, and then address our concerns for downsizing a financially troubled supply chain network and a multi-product supply chain network. We summarize the details of modeling scopes that are considered in the reviewed literature in Table 1.1. To be specific, we are interested in finding out whether the literature considers the following issues: the time value of the investment, maximizing profits or minimizing costs, debt payments, extra investment possibilities, adding or reducing supply chain facilities, facility relocation, network changes, multi-period planning, satisfying all demands, market/demand selection, and uncertainty reduction with a stochastic or robust approach. We briefly describe the reviewed literature as follows:

TABLE 1.1: Summary of issues of supply chain design problems

		(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Financial considerations	Time value	✓			✓		✓			✓	✓
	Maximizing profits		✓		✓	✓	✓				✓
	Minimizing costs	✓		✓				✓	✓	✓	
	Debt payment		✓								
	Investment possibility		✓		✓		✓	✓		✓	✓
Resource management	Adding facilities				✓		✓			✓	✓
	Reducing facilities	✓									✓
	Relocating facilities										
	Network design	✓	✓	✓	✓	✓		✓	✓	✓	✓
	Multi-period planing	✓			✓		✓			✓	✓
Demand management	Satisfying all demands	✓		✓	✓			✓	✓	✓	
	Demand selection		✓			✓	✓				✓
Uncertainty reduction	Stochastic		✓					✓			
	Robust										

(1), Roodman and Schwarz [1975]; (2), Hodder and Dincer [1986]; (3), Camm et al. [1997]; (4), Canel and Khumawala [1997]; (5), Vidal and Goetschalckx [2001]; (6), Papageorgiou et al. [2001]; (7), Santoso et al. [2005]; (8), Laval et al. [2005]; (9), Fleischmann et al. [2006]; (10),Ulstein et al. [2006]

Roodman and Schwarz [1975] study a problem of withdrawing inventory and/or service facilities for a good, or service whose overall demand is declining over time. The authors assume that the product under consideration has a high technical or economic obsolescence rate and perhaps is at the decline phase of its life cycle. The paper considers the reallocation of demands among service facilities and the closure of redundant ones. While all demands need to be satisfied, withdrawing inventory and service facilities is for reducing the operation costs. Hodder and Dincer [1986] present a model for analyzing international plant location and financing decisions under uncertainty. The model considers possible openings of new plants financed by borrowing in several currencies. By maximizing a mean-variance objective function, the authors try to hedge the impacts of uncertain product price and exchange rate movements. Canel and Khumawala

[1997] survey the available literature and propose a mixed integer linear programming (MILP) model incorporating most of the relevant factors for determining the international facility locations. The model considers establishing a global supply chain network by opening up manufacturing facilities over a planning horizon of multiple periods for satisfying demands from international markets. Vidal and Goetschalckx [2001] present a global supply chain design model that maximizes the after tax profits of a multinational corporation. Their model emphasizes the significant impact of transfer prices determination and transportation costs allocation on the profit generation. Demands from a market can be ignored when they are not profitable with any choice of transfer prices.

Papageorgiou et al. [2001] propose a MILP model for both the product portfolio selection and the production capacity planning of pharmaceutical companies. The model determines which product should be developed, when the product should be introduced, where the product should be produced, whether new investments are required for increasing production capacities, and which production facility should be invested and installed. Ignoring a supply chain network structure and transportation effects, and assuming a fixed trading structure with fixed transfer prices, the model maximizes the net present value of a supply chain. Although the model does not consider uncertainties, it requires that the total supply of products is less than or equal to the expected demand such that the future lost opportunities are minimized.

Santoso et al. [2005] propose a stochastic programming model and solution algorithm for solving supply chain network design problems facing uncertain parameters. The stochastic programming model is a two-stage stochastic program. The first-stage determines the investment and network configuration decisions with an objective minimizing investment costs and the expected future operating costs, while the second-stage determines the minimal operating costs of a network configuration for each realized scenario of the uncertain parameters. A solution algorithm is developed by integrating a sampling strategy with an accelerated Benders decomposition scheme for obtaining a good approximate solution.

Laval et al. [2005] report a strategic planning approach that combines optimization with scenario analysis for redesigning the supply chain network of Hewlett-Packard. Based on the data determined with their supply chain expertise, a MILP model tailored to the business problem generates initial solutions. A scenario model is then used for validating the MILP model, challenging the obtained solutions with alternative scenarios, performing sensitivity analysis, and refining the cost analysis of solutions. The MILP model and scenario model are used iteratively for converging to the optimal solution. The proposed approach is efficient for generating a high-quality new design of the supply chain network, and easily convinces management of the reliability of the obtained solution. The authors refer to the approach as a green-field approach, where the supply chain redesign problem is simply treated as a supply chain design problem. The costs of moving, opening, closing, and changing facilities are not considered in the MILP model, and the objective is to find the optimal supply chain structure rather than the optimal transformation strategy of the supply chain network. Camm et al. [1997] report another example of the hybrid approach that links expert judgment and mathematical optimization for restructuring the supply chain of Procter and Gamble.

Fleischmann et al. [2006] present a MILP model for the BMW's product allocation to global production sites over a 12-year planning horizon. The model minimizes the net present value of costs and investment expenditures by optimizing supply chain network structure by planning capacity based on possible expansions at each production sites and meeting the demand. The model considers the product portfolio selection is given along with the sales plans, and assumes a fixed internal transfer price as fractions of external sales price. The authors also report that the strategic planning process of BMW consists of three steps. In the first two steps, the company determining (1) the set of future products and, for each existing or future product, the year or even the month of start-up and shutdown, and (2) estimated sales figures during its life cycle for different geographical markets. The presented MILP model is used in the third step for production capacity planning.

Because of the slowdown of the global economy and the decline of product prices caused by foreign competitions, Elkem, a global manufacturing corporation of silicon, ferrosilicon, aluminum, and carbon products, realized the necessity for improving supply chain network efficiency. Ulstein et al. [2006] report the use of a mathematical programming model as an unbiased decision support tool for the multi-period strategic capacity planning of the company. Based on the aggregated product and customer information, the model maximizes the discounted value of future sales and minimizes costs by optimizing the opening and closure of plants, investments on equipments, and the allocation of production orders. The model requires satisfactory of fixed orders while allowing unsatisfactory of spot orders. The implementation of the model experiences short solution times and is facilitated with easy access of input data. Therefore, it can be used during the strategic-management meetings for quick what-if analysis.

Since providing a complete and comprehensive literature review is beyond the scope of this thesis, interest readers might read Min and Zhou [2002], Meixell and Gargeya [2005], Melo et al. [2009], and Klibi et al. [2010] for overviews on supply chain (re-)design problems.

Unlike the problems considered by the here reviewed literature, the decision problem for downsizing a global supply chain network facing financial difficulties reflects the de-investment decisions with special concerns on global resource management, demand management, and financial robustness management. To be specific, it is important in this case to (1) consider all possible reuses of resources / production facility units (including selling and relocation) and (2) ensure successful debt payments over (3) a planning horizon of multiple periods for (4) satisfying only long-term profitable demands and (5) robustness of investment returns. The reasons for this are threefold and are explained below.

First of all, because of the financial difficulties, the top priority of any company is to guarantee sufficient cash flows for debt payments over the planning horizon regardless of any future uncertainties. For this reason, the sharp re-selection of the target markets and withdrawing the supply to (maybe temporarily) unprofitable markets can be also important for the survival of the company. Secondly, because of the financial difficulties, there are limited capital resources available to the company, which makes extra investment usually not an option. The only chance for the company improving the financial performance is to find a more efficient use of available resources. In this case, both selling and relocating production facility units can be good choices when unused capacity exists or when considerable uncertainties are expected for certain markets. Thirdly, an important job for the management team of a financially troubled company is to ensure investors a stable and good future investment return. Therefore, it is important to address the solution objective from the investors' perspective.

According to Table 1.1, there is no other supply chain (re-)design problem considering the same problem setting as ours, which makes the downsizing of a financially troubled global supply chain network a unique research question. In order to address its complicated decision-making process, we define a supply chain downsizing problem (SCDP) under bankruptcy in Chapter 2 with respect to a single-product supply chain network. A MILP model is developed for simultaneously determining the downsizing reconfiguration of the supply chain network, reallocating production facilities, guaranteeing successful debt payments, and maximizing investment returns. The MILP model is further developed based on robust optimization techniques for obtaining downsizing strategies that are robust to uncertainties of demands and exchange rates.

In Chapter 3, we extend the SCDP under bankruptcy to a multi-product case. While the demand management of a single-product supply chain network mainly focuses on identifying profitable customer regions, that of a multi-product supply chain further requires the identification of profitable product lines. The demand/product substitution effect that happens when demands of an unstocked product divert to another product suggests different demands of product lines after downsizing. In order to take demand substitution effects into decision-making process, a MILP model is developed incorporating a new general formulation of demand substitution, which allows arbitrary demand diversion and arbitrary replacement rates between products under investigation. The new general formulation of demand substitution enables considering uneven substitutions for downsizing multi-product supply chain networks.

1.3 Scope 3: Closed-loop warranty distribution network re-configuration

Because of the increasing concern on the environmental sustainability and economical incentives for obtaining the "green" image and reducing the operation costs of after-sale services, a continuously growing number of companies start to pay attention to the efficient operations for the reuse of returned products/materials from customers. This is evidenced by a vast and still-growing number of researches on the reverse logistics. The reverse logistics mainly concerns the product/material flows, opposite to the conventional supply chain flows and encompasses the logistics activities all the way from used products no longer required by the user to products again usable in a market (see Fleischmann et al. [1997]). The terms "forward" and "reverse" are frequently used in the literature in order to distinguish the directions of product/material flows, which can be either going from producers to users or from users back to producers.

Following the research on the reverse logistics network design, the synergy obtained by integrating the design of the forward and reverse logistics networks has been recognized (see Fleischmann et al. [2001]). The integral design problems are often referred as the closed-loop or forward-reverse logistics network design problems. While the "forward-reverse logistics" term is used in general without specifying whether the returned products are used by the original producer, the "closed-loop logistics" term is used as the contrast to the "open-loop logistics" where returned products are not sent back to the original producer but are used by another industry. Despite the differences among these terms, the "reverse logistics" has been used interchangeably with the "closed-loop logistics" and the "forward-reverse logistics" as the main distinction from the conventional supply chain. In the following, we first review representative literature concerning one or several of the following planning problems: the forward and reverse logistics network design, recovery process design, and inventory management for product recovery. We summarize the planning problems that are considered by each of the reviewed literature in Table 1.2.

The literature looks either at network decisions or inventory related decisions. As indicated earlier one of the decisions to look at is the size and location of inventories (good and recovered product). In this regard, Teunter [2004] studies the inventory systems of original equipment manufacturers that are involved in product recovery. Assuming that the demand rate and return fraction are deterministic and that recovered products can be used for satisfying demands as new items, the author derives the simple formulae that determines the optimal lot sizes for the production of new items and for the recovery of returned items, for two policy types. One policy alternate one production lot with a number of recovery lots in a cycle, while the other policies alternate production lots with one recovery lot in a cycle. Although the optimal policy might be different from under each policy, Teunter argued that there is always a near-optimal policy based on the result of Teunter [2001]. In the earlier paper he studies a more generalized policy that allows M manufacturing batches and R recovery batches succeeding each other.

As we are also interested in the distribution warranty network decisions, we also present few related papers in this regard. Listeş and Dekker [2005] present a MILP model for designing a recovery network for recycling sand from demolition waste in The Netherlands. The MILP model is a facility location model determining the location of storage and cleaning facilities. The model assumes that three categories of used sand (clean, half-clean, and polluted sand) can be identified. Both clean and half-clean sand can be stored for the direct usage of different purposes, while polluted sand has to be cleaned before it can be stored and used as clean sand again. A stochastic programming based approach is also proposed for extending the MILP model to account for the uncertainties of supply and demand.

Salema et al. [2007] propose a generalized model for the design of a closed-loop distribution network. It extends the generalized model proposed by Fleischmann et al. [1997] with considerations on production/storage capacity limits, multi-product production, and uncertainty in demand/return flows. By assuming a finite number of discrete scenarios with known associated probabilities, the scenario-based approach minimizes the expected cost.

Kusumastuti et al. [2008] present a case study at a company providing repair services on behalf of a computer manufacturer in the Asia-Pacific region. The study is about designing the closed-loop repair network, where faulty parts are collected, consolidated,

Table 1.2: Summary of planning problems concerned by the reviewed literature

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
Forward logistics network design				✓	✓					✓	✓
Reverse logistics network design			✓	✓	✓	✓	✓	✓	✓	✓	✓
Recovery process design						✓	✓		✓		
Inventory management	✓	✓									

(1), Teunter [2001]; (2), Teunter [2004]; (3), Listeş and Dekker [2005]; (4), Salema et al. [2007]; (5), Kusumastuti et al. [2008]; (6), Brick and Uchoa [2009]; (7), Mutha and Pokharel [2009]; (8), Ashayeri and Tuzkaya [2011]; (9), Basten et al. [2011]; (10),Das and Chowdhury [2012]; (11),Piplani and Saraswat [2012] and repaired, and both repaired and newly purchased parts are used for customer service. The proposed MILP model determines the optimal locations of transition and storage points (including local sub hubs and distribution centers) and the forward and reverse flows among facilities with an objective of minimizing the total operation costs.

Mutha and Pokharel [2009] propose a mathematical model for the design of a reverse logistics network. The model assumes that used products collected by retailers are consolidated at warehouses before they are sent to reprocessing centers for inspection and dismantling. In the case that the dismantled parts are not disposed or recycled, they can be either sold at the secondary market as spare parts or sent to the factory for remanufacturing.

Ashayeri and Tuzkaya [2011] present a fuzzy goal programming model for the design of a return supply chain network for the after-sale services of high-tech products. Assuming that new and repaired products are served to customers following the opposite flows of returned products, the model determines the location of collection and repair centers by optimizing only the reverse flows of returned products. The model is formulated with four objectives recognizing the needs for (1) cost minimization, (2) maximization of weighted assignments to repair centers, (3) minimization of tardiness in the customer service, and (4) maximization of average capacity utilization levels. Analytical hierarchy process is utilized for determining the weight of objective functions and repair centers for calculating the value of the second objective function. The fuzzy goal programming model is solved via the weighted max-min approach proposed by Lin [2004].

Das and Chowdhury [2012] propose a MIP model for the design of a closed-loop logistics network and the selection of modular product design. The model assumes that used products can be collected for obtaining recoverable modules, and a product of various designs may be constructed with different sets of modules. While both newly produced and recovered modules can be used for the manufacturing of products, depending on the usage of recovered modules, products can be of different qualities, have different market prices, and subject to different demand quantities.

Piplani and Saraswat [2012] propose a MILP model for the design of a closed-loop service network of a computer manufacturer. The service network provides repair and refurbishment services for its products. The MILP model determines the optimal location of service/recovery facilities and the associated flows among facilities. In order to mitigate the uncertainties regards the supply of faulty modules, the warranty fraction, and the fraction of out-of-warranty modules sent for repair, the authors adopt the min-max robust criteria with the scenario-based optimization approach for minimizing the maximal deviation of the robust solution from the optimal solution of each scenario, over all the scenarios.

Another relevant research topic regarding the design of efficient repair or maintenance network is the level of repair analysis (LORA). It is an analysis methodology used to determine: (1) the optimal location of facilities that compose a maintenance structure; (2) the quantity of required resources in each facility; and (3) the best repair policies. Since products are often composed of a large number of components that contain relations, the repair policies determines which components to repair upon failure, which to discard, and for each component that needs repair, where in the repair network to do this. Therefore, the LORA extends the reverse logistics network design problem with the recovery process design, emphasizing the complex product structure. Brick and Uchoa [2009] present a MILP model for the discrete facility location problems and show that LORA approach can be reduced to a general formulation. However, the authors only model one echelon of repair network. Basten et al. [2011] demonstrate how the LORA approach can be modeled as a minimum cost flow problem with side constraints. The authors indicate that the proposed model is flexible for practical extensions and can solve problem instances much faster than the formulation that they proposed in 2009 (see Basten et al. [2009]). The literature on LORA is limited. For more information about the reverse or closed-loop logistics, interested readers might read Guide and Van Wassenhove [2009] and Souza [2013].

The distribution network for delivering warranty service is a typical example of the closed-loop logistics network, which involves collecting the returned (often defected) products from customers, recovering the usability of returned products, and returning customers refurbished (repaired or no defect found) products or newly purchased replacements. We refer to such a network as a warranty distribution network. In Chapter 4, we focus on the reconfiguration of a transnational warranty distribution network of a semiconductor chip maker. The supply chain network consists of distribution centers that are hybrid warehouse-repair centers, which suggests that the recovery processes of returned products can be performed at any distribution centers wherever proper recovery facilities (tools) are available. The reconfiguration model of a warranty distribution network considered in this research extends the closed-loop network redesign to include the allocation of recovery facilities among distribution centers and the location and size of inventories for replenishments. This combined approach is a contribution to the literature. The unique features of the model are outlined below.

First feature is that different recovery processes and facilities may be involved for the recovery of returned products. Some returned products can be more expensive to recovery than the rest returned products, especially when recovery facilities are placed at geographically separated locations and considerable transportation costs are involved. Foregoing the expensive recovery of certain returned products by excluding the performance of certain recovery processes can be economically attractive. Therefore, the recovery process design is important for the efficient operations of the redesigned warranty distribution network, and the recovery process design needs to answer the following questions upon receiving a returned product:

- Which distribution center should the returned product be sent to?
- Which recovery processes are performed at the distribution center?
- In the case that the recovery of the returned product needs certain recovery facilities that is not available at the current distribution center, should the returned product be discarded or sent to another distribution center for further recovery processes? If it should be sent to another distribution center, then to which one?

Second feature is that the international transportation of products generates considerable custom fees and transportation costs to the warranty distribution network. The custom fees are charged every time the flow of products across the border, representing an ordering cost. While the value of a refurbished product is determined based on the involved transportation and recovery costs, the capital resources that are locked in the inventory of refurbished products cannot be used for alternative investments, suggesting an inventory holding cost. A proper control of inventory replenishments is important for reducing the operation costs of the redesigned warranty distribution network.

As a summary, the optimal reconfiguration of a warranty distribution network needs to answer the following questions:

- Which recovery facilities should be installed at a distribution center?
- How returned products should be transferred among distribution centers?
- Which distribution center can be closed?
- How often and how many returned products should be recovered?
- How often and how many new products should be purchased?

According to Table 1.2, the here described problem is unique for integrating the closed-loop network reconfiguration with recovery process design and inventory management. Furthermore, the closed-loop distribution warranty network reconfiguration model presented in Chapter 4 evidences a real-life industry case desiring a comprehensive solution approach to the here addressed problem. Our study fills the gap in the literature by considering various decisions simultaneously and modeling it as a nonlinear and nonconvex mixed integer programming. To approximately solve the nonlinear model, we piecewise linearize nonlinear objective and constraints.

1.4 Scope 4: Production facility unit efficiency optimization

A typical production facility unit that requires constant re-optimization for gaining larger efficiency is a surface mounting machine typically known as surface mounting device (SMD). The demand for variety, short-time delivery, and low cost has been constantly pushing the development of new technology and challenging the electronics industry to reconfigure SMD operational programs. This is due to the fact that the printed circuit boards (PCBs) as the main part of electronic devices are constantly changing due to short life-cycles. Therefore, substantial attention has been paid to the efficient operations of the assembly machine of PCB in order to realize a low-cost production of low volume and high variety orders.

Surface mounting technology has replaced the pin-through-hole technology and became the major component manufacturing technology which enables and facilitates the PCB automatic assembly. A variety of SMDs have been designed and manufactured. Based on the specification and operational methods, Ayob2008 classify SMDs into five categories:

1. Dual-delivery: two placement heads operate alternatively on opposite side of a PCB table; see Ahmadi et al. [1995], Safai [1996], and Tirpak [2000].
2. Multi-station: more than one placement stations work simultaneously and independent of each other; see Csaszar et al. [2000b] and Csaszar et al. [2000a].
3. Turret-type: a rotating turret equipped with multiple heads traveling between fixed pickup and placement points allows pick and placement to perform at the same time; see Ho and Ji [2003], Klomp et al. [2000], and Ho and Ji [2010].
4. Multi-head: a xy-robot equipped with multiple heads transports a group (dependent on the number of heads) of components from feeder bank to PCB and performs placements individually; see Grunow et al. [2004] and Quadir et al. [2002].
5. Sequential pick-and-place: similar to multi-head type machine except that the xy-robot only equipped with one placement head; see Leipälä and Nevalainen [1989].

The multi-head SMD production facility unit planning problem consists of three subproblems, feeder arrangement, component and nozzle assignment to each placement head, and sequence of component placements on PCB. The literature has been focusing on the application of heuristic methods, such as, traveling salesman problem (TSP) heuristic, local search, and genetic algorithms. Because of the diversity of machine types and the range of complexity problems involved, very few papers have the same problem setting as ours. We select related literature and discuss as follows:

Lee et al. [2000] proposed a hierarchical approach which decomposes the multi-head SMD production planning problem into three subproblems, namely, construction of feeder reel-groups, assignment of those feeder reel-groups, and sequencing of pick-and-place movements. Each of the subproblems is solved by a heuristic. The reel-groups is constructed in a way of balancing the workload among heads, the feeder assignment is solved by a heuristic based on dynamic programming, and the sequencing is determined using TSP heuristic.

Burke et al. [1999, 2000, 2001] present a generalized TSP model based on hypertours for the production planning of a multi-head SMD. The model recognizes three levels of subproblems, namely, component type assignment to feeder slots, tool assignment to placement locations, and component placement sequence. The authors further propose a constructive heuristic based on “nearest neighbor” for finding an initial solution and suggest a combined use with local search algorithms such as “k-opt”, “Variable Neighborhood”, and “multi-start” for further improvements of the initial solution.

Ayob and Kendall [2003] proposed a greedy heuristic for real-time scheduling to sequence the pickup and placement of component on multi headed placement machines. They formulate a mathematical model but due to long computational time, they abandon optimization and propose heuristics that allows generating a random placement sequence only with the available placement points on PCB and a local search applied afterwards in order to improve the initial solution using free CPU time of on-board computer of SMD, while the arm is busy with a placement.

Knuutila et al. [2007] present a greedy heuristic for the nozzle selection of a multi-head type SMD in the aim of minimizing the number of pickups when the sequence of component placements is given. Although it only solves a subproblem of the multi-head SMD production planning problem, the proposed method is proven producing the optimal solution.

While assuming that the planning solution to the feeder assignment is known, our research in Chapter 5 focuses on the second and third subproblem, namely, component and nozzle assignment to each placement head and sequence of component placements on PCB. In addition, we are also interested in improving the traveling speed of the robot arm, which is referred as the handling class (HC). This speed difference is due to the fact that some nozzles fit better for certain component types and allow higher traveling speed of the robot arm. The HC is implicitly determined as a result of component and nozzle assignment to the placement heads. Therefore, extra attention is required for component and nozzle assignment.

As an effort in pursuing high quality solution, we propose a two-stage optimization approach consisting of a MILP model and a sequencing heuristics. The MILP model is derived with the variables based on batches of components. This MILP model is tractable and effective in balancing workload among placement heads, minimizing the number of nozzle exchanges, and improving the HC. To the best of our knowledge, the traveling speed of the robot arm has been for the first time incorporated in an optimization model. While the MILP model produces an optimal planning for batches of components, the sequencing heuristics determines the final sequence of component placements based on the outputs of the MILP model. Our two-stage approach guarantees that a good feasible solution to the here addressed production planning problem is reached in a reasonable time frame. The obtained solution can be used in industry as a high quality solution of an off-line optimization, which can be further tested and improved by on-line optimization techniques.

1.5 Overview of included research papers

Chapter 2–5 are based on the following research papers:

Chapter 2: Ashayeri, J., Ma, N., & Sotirov, R., (2014). Supply chain downsizing under bankruptcy: A robust optimization approach, *International Journal of Production Economics* 154(2014), 1–15.

Chapter 3: Ashayeri, J., Ma, N., & Sotirov, R., (2012). Product line pruning and supply chain network downsizing, Manuscript submitted to *Journal of the Operational Research Society.*

Chapter 4: Ashayeri, J., Ma, N., & Sotirov, R., (2014). The optimal design of a warranty distribution network, Manuscript submitted to *Transportation Research Part E: Logistics and Transportation Review.*

Chapter 5: Ashayeri, J., Ma, N., & Sotirov, R., (2011). An aggregated optimization model for multi-head SMD placements, *Computers and Industrial Engineering* 60(1), 99–105.

Related conference papers are listed as follows:

Ashayeri, J., Ma, N., Sotirov, R., 2010. Creating sustainability through robust optimization of supply chain downsizing, in: *Proceedings of the International Conference on*

Value Chain Sustainability, Edited by Carlos Andrés Romano, 15-17 November, 2010, Universidad Politécnica de Valencia, Spain. pp. 159–165. ISBN:978-84-15080-01-5.

Ma, N., 2011. A robust approach to supply chain downsizing problem, in: *Proceedings of the International Conference on Value Chain Sustainability*, 14-16 November, 2011, Katholieke Universiteit Leuven, Center of Industrial Management, Belgium. pp. 208–214. ISBN:978-94-6018-478-9.

Ma, N., Ashayeri, J., Sotirov, R., 2013. Implications of product substitutability in supply chain network downsizing optimization, in: *Proceedings of the 5th International Conference on Value Chain Sustainability*, 13-15 December, 2012. Izmir University of Economics, Turkey. pp. 295–304. ISBN:978-975-8789-50-4.

Chapter 2

Supply Chain Downsizing Problem under Bankruptcy

2.1 Introduction

Financial meltdowns over the past decade together with business globalization of the 1990s have challenged all transnational supply chains in their attempts to deliver continued earnings growth. The slower economic growth of this century and tremendous market volatility is inhibiting revenue increase, whilst pressures from rising materials (supply), manufacturing, and distribution costs exacerbate the inevitable deterioration in profit margins (voluntary or involuntary), all bringing companies to the verge of bankruptcy. Companies under bankruptcy pressure very often resort to downsize in order to survive and resolve outstanding financial obligations. A recent example of this is the downsizing case of GM following Chrysler case which faced financial difficulties and, downsized its corporation in 2010, shed capacity to reduce cost and consolidated the manufacturing and supply base to maintain earning leverage to stay afloat. We are not aware whether these companies' decisions were based on any optimization model. However, we are convinced that mathematical modeling approach should be used in such situations to increase consistency, and help to recognize the trade-off of overall supply network and eliminate over-reacted decisions. Therefore, we derive here a mathematical model that addresses a case of downsizing a supply chain. In what follows, we first sketch out a very brief definition of downsizing and explore the literature to indicate the missing areas requiring major improvement to handle downsizing optimization.

In order to gain an understanding of the context of downsizing in supply chain, we first define the underlying concept of downsizing. Contemporary literature on downsizing provides numerous definitions. While Appelbaum et al. [1999] admit this and mention that each definition comes with its inadequacies, they consider the term as systematic reduction of workforce. The term is also interchangeably used in place of restructuring, rightsizing, unbundling, rebalancing etc. These are adding to the confusion. As a result, we offer the following definition. Downsizing, as a retrenchment strategy implemented by managers for reducing the size of an organization and its work process, is first characterized by Freeman and Cameron (1993) as an intentional endeavor for improving efficiency or effectiveness of an organization, which usually results in reductions in personnel and work processes redesign. The emphasis here is not only on the workforce but also on the processes, an operational view for a strategic decision.

Given the above definition, downsizing from industrial organization perspective and as a managerial economic decision has been explored extensively under entry/exit strategy and has been a topic of interest for many researchers in organizational economics. The streamlining of firms has been a perceived essential in gaining a competitive edge in the marketplace. The entry/exit strategy also appears in the literature as Restructuring or Unbundling (Divestment or Divestiture). While restructuring stands for making operations leaner and more efficient, the divestment refers to sale of parts of a company similar to the problem that we are considering, and divestiture signifies an alteration of the firm's productive portfolio, Moschieri and Mair [2005]. Examples of such type of downsizing are Siegfried and Evans [1994] who examine the empirical evidence about why firms enter into and exit from industries. Other examples include Hamilton and Chow [1993] who studied 208 divestments made by large New Zealand companies during 1985-1990, and report that the necessity of meeting corporate liquidity requirements was among the most important objectives motivating divestment. Their findings strongly support our research initiative in a sense that when cash is scarce, selling off units and rearrangement of part of business is a prerequisite to afloat the corporate and avoid bankruptcy. Among theoretical papers we can refer to some pioneers like Fluck and Lynch [1999], they develop a theory of mergers and divestitures. An empirical study by Capron et al. [2001] analyzing 253 cases of horizontal acquisitions examines the causes of asset divestiture. While many theoretical perspectives believe that asset divesture is evidence of acquisition failure, the authors argue that acquisitions provide means of reconfiguring the structure of resources within firms and that asset divestiture is a logical consequence of this reconfiguration process. The finding is yet another evidence of the need for downsizing applications.

In general, when in downsizing supply chain network strategic decisions from operational points of view are examined, the organization economic theory or the game theory approach like the one purposed by Renna and Argoneto [2011] are not effective tools. The literature suggests that Roodman and Schwarz [1975] were among the first authors who addressed a format of downsizing problem. They solve a problem of withdrawing inventory and/or service facilities for a good or service whose overall demand is declining over time due to economic obsolescence. The proposed approach considers closing some or all of these support facilities over time and reassign demand to remaining facilities such that all continuing demand is met with minimized total discounted costs. Eppen et al. [1989] point out the excess capacity problem of GM and suggest a closure of two to four plants based on a scenario approach designed especially for its capacity planning. The proposed approach charges penalty cost for unsatisfied demands. Melachrinoudis et al. [2005] consider the consolidation and phase-out of a part of existing warehouses of a distribution network that is under the consideration based on a multiple criteria model. Melo et al. [2005] present a mathematical model for a deterministic network design problem which relocates capacities within an existing network to satisfy all demand, while capacity reduction and facility closure is addressed as a possible extension. The vast part of literature reports mainly on supply chain network design, see Cohen and Lee [1989] and Hodder and Dincer [1986] as pioneer papers. For a detailed review, interested reader might read Goetschalckx et al. [2002], Mieghem [2003], Meixell and Gargeya [2005], and Kouvelis et al. [2006].

In general, up to date literature studies classical supply chain design and consolidation problems, which pursue the operation efficiency while operation content and target are predetermined. Research questions usually face specified demands to serve, and try to minimize the total operations cost for satisfying the specified demands, while the time value of investments and loan payment are not in the core of consideration. Furthermore, none evaluates the benefits of having a flexible and robust supply network that would disregards certain demands for being able to maintain cost-effective delivery of profitable customers in times of large and unscheduled demand fluctuations.

Continued drive for ever increasing supply chain network efficiency, combined with the current recession, represents danger for supply chains facing huge debt. The focus on only increasing efficiency based revenue of entities does not necessarily results in a superior supply chain network, a strategic redesign aggregating disinvestment perspectives is required. As such options that can be explored will include reducing the risk from future demand changes, demand substitutions, and price (exchange rate) fluctuations.

As the economy is not rebounding as anticipated, priority is shifted to survival. Therefore, reactionary approach to rightsizing the supply chain network structure will not hold up a prolonged economic downturn. Downsizing a company facing bankruptcy pressure draws special attentions to the demand selection and the cash reserve in the context of supply chain management. We see this downsizing problem as a special case of supply chain redesign and capacity reallocation problem. However, the redesign and reallocation process emphasize on shedding or relocating (consolidating) capacity to maintain future earnings by reusing the existing assets of a supply chain network while extra investment is nonexistent or very limited.

In this chapter, we refer to finding the best downsizing strategy of a supply chain network with respect to both fulfilling debt obligation and maximizing the utilization of the investment as a SCDP under bankruptcy. Compared with classical supply chain redesign problems, the SCDP under bankruptcy has the following unique features:

Network status: The SCDP optimizes the closure problem of existing production centers and cutting production capacities. This is opposite to the traditional facilities network design problem which optimizes to open new production centers and to add production capacities. For instance, Lin et al. [2009] present a study which simultaneously seeks an optimal capacity allocation plan and capacity expansion policy for a computer screen production network.

Demand satisfaction: As the objective is to maximize the possible return on investment, certain demands may not be profitable to satisfy and should be disregarded from demand portfolio. Based on our knowledge of existing literature of capacity allocation, it has been very common to constraint a larger capacity than the total demand. The SCDP under consideration only allocates sufficient production capacity to the profitable demands generating earnings even when it climbs down.

Multi-period planning: A multi-period transformation plan is preferred in order to capture the tradeoffs between the benefits and the extra costs from downsizing optimization operations. Note that moving production facilities and closing factories is not only costly but also time consuming. Therefore, associated delays in relocating production facilities can be considered and demand scenarios can be incorporated.

Financial status: The cash reserve of an organization is of crucial importance for fulfilling debt payments and keeping company afloat. The selected downsizing strategy should guarantee that there is enough cash in each period of the planning horizon of the downsizing optimization operation as well as in the follow-up periods. And in case there is unavoidably lack of cash in some period, there should be enough information on how much money is needed for the organization or each entity of the organization to remain on the safe side. Here, the debt payments are liabilities that are induced by past business activities, which may include interest payments of loans and other payables caused by R&D, commercial activities, and purchases of services and goods, etc. Assuming that the business activities are financed by taking loans, the here defined debt/loan payments are tax-deductible.

Robustness to uncertainty: Loan payments act as the threshold of company's cash reserve. Every cash flow shortage threatens the livelihood of company and represents a bankruptcy risk. The supply chain network resulted from a downsizing strategy selected under financial pressure prefers to be robust in terms of profitability even to worst case scenarios of uncertainties from operations, markets, and government policies. From the investors' point of view, a robust supply chain network needs to be both financially sustainable guaranteeing successful debt payments regardless market uncertainties and operationally reliable generating stable investment returns. On the GM's bankruptcy announcement, president Obama described the downsizing plan for transforming the GM to the new GM company as "a plan that positions GM to move toward profitability, even if it takes longer than expected for our economy to fully recover." In another words robustness is of major concern for long-term, not simple survival in short-term.

The rest of the chapter is organized as follows. In Section 2.2, we list assumptions of here presented SCDP under bankruptcy in the context of a manufacturing supply chain network. We derive a MILP model for the SCDP under bankruptcy in Section 2.3. As the downsizing plan prefers to be robust to worst case scenarios of uncertainties, robust optimization techniques (see Ben-Tal et al. [2009]) are applied for developing the robust counterpart in Section 2.4. For different approaches of robust optimization, interested reader might read Ben-Tal and Nemirovski [1998, 1999, 2000], Ghaoui and Lebret [1997], Ghaoui et al. [1998], and Bertsimas and Sim [2004]. Numerical results of the MILP model and its robust counterparts are discussed in Section 2.5. Here, we validate our model and its robust counterparts with systematically generated examples and observed downsizing effects on a supply chain performance of the here presented problem. Practical implementation issues are briefly discussed in Section 2.6. A summary of results is given in Section 2.7.

2.2 A simple SCDP under bankruptcy

A manufacturer may consist of two or more subsidiaries, have more than one brand and/or product, and serve an international market. Consequently, the supply chain network of such business is usually very complicated. The ownership and financing status of entities in such supply chain network, depending on the agreements between related parties and influenced by the local regulations, differ from case to case. These features complicate the problem formulation in general. In this section, we list assumptions of a SCDP under bankruptcy that we are going to consider.

We separate assumptions into two categories; one defines explicitly the supply chain boundaries and describes the scope and limits of our research, and the other specifies downsizing setting, i.e., options as well as downsizing related costs and financial requirements.

Assumption Category I: Supply chain system boundaries

A simple supply chain network with one commodity: We consider restructuring a supply chain network of an organization with single commodity over a fixed number of periods. This commodity is not in the end of its life cycle. Commodities in the end of life cycles are often downsized empirically without deliberate optimization analysis. The supply chain network under consideration consists of the following three levels of entities; material suppliers, production centers, and distribution centers.

Cost contribution of suppliers: We assume that materials are bought through outsourcing. Hence, suppliers of materials only contribute with material costs to the supply chain network. Material cost increases linearly along with the order quantity of materials.

Material supply limitation: The supply of materials from each supplier has an upper limit which represents the supply capacity of that supplier.

Material transportation cost: Materials can only be shipped from suppliers to production centers. The transportation costs of materials depend on the pair of supplier and production center. They are assumed to increase linearly along with the transportation quantities. The material transportation costs are paid by production centers.

Individual net profit generation of production centers: Production centers are privately owned subsidiaries with a certain amount of debts. Each production center generates its own profit by selling end product to distribution centers, and pays tax according to the tax rate at the country where the production center is located.

Cost at production center: The production cost consists of fixed production cost and variable production cost. The production cost of a production center increases linearly along with its production quantity. A fixed production cost is charged whenever a production center operates in a period.

Marked-up price of end product: Production centers sell end product to distribution centers with different marked-up prices depending on the local price of end product at a distribution center. The difference between the marked-up price and the production cost contributes to the profit at production centers.

End product transportation cost: End product is only transported between production and distribution centers. The transportation cost of end product depends on the pair of production and distribution center, and they are always allocated to distribution centers. The transportation cost of end product is also assumed to increase linearly along with the transportation quantities.

Individual net profit generation of distribution centers: Distribution centers are privately owned subsidiaries with no debt. Each distribution center generates its own profit by selling end product to its customers, and pays tax according to the tax rate at the country where the distribution center is located.

Cost at distribution center: An operating distribution center needs to pay a fixed cost. We consider that variable costs at distribution centers are negligible.

Demand: The demand distribution is assumed to be known with certainty for each of the distribution centers and for each of the planning period.

Market price of end product: Distribution centers sell end product to customers with local market prices.

Assumption Category II: Downsizing Setting

Debt payment of production center: The predetermined debt needs to be paid by production centers in each period. We assume that the predetermined debts span finite periods and the planning horizon of our analysis covers all debt periods. In case that a production center is shutting down in some period, the discounted sum of the rest debts owned by this production center has to be paid in the same period.

Production facility unit: The production capacity of a production center depends on the number of production facility units (PFU) operating. A PFU represents a well balanced production line (or cell) which is assumed to be identical among all production centers. Every PFU has the same maximum production capacity of end product. We consider PFU to be the minimum reallocation unit for restructuring the supply chain network. This reflects on reconfigurable manufacturing systems (RMS), a system designed at the outset for rapid changes in structure, see Koren et al. [1999].

Capacity adjustment options: PFUs from a production center are allowed to be sold or moved to another production center at the beginning of each period.

Dummy facility buyer center: If the optimization at any period cannot identify opportunity in keeping a PFU running, selling this PFU is considered and the PFU is transferred to the facility buyer center. For the simplicity of modeling, this facility buyer center is indexed as a dummy (hypothetical) production center which neither produces nor generates costs. All activities except the inflow of PFUs are forbidden for this dummy center. A production center generates an income every time it sends a PFU to the dummy center, and the income may change over time reflecting the depreciation of machine values.

Lead time and setup time of capacity adjustment: We assume that a time to transfer PFUs from one production center to another is negligible, while the setup of the transferred PFUs at another production center take a fixed portion of the time unit. In another words, the dismantled PFUs can be setup again within the next planning period at another production center, however, the transferred PFUs cannot be utilized for a portion of the next period. Considering the period as a year, this is a reasonable assumption.

Capacity transfer cost: A fixed fee is charged for every time there is a PFU added or dismantled in a production center, and the fixed fee differs among production centers. There are variable transfer costs for moving PFUs between production centers, which are charged based on the number of PFUs transported. The transfer costs of PFUs are always paid by the destination production centers.

Penalty cost for closing production and distribution centers: Penalty needs to be paid by the headquarter when production and/or distribution centers are shut down. Penalty costs may vary among production centers and among distribution centers. Production and distribution centers cannot be reopen once they are shut down.

The above assumption categories assist developing a transparent model and facilitate the numerical study in the following sections.

2.3 The downsizing MILP model

In this section, we introduce a MILP model for solving a SCDP under bankruptcy such that the return on investment is maximized. The proposed MILP model maximizes the total discounted net profit (TDNP) over planning horizon. This is the same as maximizing return on investment, since there is no extra investment in a downsizing process.

2.3.1 Notation and definition of decision variables

Index sets

$d \in \{1, \ldots, D\}$	the index of a distribution center
$j \in \{1, \ldots, J\}$	the index of a material type that is needed to produce one end product
$o \in \{1, \ldots, O\}$	the index of a supplier
$p \in \{1, \ldots, P\}$	the index of a production center (we use $P + 1$ as the index of the dummy facility buyer center)
$t \in \{1, \ldots, T\}$	the index of a period in the planning horizon (we set $t = 0$ to indicate an initial status)

Costs and prices

b_p	the variable production cost of production center p for producing one end product
F_p^1	the fixed operation cost of production center p
F_d^2	the fixed operation cost of distribution center d
$g_{p\bar{p}}$	the cost for delivering one PFU from production center p to production center $\bar{p}$
G_p	the fixed capacity adjustment cost of production center p
K_p^1	the penalty cost for closing down production center p
K_d^2	the penalty cost for closing down distribution center d
q_d^1	the marked-up price of one end product purchased by distribution center d
q_d^2	the revenue of selling one end product at distribution center d
R_{pt}	the sale price of one PFU at production center p in period t
s_{oj}	the purchasing price of one unit material j at supplier o
tr_{opj}^1	the transportation cost for delivering one unit material j from supplier o to production center p
tr_{pd}^2	the transportation cost for delivering one end product from production center p to distribution center d
σ	a fixed portion of PFU not available due to the setup time of transferred PFUs at a production center

Rates and taxes

E_p^1 the exchange rate of production center p's local currency to the numeraire country's currency

E_d^2 the exchange rate of distribution center d's local currency to the numeraire country's currency

E_{op}^3 the exchange rate of supplier o's local currency to production center p's local currency

E_{dp}^4 the exchange rate of distribution center d's local currency to production center p's local currency

r the discount rate

tax_p^1 the tax rate at production center p

tax_d^2 the tax rate at distribution center d

Other parameters

C_{p0} the production capacity at the beginning of planning horizon in the number of PFUs at production center p

L_{pt} the predetermined debt payment of production center p in period t

m_j the number of units of material j that are needed to produce one end product

M a very large number ($> \max\limits_{d,t}\{Q_{dt}\}$)

Q_{dt} the forecasted demand at distribution center d in period t

S_{oj} the maximum supply quantity of material j at supplier o

u the maximum number of end products that can be produced by one PFU in a single period

Decision variables

$$Z_{pt} = \begin{cases} 1, & \text{if the production capacity is changed for production center } p \text{ in period } t \\ 0, & \text{otherwise} \end{cases}$$

$$B_{pt} = \begin{cases} 1, & \text{if the production center } p \text{ has positive production capacity in period } t \\ 0, & \text{otherwise} \end{cases}$$

$$A_{dt} = \begin{cases} 1, & \text{if the distribution center } d \text{ operates in period } t \\ 0, & \text{otherwise} \end{cases}$$

$X_{p\bar{p}t} \in \mathbb{N}_0$	the number of PFUs transferred from production center p to production center $\bar{p}$ in period t
$V_{pdt} \in \mathbb{N}_0$	the amount of end product delivered from production center p to distribution center d in period t
$W_{opjt} \in \mathbb{N}_0$	the amount of material j delivered from supplier o to production center p in period t
$C_{pt} \in \mathbb{N}_0$	the production capacity in the number of PFUs at production center p in period t
$\mathrm{RevP}^+_{pt} \in \mathbb{R}_+$	the positive revenue of production center p in period t
$\mathrm{RevP}^-_{pt} \in \mathbb{R}_+$	the negative revenue of production center p in period t
$\mathrm{RevD}^+_{dt} \in \mathbb{R}_+$	the positive revenue of distribution center d in period t
$\mathrm{RevD}^-_{dt} \in \mathbb{R}_+$	the negative revenue of distribution center d in period t,

where $\mathbb{N}_0 = \mathbb{N} \cup \{0\}$ and $\mathbb{R}_+ = \{x \in \mathbb{R} : x \geq 0\}$.

Note that V_{pdt} and W_{opjt} may be relaxed from integers to real numbers in order to reduce computational time for large scale problems.

2.3.2 Formulation

The downsizing MILP model is formulated as follows:

$$\text{Maximize} \sum_{t=1}^{T} r^{t-1} \{ \sum_{p=1}^{P} E^1_p [(1 - \mathrm{tax}^1_p)\mathrm{RevP}^+_{pt} - \mathrm{RevP}^-_{pt}] + \sum_{d=1}^{D} E^2_d [(1 - \mathrm{tax}^2_d)\mathrm{RevD}^+_{dt} - \mathrm{RevD}^-_{dt}] \} \tag{2.1}$$

Subject to:

$$\sum_{p=1}^{P} V_{pdt} \leq Q_{dt} \qquad \forall d, t \tag{2.2}$$

$$\sum_{o=1}^{O} W_{opjt} \geq m_j \sum_{d=1}^{D} V_{pdt} \qquad \forall p, j, t \tag{2.3}$$

$$\sum_{p=1}^{P} W_{opjt} \leq S_{oj} \qquad \forall o, j, t \tag{2.4}$$

$$\sum_{d=1}^{D} V_{pdt} \leq u \cdot (C_{pt} - \sigma \sum_{\bar{p}=1}^{P} X_{\bar{p}pt}) \qquad \forall p, t \tag{2.5}$$

$$C_{pt} = C_{p(t-1)} + \sum_{\bar{p}=1}^{P} X_{\bar{p}pt} - \sum_{\bar{p}=1}^{P+1} X_{p\bar{p}t} \qquad \forall p, t \tag{2.6}$$

$$\mathrm{M} \cdot Z_{pt} \geq \sum_{\bar{p}=1}^{P} X_{\bar{p}pt} + \sum_{\bar{p}=1}^{P+1} X_{p\bar{p}t} \qquad \forall p, t \qquad (2.7)$$

$$\mathrm{M} \cdot B_{pt} \geq C_{pt} \qquad \forall p, t \qquad (2.8)$$

$$\mathrm{M} \cdot A_{dt} \geq \sum_{p=1}^{P} V_{pdt} \qquad \forall d, t \qquad (2.9)$$

$$\begin{aligned}
&R_{pt} X_{p(P+1)t} - \sum_{\bar{p}=1}^{P} X_{\bar{p}pt} g_{\bar{p}p} + \sum_{d=1}^{D} V_{pdt}(E^4_{dp} q^1_d - b_p) \\
&- \sum_{o=1}^{O} \sum_{j=1}^{J} W_{opjt}(E^3_{op} s_{oj} + tr^1_{opj}) - B_{pt}(F^1_p + \mathrm{L}_{pt}) - Z_{pt} G_p \\
&-(B_{p(t-1)} - B_{pt})(K^1_p + \sum_{\bar{t}=t}^{T} r^{\bar{t}-t} \mathrm{L}_{p\bar{t}}) \geq \mathrm{RevP}^+_{pt} - \mathrm{RevP}^-_{pt} \qquad \forall p, t \qquad (2.10)
\end{aligned}$$

$$\begin{aligned}
&\sum_{p=1}^{P} V_{pdt}(q^2_d - q^1_d - tr^2_{pd}) - A_{dt} F^2_d - (A_{d(t-1)} - A_{dt}) K^2_d \\
&\geq \mathrm{RevD}^+_{dt} - \mathrm{RevD}^-_{dt} \qquad \forall d, t \qquad (2.11)
\end{aligned}$$

$$A_{dt} \geq A_{d(t+1)} \qquad \forall d, t = \{1, \ldots, T-1\} \qquad (2.12)$$

$$B_{pt} \geq B_{p(t+1)} \qquad \forall p, t = \{1, \ldots, T-1\} \qquad (2.13)$$

$$B_{p0} = A_{d0} = 1, \qquad \forall p, d \qquad (2.14)$$

$$\begin{aligned}
&X_{p\bar{p}t}, V_{pdt}, W_{opjt}, C_{pt} \in \mathbb{N}_0, \\
&\mathrm{RevP}^+_{pt}, \mathrm{RevP}^-_{pt}, \mathrm{RevD}^+_{dt}, \mathrm{RevD}^-_{dt} \in \mathbb{R}_+, \\
&Z_{pt}, B_{pt}, A_{dt} \in \{0, 1\}. \qquad (2.15)
\end{aligned}$$

The objective (2.1) maximizes the TDNP over the planning horizon. Note that taxes are paid only when revenue is positive. Constraint (2.2) requires that the total supply from production centers in period t to distribution center d is no more than the demand of distribution center d in period t, while (2.3) requires that the total supply of raw material j in period t to production center p is no less than the demand of material j at production center p in period t. Constraint (2.4) requires that the total demand of raw material j in period t at supplier o cannot be more than the capacity of supplier o. Constraint (2.5) requires that the production volume of end product at production center p does not exceed the production capacity of production center p in period t. Note that in case there is a production facility set up in a period, σ portion of its production capacity is lost. Constraints (2.6) balances production capacity between periods while (2.7) forces Z_{pt} to be equal to one when the production capacity at production center p is changed in period t. Constraint (2.8) forces B_{pt} to be equal to one when production center p has positive production capacity. Constraint (2.9) forces A_{dt} to be equal to one as long as distribution center d is supplied in period t. In order to avoid the unstable performance of Big M formulations, constraints (2.7), (2.8), and (2.9) are implemented as indicator constraints in AIMMS. Constraint (2.10) is the revenue of production center p in period t. Constraint (2.11) is the revenue of distribution center d in period t. Note that we allow revenues of production and distribution centers to be either positive or negative in correspondence with tax charges of positive revenues in objective (2.1). Constraint (2.12) (resp. (2.13)) guarantees that distribution (resp. production) centers cannot be reopened after closing. Constraint (2.14) ensures that all production and distribution centers are operating at the beginning of the production process.

In the sequel, we list several remarks on the MILP model (2.1)–(2.15):

Demand selection: With a combination of constraints (2.2) and (2.5), we require the production capacity to be sufficient for the planned production rather than for the total demand. The combination permits a selection of demands for fulfillment and an exclusion of unprofitable demands for production planning.

Four states of production center: A production center can only be closed when all production facilities are sold or moved to other production centers (see constraint (2.8)). This closing criteria offers an opportunity to identify four different states of a production center:

- operating (when $B_{pt} = 1$, $C_{pt} > 0$, $\sum_{d=1}^{D} V_{pdt} > 0$)
- facility idling with no production (when $B_{pt} = 1$, $C_{pt} > 0$, $\sum_{d=1}^{D} V_{pdt} = 0$)
- production center idling with no production facility (when $B_{pt} = 1$, $C_{pt} = 0$, $\sum_{d=1}^{D} V_{pdt} = 0$)
- closed (when $B_{pt} = 0$, $C_{pt} = 0$, $\sum_{d=1}^{D} V_{pdt} = 0$)

Three states of distribution center: A distribution center can only be closed when the service to its corresponding demand region is withdrawn (see constraint (2.9)). This closing criteria offers an opportunity to identify three different states of a distribution center:

- operating (when $A_{dt} = 1$, $\sum_{p=1}^{P} V_{pdt} > 0$)
- idling (when $A_{dt} = 1$, $\sum_{p=1}^{P} V_{pdt} = 0$)
- closed (when $A_{dt} = 0$, $\sum_{p=1}^{P} V_{pdt} = 0$)

Loan payment flexibility: Although we take predetermined loan payment for the model development, different payment policies can be examined based on a scenario approach. This can be valuable for finding alternative payment solutions which are of better interest for both debt holder and creditor.

Tax exemption on negative revenue: Companies facing financial difficulties often experience low incomes. Since taxes are only charged on positive revenues, negative revenues in constraints (2.10) and (2.11) provide the opportunity for exploring tax exemptions in difficult periods. As a result, the downsizing solution has incentive to reduce loss before maximizing profit.

Cash reserve for negative revenue: Negative revenue of an operation center suggested by a downsizing solution provides managers the information on possible losses at a part of the supply chain in certain downsizing period. Therefore, a corresponding level of cash should be reserved for completing planned operations. Depending on the company's financial status and its negotiation with creditors, the ability of borrowing varies from case to case. Our research emphasizes on estimating the lacking amount in its present value, while the modeling feature for finding the optimal borrowing and paying options can be easily cooperated in the downsizing MILP model by introducing bounds to negative revenues, e.g., $\sum_{p=1}^{P} \mathrm{RevP}_{pt}^{-} \leq \mathrm{Borrow}_t$, where Borrow_t stands for the total borrowing amount available to the company in planning period t.

Only inbound or outbound flow of PFUs: In problem (2.1)–(2.15), we do not require the alternatives of inbound and outbound PFUs flow of a production center. Our model ascertains that the optimal solution will only have either inbound or outbound PFUs flow for a production center, but never both in the same period. To show this, we prove the following lemma.

Lemma 2.1. *Assume that there is a connection between each production center in both directions, and transferring costs of PFUs between all production centers are nontrivial and satisfy triangle inequalities. Then in an optimal solution of the MILP problem (2.1)–(2.15) facilities are transferred out or into a production center, but never in both directions in a certain period.*

Proof. We prove lemma by showing the non-optimality of the following two cases.

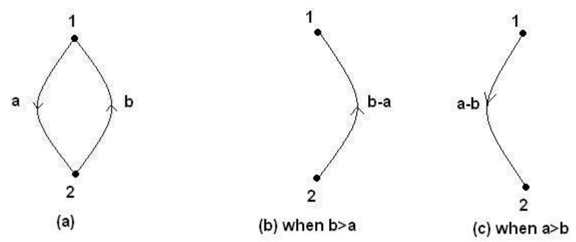


FIGURE 2.1: PFUs transfer circle between two production centers

Case 1. (see Figure 2.1 (a)) Let us assume that there is a solution of (2.1)–(2.15) for which $X_{p_1p_2t} = a$ and $X_{p_2p_1t} = b$ is a PFUs flow between production center p_1 and p_2, where $b \geq a > 0$. We show here that such solution is not optimal. While other settings remain the same, setting $X'_{p_1p_2t} = 0$ and $X'_{p_2p_1t} = b - a$ is still a feasible PFUs flow (see Figure 2.1 (b)). Since $X'_{p_1p_2t} < X_{p_1p_2t}$ and $X'_{p_2p_1t} < X_{p_2p_1t}$, based on constraint (2.10) we know that the later PFUs flow generates less transfer costs for both production centers p_1, p_2. Hence, a higher profit and objective value can be obtained with $X'_{p_1p_2t}$, $X'_{p_2p_1t}$. A similar result can be derived when $a \geq b > 0$ (See Figure 2.1 (c)).

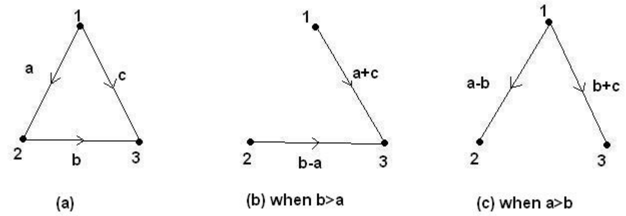


FIGURE 2.2: PFUs transfer flow among three production centers

Case 2. (See Figure 2.2 (a)) It is not optimal to have another production center as a transit point. We assume that there is a solution of (2.1)–(2.15) for which $X_{p_1p_2t} = a$, $X_{p_2p_3t} = b$, and $X_{p_1p_3t} = c$ is a PFUs flow among production centers p_1, p_2 and p_3, where p_2 is the transit point. When $b \geq a > 0$ and $c > 0$, setting $X'_{p_1p_2t} = 0$, $X'_{p_2p_3t} = b - a$ and $X'_{p_1p_3t} = a + c$ is another feasible PFUs flow (see Figure 2.2 (b)), while other settings remain the same. Note that,

$$\begin{aligned}
\text{TransportationCost} &= X_{p_1p_2t}g_{p_1p_2} + X_{p_2p_3t}g_{p_2p_3} + X_{p_1p_3t}g_{p_1p_3} \\
&= X_{p_1p_2t}g_{p_1p_2} + (X_{p_1p_2t} + X'_{p_2p_3t})g_{p_2p_3} + X_{p_1p_3t}g_{p_1p_3} \\
&= X_{p_1p_2t}(g_{p_1p_2} + g_{p_2p_3}) + X'_{p_2p_3t}g_{p_2p_3} + X_{p_1p_3t}g_{p_1p_3}.
\end{aligned}$$

Based on the assumption of the triangle inequality of the transfer costs among production centers p_1, p_2 and p_3, $X_{p_1p_2t}(g_{p_1p_2} + g_{p_2p_3}) \geq X_{p_1p_2t}g_{p_1p_3}$. Hence,

$$\begin{aligned}
\text{TransportationCost} &\geq X_{p_1p_2t}g_{p_1p_3} + X'_{p_2p_3t}g_{p_2p_3} + X_{p_1p_3t}g_{p_1p_3} \\
&= (X_{p_1p_2t} + X_{p_1p_3t})g_{p_1p_3} + X'_{p_2p_3t}g_{p_2p_3} \\
&= X'_{p_1p_3t}g_{p_1p_3} + X'_{p_2p_3t}g_{p_2p_3},
\end{aligned}$$

i.e., the sum of transfer costs of production centers p_1, p_2 and p_3 is lower with $X'_{p_1p_2t}$, $X'_{p_2p_3t}$, and $X'_{p_1p_3t}$ than with $X_{p_1p_2t}$, $X_{p_2p_3t}$, and $X_{p_1p_3t}$. Hence, the later PFUs flow generates a higher profit. Similar results can be obtained when $b \geq a > 0$ and $c = 0$ or when $a \geq b > 0$ and $c \geq 0$ (See Figure 2.2 (c)). □

Note that the inbound and outbound refers to transportation of PFUs, while the selling of PFUs is not considered as an outbound. The following lemma shows that, in an optimal solution, either RevP^+_{pt} or RevP^-_{pt} is equal to zero for every p and t.

Lemma 2.2. *In an optimal solution of model (2.1)–(2.15), either* RevP^+_{pt} *or* RevP^-_{pt} *is equal to zero for every* (p,t). *Moreover, constraint (2.10) is active in an optimal point.*

Proof. We first show that RevP^+_{pt} or RevP^-_{pt} is equal to zero for every (p,t).

Let us assume that there exist $\text{RevP}^+_{pt} > 0$ and $\text{RevP}^-_{pt} > 0$ for some (p,t). Then $\text{RevP}^{+*}_{pt} = \text{RevP}^+_{pt} - \text{RevP}^-_{pt}$ and $\text{RevP}^{-*}_{pt} = 0$ is also feasible for (2.1)–(2.15). Moreover, we have:

$$
\begin{aligned}
&\sum_{t=1}^{T} r^{t-1}\{\sum_{p=1}^{P} E^1_{ph}[(1-\text{tax}^1_p)\text{RevP}^{+*}_{pt} - \text{RevP}^{-*}_{pt}] \\
&+\sum_{d=1}^{D} E^2_{dh}[(1-\text{tax}^2_d)\text{RevD}^+_{dt} - \text{RevD}^-_{dt}]\} \\
&=\sum_{t=1}^{T} r^{t-1}\{\sum_{p=1}^{P} E^1_{ph}[(1-\text{tax}^1_p)(\text{RevP}^+_{pt} - \text{RevP}^-_{pt})] \\
&+\sum_{d=1}^{D} E^2_{dh}[(1-\text{tax}^2_d)\text{RevD}^+_{dt} - \text{RevD}^-_{dt}]\} \\
&=\sum_{t=1}^{T} r^{t-1}\{\sum_{p=1}^{P} E^1_{ph}[(1-\text{tax}^1_p)\text{RevP}^+_{pt} - (1-\text{tax}^1_p)\text{RevP}^-_{pt}] \\
&+\sum_{d=1}^{D} E^2_{dh}[(1-\text{tax}^2_d)\text{RevD}^+_{dt} - \text{RevD}^-_{dt}]\} \\
&>\sum_{t=1}^{T} r^{t-1}\{\sum_{p=1}^{P} E^1_{ph}[(1-\text{tax}^1_p)\text{RevP}^+_{pt} - \text{RevP}^-_{pt}] \\
&+\sum_{d=1}^{D} E^2_{dh}[(1-\text{tax}^2_d)\text{RevD}^+_{dt} - \text{RevD}^-_{dt}]\},
\end{aligned}
$$

which is a contradiction to the optimality of RevP^+_{pt} and RevP^-_{pt}. Above we use $\text{tax}^1_p > 0$ for every p.

Therefore, in an optimal solution, either RevP^+_{pt} or RevP^-_{pt} is equal to zero.

Similarly, we can also show that constraint (2.10) is active in an optimal point. □

The MILP problem (2.1)–(2.15) solves the SCDP under bankruptcy assuming all parameters are known with exact values. With uncertainties around a supply chain network, the performance of a downsizing plan obtained from the MILP problem (2.1)–(2.15) is not guaranteed. In the sequel, we use a robust optimization approach to deal with uncertain demands and volatile exchange rates.

2.4 Robust counterpart

Entities involved in a SCDP under bankruptcy are coupled with external financial pressures and need a robust solution to uncertainties for managing risks effectively across the supply chain, by looking into volatility. In this section, we discuss a robust optimization approach for coping with uncertainties from demands and exchange rates, while the same technique can be easily adapted for various sources of uncertainties. The approach is proven to be efficient for improving the robustness of the obtained downsizing plan, allowing management to measure the value at risk when opting for a solution and avoid future disillusionment.

Robust optimization as proactive approach in the face of uncertainties has been already applied to different aspects of supply chain management, but not yet the subject of downsizing. For example Bertsimas and Thiele [2006] and Bertsimas and Thiele [2004] present the classical stock allocation in a network in case of uncertain demand. Shukla et al. [2011] explore supply network location/allocation when may occur disruptions due to natural events. Ben-Tal et al. [2005] propose a robust optimization model for supply contracts with uncertain demand. Other example is Pishvaee et al. [2011], who discuss the classical models of closed loop supply chain network design with robust counterparts for unknown returns.

2.4.1 Uncertain demands and the box robust counterpart

Let Q_{dt} stands for the demand of the distribution center d in period t as in previous section. Instead of giving it an exact value, we draw a boundary to its possible realizations. Let Q^0_{dt} be the mean of the possible realization while $\widehat{Q_{dt}}$ stands for the maximum deviation of realizations from the mean. A realization of Q_{dt} can be any value from the interval $[Q^0_{dt} - \widehat{Q_{dt}}, Q^0_{dt} + \widehat{Q_{dt}}]$. Similar to the box uncertainty region introduced by Ben-Tal et al. [2009], we define our uncertainty region of Q_{dt} as:

$$Q_{dt} \in \{Q^0_{dt} + \widehat{Q_{dt}}\xi_{dt}, |\xi_{dt}| \leq \alpha_{dt}\}, \qquad \forall d, t, \tag{2.16}$$

where ξ_{dt} is a relative perturbation of Q_{dt} and $\alpha_{dt} \in (0, 1]$ serves as a generalized bound to the deviation of ξ_{dt} from zero.

Based on the worst case scenarios of demands, the robust counterpart of constraint (2.2) can be formulated as:

$$\sum_{p=1}^{P} V_{pdt} \leq Q_{dt}^{0} + \widehat{Q_{dt}} \min_{-\alpha_{dt} \leq \xi_{dt} \leq \alpha_{dt}} \{\xi_{dt}\} = Q_{dt}^{0} - \widehat{Q_{dt}} \alpha_{dt}, \qquad \forall d, t. \tag{2.17}$$

Here, ξ_{dt} belongs to the uncertainty region of Q_{dt}, see 2.16. When we have $\alpha_{dt} = 1$, this robust counterpart ensures that the obtained downsizing plan maintains its performance in case of any possible realization of demands. Since realizations of demands do not always result in the worst cases, a downsizing plan with a certain risk can be desirable to managers in a case when a tempting extra profit can be generated. By choosing different values of α_{dt} from $(0, 1)$, managers may vary the strictness of the robust counterpart and as such adjust their target risks.

Since the remaining constraints in the MILP model do not involve uncertain demands as parameters, they remain the same. By replacing constraint (2.2) with its robust counterpart (2.17), we obtain the robust counterpart of the MILP model as (2.1), (2.3)–(2.15), (2.17). We refer to this robust formulation as the box robust counterpart (BRC).

2.4.2 Uncertain exchange rates and the extended BRC

Managing a global supply chain network requires special attentions on factors, such as tariffs / duties, trade barriers, currency exchange rates, corporate income taxes, transportation lead times, and worker skills / availabilities (see Meixell and Gargeya [2005]). One of the main risks of globalized operations is due to volatile currencies. Appreciation in the numeraire country's currency will shrink the gross margin, while depreciation in the numeraire country's currency will have an opposite effect. Below we show how our proposed robust optimization approach can be applied to uncertainties from exchange rates.

First we give two remarks to the current formulation of our downsizing MILP model:

1. The MILP model is formulated with four different types of exchange rate; E_p^1, E_d^2, E_{op}^3, and E_{dp}^4. They are not independent since d, p, and o may use the same type of currency. Therefore we cannot introduce uncertainties to these parameters separately.

2. The computation of production center's profits in the numeraire country's currency involves three exchange rates: E_p^1 in objective function (1), E_{op}^3 and E_{dp}^4 in constraint (2.10). Since robust optimization techniques are applied to individual constraints which are formulated with uncertain parameters, if we introduce robust

counterparts of (2.1) and (2.10) directly, the robustness to volatile currencies will be considered twice upon profits of production centers. Therefore a reformulation of (2.1) and (2.10) is required such that uncertainties related to the computation of a production center's profit are grouped into only one constraint.

For the above mentioned reasons, we need to reformulate (2.1)–(2.15). In the sequel, we discuss a modification to the MILP model such that robust optimization techniques can be applied without duplicating robustness considerations.

We sort d, p, and o according to the currency types that they use. Let Y be the set of all currency types involved and $y \in Y$. Define E_y as the exchange rate of y currency to the numeraire country's currency. We can now redefine exchange rates we used in MILP model as:

$$\begin{aligned} E_p^1 &:= E_{y_p} \\ E_d^2 &:= E_{y_d} \\ E_{op}^3 &:= \frac{E_{y_o}}{E_{y_p}} \\ E_{dp}^4 &:= \frac{E_{y_d}}{E_{y_p}}. \end{aligned}$$

By using above definitions and multiplying constraint (2.10) by E_{y_p}, constraint (2.10) becomes:

$$\begin{aligned} &E_{y_p} R_{pt} X_{p(P+1)t} - \sum_{\bar{p}=1}^{P} E_{y_p} X_{\bar{p}pt} g_{\bar{p}p} + \sum_{d=1}^{D} V_{pdt}(E_{y_d} q_d^1 - E_{y_p} b_p) \\ &- \sum_{o=1}^{O} \sum_{j=1}^{J} W_{opjt}(E_{y_o} s_{oj} + E_{y_p} tr_{opj}^1) - E_{y_p} B_{pt}(F_p^1 + \mathrm{L}_{pt}) - E_{y_p} Z_{pt} G_p \\ &- E_{y_p}(B_{p(t-1)} - B_{pt})(K_p^1 + \sum_{\bar{t}=t}^{T} r^{\bar{t}-t} \mathrm{L}_{p\bar{t}}) \geq \mathrm{ERevP}_{pt}^{+} - \mathrm{ERevP}_{pt}^{-} \qquad \forall p, t, \end{aligned} \tag{2.18}$$

where $\mathrm{ERevP}_{pt}^{-} := E_{y_p}\mathrm{RevP}_{pt}^{-}$ and $\mathrm{ERevP}_{pt}^{+} := E_{y_p}\mathrm{RevP}_{pt}^{+}$.

Similarly, the objective function becomes

$$\begin{aligned} \text{Maximize} \sum_{t=1}^{T} r^{t-1} \{ &\sum_{p=1}^{P} [(1 - \mathrm{tax}_p^1)\mathrm{ERevP}_{pt}^{+} - \mathrm{ERevP}_{pt}^{-}] \\ &+ \sum_{d=1}^{D} E_{y_d}[(1 - \mathrm{tax}_d^2)\mathrm{RevD}_{dt}^{+} - \mathrm{RevD}_{dt}^{-}] \}. \end{aligned} \tag{2.19}$$

By replacing constraint (2.10) and objective function (2.1) of the MILP model with their re-scaled formulations (2.18) and (2.19) respectively, we obtain a re-scaled MILP model. To show that these two models are equivalent, we prove the following lemma.

Lemma 2.3. *The downsizing MIP model and its re-scaled formulation are equivalent MIP models.*

Proof. Let ${X_{ppt}}^*$, ${V_{pdt}}^*$, ${W_{opjt}}^*$, ${B_{pt}}^*$, ${Z_{pt}}^*$, RevD_{dt}^{+*}, RevD_{dt}^{-*}, RevP_{pt}^{+*}, and RevP_{pt}^{-*} be a feasible solution of the downsizing MIP model. We define $\mathrm{ERevP}_{pt}^{+*} := E_{y_p}\mathrm{RevP}_{pt}^{+*}$ and $\mathrm{ERevP}_{pt}^{-*} := E_{y_p}\mathrm{RevP}_{pt}^{-*}$; and show that ${X_{ppt}}^*$, ${V_{pdt}}^*$, ${W_{opjt}}^*$, ${B_{pt}}^*$, ${Z_{pt}}^*$, RevD_{dt}^{+*}, RevD_{dt}^{-*}, along with ERevP_{pt}^{+*} and ERevP_{pt}^{-*} is a feasible solution of the re-scaled formulation. Namely, we have:

$$
\begin{aligned}
&R_{pt}X^*_{p(P+1)t} - \sum_{\bar{p}=1}^{P} X_{\bar{p}pt}{}^* g_{\bar{p}p} + \sum_{d=1}^{D} V_{pdt}{}^*(E^4_{dp}q^1_d - b_p) \\
&- \sum_{o=1}^{O}\sum_{j=1}^{J} W_{opjt}{}^*(E^3_{op}s_{oj} + tr^1_{opj}) - B_{pt}{}^*(F^1_p + \mathrm{L}_{pt}) - Z_{pt}{}^* G_p \\
&-(B_{p(t-1)}{}^* - B_{pt}{}^*)(K^1_p + \sum_{\bar{t}=t}^{T} r^{\bar{t}-t}\mathrm{L}_{p\bar{t}}) \geq \mathrm{RevP}_{pt}^{+*} - \mathrm{RevP}_{pt}^{-*} && \forall p,t, \\
\Leftrightarrow &E_{y_p}R_{pt}X^*_{p(P+1)t} - \sum_{\bar{p}=1}^{P} E_{y_p}X_{\bar{p}pt}{}^* g_{\bar{p}p} + \sum_{d=1}^{D} V_{pdt}{}^*(E_{y_d}q^1_d - E_{y_p}b_p) \\
&- \sum_{o=1}^{O}\sum_{j=1}^{J} W_{opjt}{}^*(E_{y_o}s_{oj} + E_{y_p}tr^1_{opj}) - E_{y_p}B_{pt}{}^*(F^1_p + \mathrm{L}_{pt}) - E_{y_p}Z_{pt}{}^* G_p \\
&-E_{y_p}(B_{p(t-1)}{}^* - B_{pt}{}^*)(K^1_p + \sum_{\bar{t}=t}^{T} r^{\bar{t}-t}\mathrm{L}_{p\bar{t}}) \geq E_{y_p}\mathrm{RevP}_{pt}^{+*} - E_{y_p}\mathrm{RevP}_{pt}^{-*} && \forall p,t, \\
\Leftrightarrow &E_{y_p}R_{pt}X^*_{p(P+1)t} - \sum_{\bar{p}=1}^{P} E_{y_p}X_{\bar{p}pt}{}^* g_{\bar{p}p} + \sum_{d=1}^{D} V_{pdt}{}^*(E_{y_d}q^1_d - E_{y_p}b_p) \\
&- \sum_{o=1}^{O}\sum_{j=1}^{J} W_{opjt}{}^*(E_{y_o}s_{oj} + E_{y_p}tr^1_{opj}) - E_{y_p}B_{pt}{}^*(F^1_p + \mathrm{L}_{pt}) - E_{y_p}Z_{pt}{}^* G_p \\
&-E_{y_p}(B_{p(t-1)}{}^* - B_{pt}{}^*)(K^1_p + \sum_{\bar{t}=t}^{T} r^{\bar{t}-t}\mathrm{L}_{p\bar{t}}) \geq \mathrm{ERevP}_{pt}^{+*} - \mathrm{ERevP}_{pt}^{-*} && \forall p,t.
\end{aligned}
$$

Now, we show that objectives coincide. Indeed,

$$\begin{aligned}
&\sum_{t=1}^{T} r^{t-1}\{\sum_{p=1}^{P} E_{y_p}[(1-\mathrm{tax}_p^1)\mathrm{RevP}_{pt}^{+\,*} - \mathrm{RevP}_{pt}^{-\,*}] \\
&+\sum_{d=1}^{D} E_{y_d}[(1-\mathrm{tax}_d^2)\mathrm{RevD}_{dt}^{+\,*} - \mathrm{RevD}_{dt}^{-\,*}]\} \\
=&\sum_{t=1}^{T} r^{t-1}\{\sum_{p=1}^{P}[(1-\mathrm{tax}_p^1)E_{y_p}\mathrm{RevP}_{pt}^{+\,*} - E_{y_p}\mathrm{RevP}_{pt}^{-\,*}] \\
&+\sum_{d=1}^{D} E_{y_d}[(1-\mathrm{tax}_d^2)\mathrm{RevD}_{dt}^{+\,*} - \mathrm{RevD}_{dt}^{-\,*}]\} \\
=&\sum_{t=1}^{T} r^{t-1}\{\sum_{p=1}^{P}[(1-\mathrm{tax}_p^1)\mathrm{ERevP}_{pt}^{+\,*} - \mathrm{ERevP}_{pt}^{-\,*}] \\
&+\sum_{d=1}^{D} E_{y_d}[(1-\mathrm{tax}_d^2)\mathrm{RevD}_{dt}^{+\,*} - \mathrm{RevD}_{dt}^{-\,*}]\}.
\end{aligned}$$

Conversely, let $X_{ppt}{}^{\circ}$, $V_{pdt}{}^{\circ}$, $W_{opjt}{}^{\circ}$, $B_{pt}{}^{\circ}$, $Z_{pt}{}^{\circ}$, $\mathrm{RevD}_{dt}^{+\,\circ}$, $\mathrm{RevD}_{dt}^{-\,\circ}$, $\mathrm{ERevP}_{pt}^{+\,\circ}$, and $\mathrm{ERevP}_{pt}^{-\,\circ}$ be a feasible solution of the re-scaled formulation. It follows by direct verification that $X_{ppt}{}^{\circ}$, $V_{pdt}{}^{\circ}$, $W_{opjt}{}^{\circ}$, $B_{pt}{}^{\circ}$, $Z_{pt}{}^{\circ}$, $\mathrm{RevD}_{dt}^{+\,\circ}$, $\mathrm{RevD}_{dt}^{-\,\circ}$, along with $\mathrm{RevP}_{pt}^{+\,\circ}$ and $\mathrm{RevP}_{pt}^{-\,\circ}$ is a feasible solution of the downsizing MIP model (2.1)–(2.15), where $\mathrm{RevP}_{pt}^{+\,\circ} := \mathrm{ERevP}_{pt}^{+\,\circ}/E_{y_p}$ and $\mathrm{RevP}_{pt}^{-\,\circ} := \mathrm{ERevP}_{pt}^{-\,\circ}/E_{y_p}$.

□

We introduce uncertainty to E_y, and assume that its possible realizations are bounded by a box uncertainty region:

$$E_y \in \{E_y^0 + \widehat{E_y}\eta_y, |\eta_y| \le 1\}, \qquad \forall y,$$

where η_y is a relative perturbation of E_y, E_y^0 is the mean of the possible realization, and $\widehat{E_y}$ stands for the maximum deviation. Note that in this way, uncertainties of E_p^1, E_d^2, E_{op}^3, and E_{dp}^4 are captured within uncertainties of E_y. Similarly to derivation of the robust counterpart of constraint (2.2) (see (2.17)), we derive the robust counterpart of (2.18) and (2.19). Interested readers may note that, similar to demands, the exchange rates can also be defined per time period. It allows tracking the changes of exchange rates over time. However, our focus here is on finding the best resource allocation that protects the supply chain network from volatile exchange rates rather than determining the timing of reconfiguration operations based on exchange rate forecasts. We leave the application choice to interested readers.

In the sequel, we refer to the robust counterpart of the MILP model which considers uncertainties from both demands and exchange rates, as the *extended* BRC. The extended BRC can be derived by replacing constraint (2.2), constraint (2.18) and objective function (2.19) of the re-scaled downsizing MILP model with their robust counterparts. Note that the computation of profits of production centers only involves uncertainties of E_y in constraint (2.18), which suggests that the extended BRC will only consider once robustness upon profits of production centers.

The downsizing MILP model and its robust counterparts are tested with generated test cases of SCDP under bankruptcy in the following section.

2.5 Numerical results

In this section, we discuss the test results of 50 random size downsizing cases of the MILP model and an extensive study of one large case using the BRC and the extended BRC. Obtained results not only verify our proposed approach in discovering feasible downsizing strategies, but also demonstrate its potential in identifying and quantifying benefits and risks of different downsizing strategies, and eventually helping managers selecting the most suitable strategy.

All testing cases are solved by CPLEX using AIMMS interface, running on a PC with Intel Core2 Quad CPU, 2.66GHz, and 3.21GB of memory. We discuss the obtained results in the rest of this section.

2.5.1 Results of the MILP problem: downsizing in face of deterministic demand

To assess our MILP problem, 50 random size downsizing cases are used. This set of cases is systematically generated using a realistic value added model in the network, departing from final product value based on which constructing costs/value added at each echelon. The generation procedure takes four major steps to produce one random case. These four steps are:

(a) Product generation: First, we randomly generate a product value and J the number of raw material types required for producing this product. Then we split the product value into $2J+4$ parts of random proportions, which represent value bases of the following parameter categories: purchasing and transportation costs of each raw material type, product production and transportation costs, and profit margins at production and distribution centers. The value bases define a product cost structure for further generation.

(b) Network specifics generation: In order to derive specifics of a network consisting of suppliers, production centers and distribution centers, for a 10-period planning horizon, we add to each value base of different parameter categories a random adjustment which is drawn from the uniform distribution. For example, if we have $\overline{s_j}$ as the value base of purchasing cost of raw material j, then value of s_{oj} can be determined following $s_{oj} = \overline{s_j} + a_{oj}\overline{s_j}(0.5 - \text{rand}_{oj})$, where a_{oj} stands for a scale factor which adjusts the maximum deviation of randomly generated parameter value from its value base, and rand_{oj} stands for a random value generated from the uniform distribution $U(0, 1)$.

(c) Network determination: An optimization model derived from the downsizing MILP model is used to select production centers and suppliers such that all demands of distribution centers can be satisfied with minimum operation costs. We refer to the corresponding optimization model as the initial MILP. Given the fact that distributions are treated as demand centers which generate demands, all distribution centers are opened in every generated downsizing case.

(d) Demand reduction: Finally, we assume that economic downtrend strikes the market in the second period of the planning horizon and a demand decline is expected to last for the next six periods (see Figure 2.3). Demands recover in the eighth period. Managers of the optimized supply chain realize this change and would like to downsize the supply chain such that the investment is protected for the remaining nine periods. To reduce the six periods demands of any distribution center, a percentage is drawn randomly from the uniform distribution $U(0, 0.9)$. By doing so we obtain a downsizing case with a planning horizon of nine periods. We refer to the remaining nine periods as the downsizing periods.

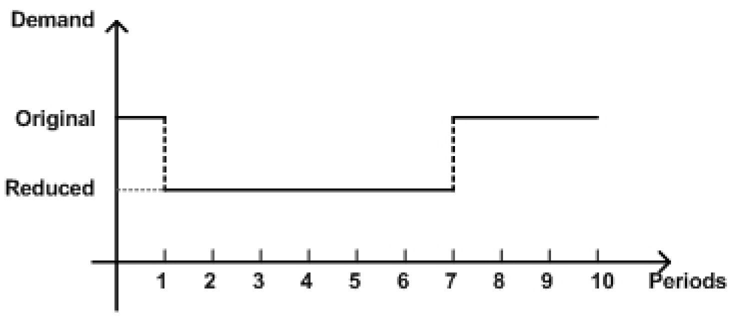


Figure 2.3: The changes of demands over periods

The first two steps are conducted in Matlab while the third and fourth steps in AIMMS. The approach constructs close to "real" problem situation data set, the lack of which necessitated the development of this generator. This platform can be used for a wide-variety of purposes as it produces an "optimal" data set. The Matlab programs of step (a) and (b) and the initial MILP model of step (c) can be found at following link:

https://www.dropbox.com/s/svw8iwsyfwqsjou/random_data_generation.zip

Table 2.1 lists the downsizing results of generated cases. The columns two to four of this table specify the following features of downsizing cases: the aggregated decline percentage of the total demand, the number of initial operating production centers, and the number of initial operating PFUs respectively. Downsizing results of each case, including selling or relocating PFUs, closing distribution centers, closing production centers, are presented respectively in columns five to eight of Table 2.1. The last column of the table presents the computation time of each case. While most of the downsizing operations are planned in the first downsizing period, we present the value after a "+" sign to indicate that downsizing operations are planned in a later downsizing period. The number in parentheses provides the period when the downsizing operations take place. The test results suggest downsizing operations for almost all generated cases. Only four out of 50 cases suggest no downsizing at all, i.e. Cases 2.5, 2.7, 2.18, and 2.33. We refer to these four cases as the insignificant downsizing cases, meaning that downsizing is found to be an ineffective strategy in these cases. These cases are further investigated below.

Taking 11 of 50 cases, we perform a sensitivity analysis on parameters such as demand volume, machine (PFU) value, product price, and the numeraire country's currency value. These 11 cases contain three insignificant downsizing cases, Cases 2.7, 2.18, and 2.33. During the sensitivity analysis we change values of the above mentioned parameters one by one and set at 20% higher or 20% lower from their original values for each downsizing case. We summarize in Table 2.2 the influence of the parameter value changes to downsizing decisions. The value at each entry, varying between [0,11], represents the number of times that a downsizing decision is affected by the change of certain parameter. Hence, the higher the value of an entry is, the more consistent the impact of a parameter value change is on a downsizing decision.

The results show that downsizing optimization represents a reactive and offensive or proactive and anticipatory strategy on managing the resources like production centers, PFUs, and distribution centers in order to protect the investment. Some highlights of results are:

TABLE 2.1: Downsizing results of 50 random cases

Case	Demand decline (in%)	♯ of Prod. centers	♯ of PFUs	♯ of prod. centers closed	♯ of PFUs sold	♯ of PFUs relocated	♯ of distr. centers closed	CPU (s)
2.1	30	4	16	1	4	0	4+1(8)	2
2.2	23	5	15	1	2	0	2	6
2.3	29	4	16	0	1	0	+1(8)	0.67
2.4	24	4	16	0	3	0	2+2(8)	3
2.5	28	5	16	0	0	0	0	3
2.6	18	3	15	0	1	0	0	0.45
2.7	33	5	15	0	0	0	0	5
2.8	32	4	14	0	2	0	3	1
2.9	35	5	17	0	5	0	6+1(8)	6
2.10	28	6	15	2	2	1	1+1(8)	85
2.11	22	3	16	0	2	0	1+1(8)	1
2.12	32	6	16	1	2	0	1+1(8)	1
2.13	30	6	16	1	3	0	1+2(8)	8
2.14	34	3	14	0	2	0	3	0.48
2.15	31	8	18	3	5	0	4	24
2.16	32	3	15	0	1	0	1	10
2.17	27	5	16	0	1	0	0	0.94
2.18	26	2	15	0	0	0	0	0.22
2.19	31	3	15	0	1	0	1	1
2.20	36	3	15	0	1	0	1	2
2.21	33	7	16	2	4	+1(7)	5	14
2.22	26	5	16	1	3	0	2+1(8)	4
2.23	31	8	17	1	1	+1(8)	1	15
2.24	34	3	16	0	1	0	0	0.31
2.25	29	3	16	0	2	0	2	2
2.26	35	4	15	0	2	0	1+1(8)	2
2.27	28	4	16	0	1	0	1	0.95
2.28	30	5	15	0	2	0	2	8
2.29	27	4	16	0	1	0	1	3
2.30	29	4	16	0	3	0	3+1(8)	10
2.31	30	5	16	1	2	0	+2(8)	12
2.32	23	3	15	0	1	0	0	0.48
2.33	30	5	15	0	0	0	0	4
2.34	23	4	14	0	2	0	2+1(8)	1
2.35	28	5	17	0	5	0	6+1(8)	6
2.36	20	6	15	2	2	1	1+1(8)	19
2.37	33	3	16	0	2	0	1+1(8)	0.66
2.38	30	6	16	1	2	0	1+1(8)	1
2.39	35	6	16	0	2	0	1+1(8)	23
2.40	26	3	14	0	2	0	2+1(8)	0.86
2.41	23	8	18	3	5	0	4	25
2.42	31	3	15	0	1	0	1	10
2.43	30	5	16	0	1	0	0	0.58
2.44	34	2	15	0	1	0	1	0.23
2.45	31	3	15	0	1	0	1	1
2.46	32	3	15	0	1	0	+1(8)	0.66
2.47	26	7	16	2	4	+1(7)	5	16
2.48	26	5	16	1	4	0	3+2(8)	1
2.49	31	8	17	1	1	+1(8)	1	8
2.50	37	3	16	0	1	0	0	0.38

1. Variation of parameter values can alter the downsizing decisions significantly. The expected return on investment resulted from an obtained downsizing decision can be very sensitive to changes of parameter values.

2. When certain parameter values are changed, the test results of the three insignificant downsizing cases also result with downsizing operations. For example in Case 2.7, the test results suggest downsizing operations when 20% increase or decrease of certain parameters is implemented. Details of downsizing results for Case 2.7 are summarized in Table 2.3.

TABLE 2.2: Sensitivity analysis of the downsizing MILP model

Parameter changes	Downsizing decisions of							
	♯ prod. centers cut		♯ PFUs sold		♯ PFUs relocated		♯ dist. centers closure	
	Less	More	Less	More	Less	More	Less	More
1.Increasing demands	4		8			5		7
2.Decreasing demands		3		11	3		1	5
3.Increasing machine value				3				1
4.Decreasing machine value	1				1			
5.Increasing product price	6		7		3	3	7	
6.Decreasing product price		6		11	2	1		11
7.Increasing numeraire country's currency value	3	2		10	3	1		11
8.Decreasing numeraire country's currency value	2	1	1	5		4	3	2

TABLE 2.3: Downsizing results of Case 2.7

Case 2.7	♯ production centers closed	♯ PFUs sold	♯ PFUs relocated	♯ distribution centers closed
Demand 20% ↑	0	0	0	+2(8)
Demand 20% ↓	1	4	0	+1(8)
Machine value 20% ↑	0	1	0	0
Product price 20% ↓	2	4	0	5
currency value 20% ↑	1	2	0	2
currency value 20% ↓	0	1	0	0

3. While the variation of the product price at a distribution center changes the marginal profit of serving the demand of that distribution center, it also changes the total number of profitable demands. Hence, the variation of product prices changes the profitability of keeping certain distribution centers, and consequently, also changes the profitability of keeping certain PFUs and production centers.

4. Higher demands may cause the total profitable demand exceeding the production capacity. As a result, production capacities are reassigned to serve more-profitable demands, while less-profitable demands are discarded and not served. Hence, more PFUs are relocated and more distribution centers are closed.

5. Changes of numeraire country's currency value impact cost structure as well as profit margin. Profitable demand may become unprofitable, less profitable, or more profitable. Hence, all downsizing operations change accordingly.

6. A PFU is sold whenever the machine salvage value is higher than its possible profit generation from serving certain remaining demands. Hence, more PFUs may be sold when machine value increases. However, observations in Table 2.2 do not suggest a significant impact of machine value changes on downsizing decisions.

7. PFU relocation happens only when the relocation operation can result in more profit generation. We can see from Table 2.2 that parameter value changes often

result in changes of PFU relocation decisions on both sides, which suggests the absence of a dominant impact behavior of PFU relocation on profit generation.

As an extension of the above remarks, we elaborate on the following special case which demonstrates the influence of tax on a PFU relocation and selling decisions. When we decrease product marked-up and selling prices of Case 2.21 from Table 2.1 for 20%, the corresponding optimal downsizing solution suggests moving one PFU from one production center to another production center which has PFUs sold in the same downsizing period. Since in this example PFU values are identical among production centers and relocation generates extra transportation cost, it is counterintuitive to relocate the PFU and not have it sold at its origin production center. Nevertheless, the relocation of the PFU occurs, because a positive profit needs to pay a tax (of 25% in our downsizing cases) while no tax is charged for a negative profit. Consequently, the same amount of profit contribution from PFU selling can bring higher return on investment when it contributes to the reduction of a negative profit than when it contributes to the increase of a positive profit. This is consistent with the test result observations which indicate a positive profit at the production center where this PFU is relocated from and a negative profit at the production center where this PFU is brought to, when the PFU relocation takes place. To prove the tax influences on PFU relocation we rerun the same test with taxes of all production centers set as zero. The results of the mentioned experiment show that the relocation of this PFU to the negative profit production center is canceled and this PFU is sold at its original production center. We refer to Table 2.4 for the details of the experiment. In this table, “11” is a positive profit production center, “17” is the negative profit production center, and “21” indicates the imaginary production center for PFU selling.

Table 2.4: Example of tax effect on PFU relocation

	$X_{11,21,2}$	$X_{11,17,2}$	$X_{17,21,2}$
25% tax	2	1	2
zero tax	3	0	1

2.5.2 Results of the BRC: downsizing in face of uncertain demand

One large case of SCDP under bankruptcy is specially generated for testing the BRC and the extended BRC. The generation procedure follows the same steps as in the previous section but with different parameter settings in step (b) and involves additional restrictions of transportation between randomly selected production and distribution centers after completing step (b). This test case involves a supply chain network of 20 suppliers, 10 production centers, and 50 distribution centers. The initial status of the supply chain has in total 17 PFUs. We introduce an aggregated demand decline for 30%. For details of this large case, interested readers can refer to:

https://www.dropbox.com/s/kwrpox46yds0ww4/generatedtestcase.txt

While this large case considers no uncertainties, taking the generated demands as the expectations, we now assume that demands of distribution centers are uncertain and can vary maximally 40% from the expectations. By adding this assumption of uncertain demands, we obtain an uncertain downsizing problem which we use to test the BRC with various α values (see (2.16)). The test results are listed in Table 2.5.

TABLE 2.5: Downsizing solutions of BRC

Downsizing	Capacity status of										♯ PFU	TDNP			CPU
Optimization	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	sold	Expected	Lowest	Highest	(s)
Init. status	1	2	3	2	1	1	3	2	1	1	−−	759394	59.3%	29.3%	−−
MILP ($\alpha = 0$)	0	2	2	2	1	1	3	2	0	0	4	769748	57.4%	24.3%	842
$\alpha = 0.2$	0	2	1	2	1	1	3	2	0	0	5	764110	56.6%	23.0%	455
$\alpha = 0.4$	0	2	0	2	1	1	3	2	0	0	6	754139	55.2%	22.4%	103
$\alpha = 0.6$	0	2	0	2	1	1	2	2	0	0	7	739622	53.9%	22.3%	89
$\alpha = 0.8$	0	2	0	1	1	1	2	2	0	0	8	721124	52.3%	21.0%	741
$\alpha = 1$	0	1	0	1	1	1	2	2	0	0	9	703147	50.6%	19.7%	153

Downsizing plans obtained from the BRC with various α values have all downsizing optimization operations done in the first year of the planning horizon and the adjusted capacity status of production centers remains unchanged for the rest years. While the second row of Table 2.5 present the initial capacity status of production centers, we list the adjusted capacity statuses of production centers in rows $3-8$ for different α. Note that the downsizing solution obtained from the BRC with $\alpha = 0$ is the same as that from the downsizing MILP problem. Results show that as we increase the value of α, thus the strictness of the BRC, the number of PFUs sold increases.

The expected TDNP of downsizing plans as well as their lower and upper bound addressed as the maximum decrease and increase percentage from the expectation, respectively, are listed in the columns $13-15$ of Table 2.5. Comparing with the expected TDNP of the initial capacity allocation, data suggest that higher expected TDNP are generated with the downsizing plans obtained from the MILP model and from the BRC with $\alpha = 0.2$, which confirms the benefit of downsizing optimization operations.

We further test downsizing plans obtained from the BRC with 21 demand scenarios, including 10 scenarios of demands increase with maximal increase of 20%, 10 scenarios of demands decrease with maximal decrease of 40%, and one scenario with expected demands. We assume a stronger decline than increase of demands in order to be consistent with the setting of economic downtrend. In each of these scenarios, demands are simultaneously increased or decreased from their expected values by certain percentages. To be specific, there is a 2% difference between consecutive demand increase scenarios and a 4% difference between consecutive demand decrease scenarios. In order to clearly demonstrate the outcomes of different downsizing plans, test results are divided into two categories, demand reduction and demand increase. The results from demand reduction and demand increase are plotted into box charts in Figure 2.4 and 2.5 respectively. The bottom and top of each box indicates the 25th and 75th percentile respectively, and the band near the middle of the box indicates the median.

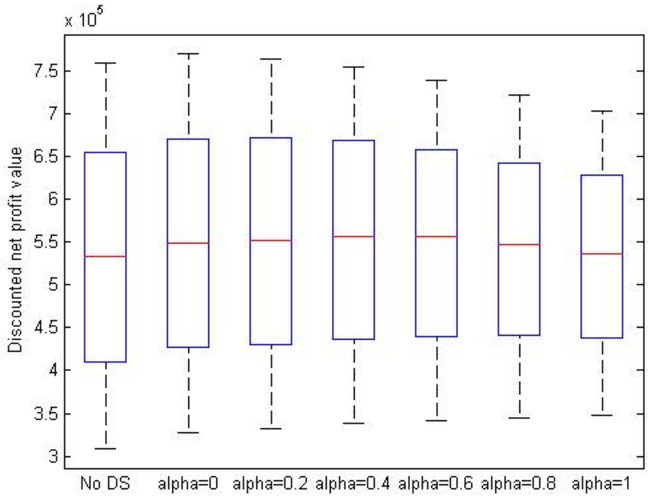


FIGURE 2.4: Box chart of demand level reduction tests

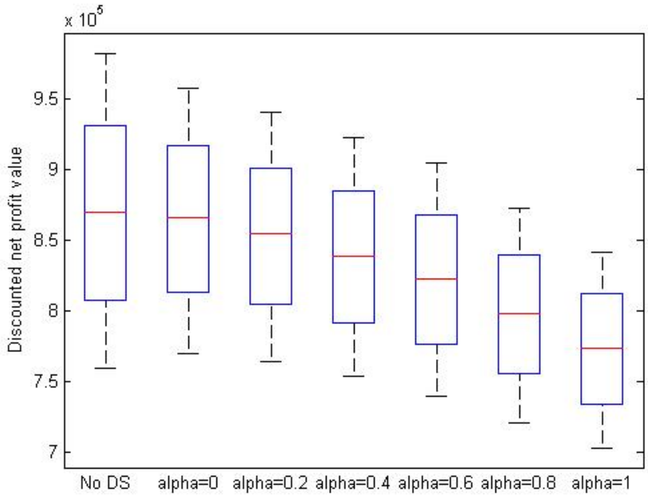


FIGURE 2.5: Box chart of demand level increase tests

We summarize our observations as follows:

- TDNPs of downsized supply chain networks have less significant variations corresponding to the same demand uncertainty. The length of boxes in both Figure 2.4 and 2.5 shrinks as the value of α increases.

- The downsizing plan obtained from the BRC provides better protections to further demand declines from the expectation than the initial capacity status, and the protection can be improved by increasing the value of α. As we can observe in Figure 2.4, the lower bound of TDNPs is improved significantly along with the increase of the value of α.

- Downsizing optimization operations stabilize outcomes of the TDNP by sacrificing possible extra profit generation in a case that the demand decline is less severe than the expectation. As we can see from Figure 2.5, TDNPs decline steeply as the value of α increases. In another words, the price of robustness to demand uncertainty is the loss of potential profits. While extra investment would be difficult for a company facing bankruptcy risks, it is rational to reestablish a healthy financial condition with certain reduction on profits (for a period) before being able to invest.

The financially troubled supply chain often experiences losses at local operation centers. Table 2.6 lists the sum of negative revenues (losses) in each downsizing period of the obtained downsizing strategies when facing the worst demand situation. The results show that losses exist in all periods, and downsizing operations can trigger extra losses at certain locations in the supply chain. Therefore, in order to sustain business operations, a sufficient amount of cash has to be reserved, and the sum of negative revenues provides an indication of the minimum cash level that the company needs in each planning period. Considering that the company may be subject to limited cash availability, we conducted a further analysis to identify the impact of available cash levels on the performance of obtained downsizing strategies. By forcing the sum of negative revenues in each planning period to be less than a certain amount and gradually decreasing the amount from 70000 to 30000, Figure 2.6 shows the availability and performance of each downsizing strategy in the case of the worst demand situation. The results show that when the amount of cash is sufficient (above 70000), downsized supply chains can generate higher profits than the current network. However, when the cash level gradually decreases, the differences between the profits of downsized supply chains and that of the current supply chain also decrease, suggesting that less benefits can be obtained from downsizing operations. When the cash level continue to drop to 35000, robust downsizing strategies obtained when α = 0.4, 0.6, 0.8, or 1 became infeasible. When the cash level is lower than 30000, all network structures fail to operate functionally, suggesting that bankruptcy is unavoidable.

TABLE 2.6: The sum of negative revenues in each downsizing period

Downsizing optimization	Downsizing periods 1	2	3	4	5	6	7	8	9
Init. status	46871	31161	31161	31161	31161	31161	33671	33671	33671
MILP ($\alpha = 0$)	56235	31441	31441	31441	31441	31441	34401	34401	34401
$\alpha = 0.2$	56235	31441	31441	31441	31441	31441	34482	34482	34482
$\alpha = 0.4$	61223	31992	31992	31992	31992	31992	35256	35256	35256
$\alpha = 0.6$	61223	31992	31992	31992	31992	31992	35256	35256	35256
$\alpha = 0.8$	61223	31992	31992	31992	31992	31992	35256	35256	35256
$\alpha = 1$	61223	31992	31992	31992	31992	31992	35349	35349	35349

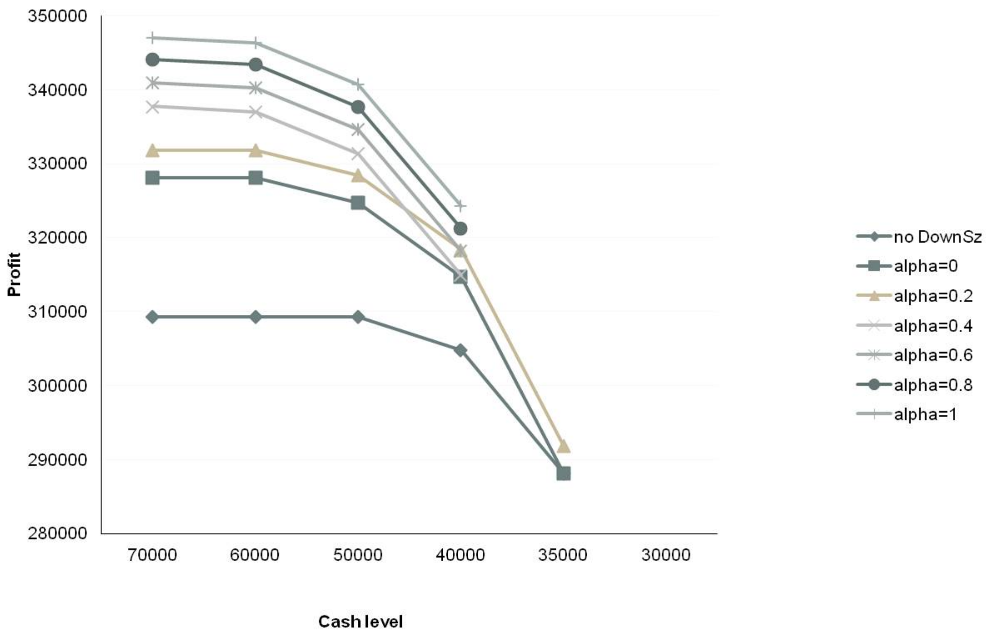


FIGURE 2.6: Tests on cash level

2.5.3 Results of the extended BRC: downsizing in face of exchange rate uncertainty

Compared with the BRC, the extended BRC adds considerations for the robustness to volatile exchange rates. We test this extended robust feature with five exchange rate uncertainty cases, while α is always equal to 1. Namely, we take into consideration the worst demand case which allows the demand deviation from the expectation for a maximum of 40%. In each of the uncertainty case, we assume the exchange rates associated with the production centers, P_2, P_3, P_4, and P_5, to be uncertain. These uncertain exchange rates can deviate maximally a certain percentage from the exchange rate values of the generated test case, which are now taken as the expectations. The adjusted capacity statuses of production centers obtained from different uncertainty cases are listed in Table 2.7.

TABLE 2.7: Downsizing solutions of the extended BRC

Exch. rate variation	Capacity status of P_1	P_2	P_3	P_4	P_5	P_6	P_7	P_8	P_9	P_{10}	♯ PFU sold	TDNP Objective	TDNP Expected	CPU (s)
0%	0	1	0	1	1	1	2	2	0	0	9	347048	703147	147
5%	0	1	0	1	0	1	2	2	1	0	9	331485	692571	216
10%	0	1	0	1	0	0	2	2	1	1	9	323925	687431	83
15%	1	1	0	0	0	1	1	2	1	1	9	318075	678194	172
20%	1	1	0	0	0	1	1	2	1	1	9	314167	678194	140

The test results show that the PFUs are allocated differently over different test cases. The number of PFUs sold, however, is not affected significantly by the change of uncertainties. As a matter of fact, the uncertainties of exchange rates affect purchasing costs and the income at a production center; hence they affect the profit of this production center from serving certain demands. Along with the increase of the variation, depending on the profit margins at production centers, demands, hence also PFUs, are assigned differently among production centers. A main trend is that more PFUs are shifted from the first four production centers to the rest production centers as the variation increases, which improves the stability of TDNPs. This shows that the model strategically moving capacity to hedge and manage potential risks of exchange rate fluctuations. This careful deployment of capacity provides the flexibility to reduce the impact of large and long term shifts in currency values on costs and revenues of downsizing decisions, a unique feature in our model.

The objective value obtained for each case, similar to that of the BRC, is a lower bound to the possible outcomes of TDNP in case the realized exchange rates fall within the expected uncertainty. We may see that the objective values decreases as the variation increases. The expected TDNP, however, is rather stable in a certain range, which is consistent with the slightly adjusted number of PFUs possessed by production centers and with the similar volume of total demand they supply.

2.6 Practical implementation issues and future research

It is worth mentioning while our proposed approach is tractable, both theoretically and empirically, the implementation requires extensive data preparation. The various aggregated data, such as the discount rate, the exchange rates, transportation costs, tax rate, etc., are to be collected throughout the supply network, involving various parties such as financing institutions, regional manufacturing and distribution divisions, and supplier groups of the company under study. Therefore, the determination of the values of aggregated data related to different interest groups demands consensus building. The determination of demand volumes involves both rational analysis and subjective judgement; it therefore requires interactive and participative methods. Here, we would suggest the use of a multi-criteria study in advance, for example, the Analytical Network Process (see Saaty [1996]), for achieving management consent over data to be used in our approach.

An important piece of data is future demand. Forecast is normally determined by sales managers who usually face the daunting challenge of satisfying today's demands. Downsizing is a strategic decision and requires being in line with top decision maker's vision of stability, development, and opportunities for future expansion. Top decision maker may see growth of certain markets more important than the rest with respect to its future prosperity. Therefore, the expected demands and their variations in our approach need the forecast data to be further adjusted such that it would reflect top decision maker's strategic vision.

2.7 Summary

Empirical study of different external supply chain linkages suggests the need for developing efficient and effective optimization models that provide not only supports for decision making but also insights into the importance and usefulness of information and guidelines for data collection (Barratt and Barratt [2011], Barratt and Oke [2007]). We believe when we add the uncertainty dimension of information, the necessity is much higher. Most optimization techniques separate possible realizations into categories of large and small probability events, and favor exploring the large probability events which is beneficial to the overall performance, while protections to small probability events are often overlooked. Surana et al. [2005] argue the need of having a Complex Adaptive System (CAS) for supply chain network. This discussion leads to characterize models and tools under stationary state to measure performance. However, downsizing under the bankruptcy should consider extreme market changes. To our knowledge most optimization models have failed to address this issue and their use would put the company survival at risk.

Our downsizing approach to supply chain under bankruptcy looks for improving long-term effectiveness of scattered resources while downsizing issue in the literature has been treated mainly by improving operations efficiency and boosting profit. Downsizing due to bankruptcy pressure requires a shifted management concern for balancing short-term survival and long-term prosperity. To be specific, a downsizing solution of company facing bankruptcy risks should first guarantee debt fulfillment, preventing liquidity crisis and mitigating this risk through creating more resilient supply chain to economy downtrends. Then it focuses on the maximization of the return on investment with limited resource at its disposal, which in turn amplifies the importance of demand selection. Without a correct strategic framework to analyze and guide the top decision making process, the company in trouble may over-reconfigure the network through capacity cutting and would fail to redesign its business properly at its last chance, which results in less competitiveness for future market growth, and is more likely to retain future vulnerability to the bankruptcy risk again.

In essence we developed a non-classical MILP model, which provides a framework for the downsizing optimization, considering selection of profitable demands and selling of redundant PFUs based on expected demand and exchange rates, it maximizes the expected TDNP with all financial obligations met. We formally developed a rigorous method to generate test bed and evaluate the model. The numerical results of the MILP model confirm its valid functionality in solving a series of generated static SCDPs under bankruptcy. Uncertainties of both demands and exchange rates are introduced to our modeling step by step by applying robust optimization techniques to the MILP model. The resulting formulations, the BRC and the extended BRC, guarantee the robustness of a downsizing solution with respect to the concerned uncertainty and assure a lower bound to all possible realized returns both for individual entities and for the supply chain as a whole. We tested the BRC and the extended BRC with a large generated case. The numerical results show that BRC model and its extension permit downsizing managers to consider two types of hedging for uncertainties involved; (a) production capacity hedging, where due to demand variation, the supply chain intentionally produces and distributes less than demands, and discards unprofitable demands from production planning, (b) allocation hedging, where due to volatile exchange rates, demands and PFUs are relocated among production centers. Based on different restrictions to the concerned uncertainty of the large case, a set of downsizing solutions are obtained. A further analysis of the obtained solutions could help management to measure easily value at risk due to downsizing strategies since the approach maximizes the effectiveness of downsizing in trading potential profit generation with stability of supply chain performance.

Note that future demand developments for certain markets could be correlated to downsizing decisions to be made now. As such, a possible extension of our research can explore the possibility of having future demand as a function of downsizing activities. In practice, a SCDP under bankruptcy can be further complicated when there are more than one products involved in the supply chain. Demands may shift among substitutable products when a product is terminated from production. Besides, there may be more than one type of PFU operating. When plants are designed according to Reconfigurable Manufacturing Systems (RMS), the rapid change in structure is much more feasible. Among the rich literature on the subject we can refer to Bruccoleri et al. [2006], Koren et al. [1999], Renna [2011] who are elaborating on what it takes to introduce an RMS. A downsizing problem with RMS requires a product portfolio analysis and a selection of different PFU types for cutback or for reconfiguration. We discuss the details of downsizing a multi-product supply chain network in the next chapter.

Chapter 3

Product Line Pruning and Supply Chain Downsizing Problem

3.1 Introduction

In the past decade, the world economy experienced a major downturn caused by the global financial crisis of 2007 – 2008 and the Europe's debt crisis of 2010 – 2013. A pervasive response to this was some form of downsizing. However, the continued drive for ever increasing supply chain network cost efficiency in the past decades has reduced the flexibility for responding to sudden economy changes. The evidence of such vulnerabilities is documented by Tang and Tomlin [2008]. The tremendous market volatility and raising cost from raw material purchasing, manufacturing, and distribution, deteriorated the business performance of many large transnational firms, some of which face bankruptcy risks. The downsizing cases of GM, Chrysler, Boeing, and General Electric are a few examples. These corporations have downsized more than once in an effort to cut costs and remain competitive (see Strain and Media, n.d.). Downsizing is therefore deemed as one of the most effective rescue means, and has been widely applied by companies for rightsizing their supply chain networks. However, without a correct strategic framework to analyze and guide the decision process, any company in trouble may fail to redesign its business properly at its last chance. Due to the rapid development of computational platforms and mixed integer programming solvers, it is clear that mathematical optimization is the best approach to tackle downsizing issues. Therefore, we propose a mathematical model that addresses a downsizing problem and test it i.e., solve it to optimality for small and medium size instances. In what follows, we first briefly highlight the downsizing application of a supply chain network facing bankruptcy risks, then we explore the up-to-date literature.

Freeman and Cameron [1993] first characterize downsizing as an intentional endeavor for improving efficiency or effectiveness of an organization, which usually results in reductions in personnel and work processes redesign. Downsizing due to bankruptcy pressure, however, requires a shifted management concern for balancing short-term survival and long-term prosperity. Hence, downsizing a supply chain under financial difficulties influences the network configuration, which aims for improving survival chance and future profitability of the supply chain. It often results in reduction of supply chain entities (e.g., supplier, production and distribution centers, customers), production facilities, material flow, and/or production output.

In order to address the delicate decision process for downsizing a supply chain facing financial difficulties, we define in Chapter 2 a SCDP under bankruptcy. The problem captures comprehensively demand management and debt payment in accordance with the decline of demand for the reconfiguration of a supply chain with one product. Compared with classical supply chain design problems, the SCDP under bankruptcy has five unique features:

- The SCDP under bankruptcy optimizes the closure of operation centers and the reduction of production capacities. While selling redundant facilities contributes cash generation, extra investment for adding new facilities to a supply chain network is unavailable because of financial constraint.
- By allowing reselection of customer and disregard of unprofitable demands, the SCDP under bankruptcy only allocates sufficient production capacity to demands which generate earnings.
- A multi-period planning is adopted for taking into account the execution time of downsizing decisions, the decline of machine values, the expected demand diversions and changes, and debt payment obligations.
- Cash flow is continuously observed for each planning period such that smooth daily operation and successful debt payment are not hindered.
- Robustness of profitability to uncertainties from operations, markets, and government policies is ensured.

In Chapter 2, we propose a downsizing MILP model for solving the SCDP under bankruptcy, which maximizes the utilization of investment resources through a combined operation of demand selection and production assets reallocation. Based on robust optimization techniques, we further develop robust counterparts to deal with uncertainties of demands and exchange rates. The numerical results confirm the validity of the proposed approach in delivering effective downsizing plans for cash release, profit generation and variation reduction, which leads to higher and sustainable economic value of an existing supply chain network. For related conference articles, interested readers might read Ashayeri et al. [2010] and Ma [2011]. For other literature addressing downsizing possibilities, interested readers might read Roodman and Schwarz [1975], Eppen et al. [1989], Melachrinoudis et al. [2005], and Melo et al. [2005]. While these supply chain configuration studies search downsizing solutions for advancing operation efficiencies, Huang et al. [2013] illustrate the use of a MILP model for reassessing the global manufacturing position of China through a case study. Because of the cost pressures caused by Chinese currency appreciation, rising labor costs, higher oil price and reduced value-added tax rebates, the study considers moving production operations from China to lower-cost Asian countries or to be near major markets, and removing the intermediate trade operations in Hong Kong.

In this chapter, we extend the SCDP under bankruptcy to a multi-product case, where additional options to cut certain product types are also included. In particular, here described SCDP under bankruptcy has following additional features when comparing with that of the previous chapter:

- There is more than one product. The products generate non-unique marginal profits depending on network configuration.
- Multi-functional machines are shared for manufacturing products of different types with various output rates. The machines represent alternative liquidities in case of capacity contraction.
- Products are substitutable. Namely, a customer with unmet demand may buy one, or more similar products which are available instead.

For viewing the dynamic combinatorial nature of the decisions involved in this problem, Figure 3.1 demonstrates how reduction in product types may interact with other downsizing decisions and influence the financial performance of the downsized supply chain. In particular, a reduced number of product types may result in a reduced production volume and an altered potential demand. The decline of production volume suggests capacity contraction. Available production capacities are reallocated along with network reconfiguration such that remaining product types are cost-efficiently produced, while unused capacities are sold for the cash generation. The new potential demand that results from the demand substitution impacts the network reconfiguration which in turn satisfies a part of the potential demand. Depending on how available capacities are reallocated, the served demand contributes to income. Since key financial elements, such as, income, cost, cash generation, and debt payment, determine actual cash flow

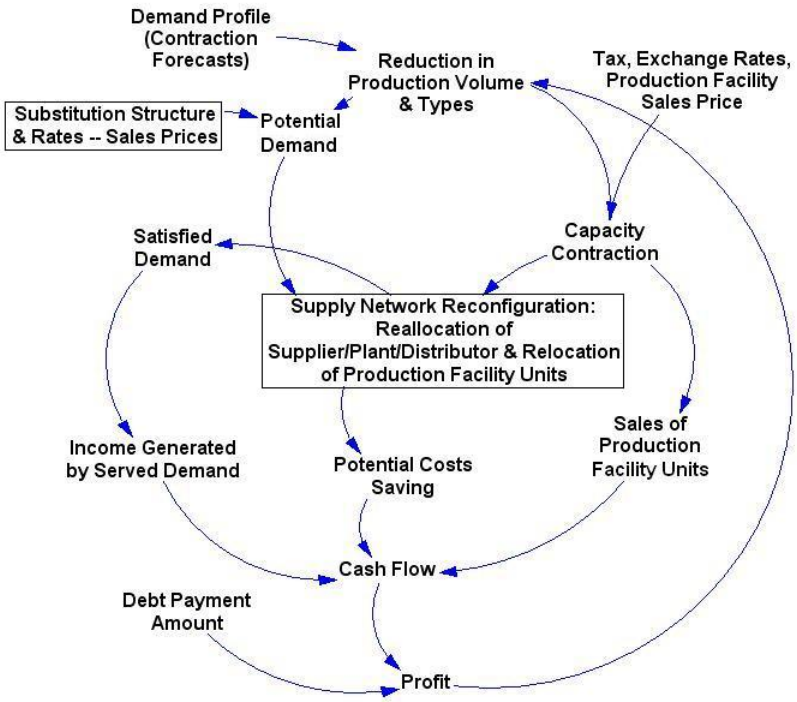


Figure 3.1: Causal loop of product type reduction.

and profit of the downsized supply chain, the downsizing optimization requires a wise choice of reduction in product types.

We propose a MILP model for solving the SCDP under bankruptcy of a multi-product supply chain network. Incorporated with the here introduced general formulation of demand substitution, the proposed MILP model for downsizing a multi-product supply chain facing bankruptcy risks is the first formulation of network design that allows *uneven* substitutions among products under investigation. In particular, we relate the commonly used substitution rate to the replacement rate of products and to the demand diversion rate of customers. A replacement rate is a factor that measures the change of demand quantity when a customer of an unavailable product diverts to a substitute. A demand diversion rate measures the proportion of customers of an unavailable product that diverts to a substitute. We also show the validity of the general substitution formulation for downsizing applications in the here described multi-product supply chain. However, our substitution formulation can also be used for other decision purposes such as inventory (product / component buffer stocks) allocation in a supply chain network or evaluating suppliers collaboration of a focal company. Finally, our numerical results confirm that the presented approach provides a valuable tool for analyzing downsizing processes.

The rest of the chapter is organized as follows. Section 3.2 introduces the multi-product downsizing MILP model for downsizing a multi-product supply chain facing financial difficulties. In Section 3.3 we derive the general formulation of demand substitution, and prove its validity for downsizing applications. Numerical results are discussed in Section 3.4, and a summary is given in Section 3.5.

3.2 The multi-product downsizing MILP model

In this section, we present the MILP model for solving a multi-product supply chain downsizing problem under bankruptcy. We consider downsizing a supply chain network facing financial difficulties over a multi-period planning horizon. The supply chain is owned by a transnational manufacturing company and consists of three levels of entities, which are suppliers, production and distribution centers. Their operation activities, involved costs, and profits can be briefly summarized as follows:

The company produces and supplies the market with more than one product, which are substitutable with each other. The manufacturing processes at production centers are conducted using multi-functional PFUs. A multi-functional PFU is a self sufficient production unit that can be used for producing more than one product. While multi-functional PFUs of various types are used for producing different ranges of products, their output rates differ depending on the product-PFU match. Therefore, the production capacity of a production center depends on the number and types of PFUs operating. Suppliers conduct subcontracted works and provide production centers with materials. Distribution centers are located at geographically separated regions and collect local demands.

Suppliers have no fixed overhead cost and only contribute purchasing costs to the supply chain network. A unit purchasing cost is assumed for each material and each supplier. Production and distribution centers are privately owned subsidiaries of the manufacturing company and pay taxes according to their local tax rates. Production centers generate profits by manufacturing and selling end products to distribution centers at predetermined internal transfer prices. The transfer prices are determined based on the local market prices of end products at distribution centers. An operating production center needs to pay a fixed overhead cost. A unit variable production cost is assumed for each product, and is a function of production center location considering the labor to be dominating variable cost for operating PFUs. Distribution centers generate profits by selling end products to customers at local market prices. Customer demands are assumed to be known with certainty for each distribution center, each product, and each planning period. An operating distribution center needs to pay a fixed overhead cost. However, variable costs at distribution centers are negligible. A unit transportation cost between a supplier and a production center is assumed for each material, and a unit transportation cost between a production center and a distribution center is assumed for each product. Transportation costs are always paid by the destination entities. Production centers carry certain amounts of predetermined debts for the purchase and installation of PFUs. The debt payments span finite periods and the planning horizon covers all debt periods.

Because of financial difficulties and anticipating future demand declines, the company decides to downsize the supply chain network in order to protect investments and ensure successful debt payments. The downsizing operations under consideration include customer reselection, reducing product types and production volumes, relocation and sale of PFUs, and closing production and distribution centers. The transfer of PFUs among production centers is always carried out at the beginning of a period. A transferred PFU cannot be utilized for a portion of the planning period because of the lead time and installation at the new location. Note that although in our downsizing case the transfer of PFUs is mainly justified by the limited investment possibilities for capacity adjustments, moving machines indeed happened in 80's, 90's, and even happens now for the "off-shoring" and "re-shoring" activities. A unit transportation cost between two production centers is assumed for each PFU. Transportation costs are always paid by the destination production center. A fixed capacity adjustment cost needs to be paid by the production center where the number of PFUs is changed. Redundant PFUs can be sold. For the simplicity of modeling, all sold PFUs are assumed to be transferred to a dummy facility buyer center. The dummy facility buyer center generates neither profits nor costs. A production center generates an income every time it sends a PFU to this dummy center. The income may vary depending on the location of the production center, the PFU type, and the time of selling reflecting the change of PFU values. A production center can only be closed after all PFUs are transferred out or sold. When shutting down a production center, all its debt payments need to be cleared. Closing penalty costs are charged when production and/or distribution centers are shut down. Production and distribution centers cannot be reopened once they are closed, although a production center with no PFU may remain open for reserving its facility location.

In what follows, Section 3.2.1 provides notation and definitions of decision variables used in the MILP model. Section 3.2.2 presents the MILP model along with its explanation.

3.2.1 Notation and definitions of decision variables

Index sets

$d \in \{1, \dots, D\}$	the index of a distribution center
$i \in \{1, \dots, I\}$	the index of a product type
$j \in \{1, \dots, J\}$	the index of a material type
$n \in \{1, \dots, N\}$	the index of a PFU type
$o \in \{1, \dots, O\}$	the index of a supplier
$p \in \{1, \dots, P\}$	the index of a production center (we use $P + 1$ as the index of the dummy facility buyer center)
$t \in \{1, \dots, T\}$	the index of a period in the planning horizon (we set $t = 0$ to indicate the initial status)
$y \in \{1, \dots, Y\}$	the index of a currency type ($Y \leq D + O + P$)

Costs and prices

b_{ip}	the variable production cost of production center p for producing one unit of product i
F^1_p	the fixed operation cost of production center p
F^2_d	the fixed operation cost of distribution center d
$g_{np\bar{p}}$	the transfer cost for delivering one PFU of type n from production center p to production center $\bar{p}$
G_p	the fixed capacity adjustment cost of production center p
K^1_p	the penalty cost for closing production center p
K^2_d	the penalty cost for closing distribution center d
q^1_{id}	the internal transfer price of one unit of product i purchased by distribution center d
q^2_{id}	the revenue of selling one unit of product i at distribution center d
R_{npt}	the sales price of one PFU of type n at production center p in period t
s_{oj}	the purchasing price of one unit material j at supplier o
tr^1_{opj}	the transportation cost for delivering one unit material j from supplier o to production center p

tr^2_{ipd} the transportation cost for delivering one unit of product i from production center p to distribution center d

σ a fixed portion of PFU not available due to the lead time and installation of transferred PFUs

Rates and taxes

E_y the exchange rate of y currency to the numeraire country's currency

r the discount rate

tax^1_p the tax rate at production center p

tax^2_d the tax rate at distribution center d

Other parameters

C_{np0} the number of PFUs of type n in production center p at the beginning of planning horizon

L_{pt} the predetermined debt payment of production center p in period t

m_{ij} the number of units of material j that are needed to produce one unit of product i

M a constant that is larger than $\max_{d,t}\{\sum_{i=1}^{I} Q_{idt}\}$

Q_{idt} the forecasted demand of product i at distribution center d in period t

S_{oj} the maximum supply quantity of material j at supplier o

u_{in} the fraction of the unit capacity of PFU type n that is utilized for producing one unit of product i

Decision variables

$$Z_{pt} = \begin{cases} 1, & \text{if the production capacity of production center } p \text{ is changed in period } t \\ 0, & \text{otherwise} \end{cases}$$

$$B_{pt} = \begin{cases} 1, & \text{if the production center } p \text{ has positive production capacity in period } t \\ 0, & \text{otherwise} \end{cases}$$

$$A_{dt} = \begin{cases} 1, & \text{if the distribution center } d \text{ operates in period } t \\ 0, & \text{otherwise} \end{cases}$$

$X_{np\bar{p}t} \in \mathbb{N}_0$ the number of PFUs of type n transferred from production center p to production center $\bar{p}$ in period t

$V_{ipdt} \in \mathbb{N}_0$ the amount of product i delivered from production center p to distribution center d in period t

$W_{opjt} \in \mathbb{N}_0$ the amount of material j delivered from supplier o to production center p in period t

$C_{npt} \in \mathbb{N}_0$ the number of PFUs of type n located at production center p in period t

$\mathrm{ERevP}^{+}_{pt} \in \mathbb{R}_+$ the positive revenue of production center p in period t in the numeraire country's currency

$\mathrm{ERevP}^{-}_{pt} \in \mathbb{R}_+$ the loss (negative revenue) of production center p in period t in the numeraire country's currency

$\mathrm{RevD}^{+}_{dt} \in \mathbb{R}_+$ the positive revenue of distribution center d in period t in the local currency

$\mathrm{RevD}^{-}_{dt} \in \mathbb{R}_+$ the loss of distribution center d in period t in the local currency,

where $\mathbb{N}_0 = \mathbb{N} \cup \{0\}$ and $\mathbb{R}_+ = \{x \in \mathbb{R} : x \geq 0\}$.

3.2.2 Formulation

The multi-product downsizing MILP model is formulated as follows:

$$\begin{aligned}\text{Maximize} \sum_{t=1}^{T} r^{t-1} \Big\{ & \sum_{p=1}^{P} [(1-\mathrm{tax}^1_p)\mathrm{ERevP}^{+}_{pt} - \mathrm{ERevP}^{-}_{pt}] \\ & + \sum_{d=1}^{D} E_{y_d}[(1-\mathrm{tax}^2_d)\mathrm{RevD}^{+}_{dt} - \mathrm{RevD}^{-}_{dt}] \Big\} \end{aligned} \tag{3.1}$$

Subject to:

$$\sum_{p=1}^{P} V_{ipdt} \leq Q_{idt} \qquad \forall i, d, t \tag{3.2}$$

$$\sum_{o=1}^{O} W_{opjt} \geq \sum_{i=1}^{I} \sum_{d=1}^{D} m_{ij} V_{ipdt} \qquad \forall p, j, t \tag{3.3}$$

$$\sum_{p=1}^{P} W_{opjt} \leq S_{oj} \qquad \forall o, j, t \tag{3.4}$$

$$\sum_{i=1}^{I}\sum_{d=1}^{D} u_{in} V_{ipdt} \leq C_{npt} - \sigma \sum_{\bar{p}=1}^{P} X_{n\bar{p}pt} \qquad \forall n,p,t \qquad (3.5)$$

$$C_{npt} = C_{np(t-1)} + \sum_{\bar{p}=1}^{P} X_{n\bar{p}pt} - \sum_{\bar{p}=1}^{P+1} X_{np\bar{p}t} \qquad \forall n,p,t \qquad (3.6)$$

$$\mathrm{M} \cdot Z_{pt} \geq \sum_{n=1}^{N} (\sum_{\bar{p}=1}^{P} X_{n\bar{p}pt} + \sum_{\bar{p}=1}^{P+1} X_{np\bar{p}t}) \qquad \forall p,t \qquad (3.7)$$

$$\mathrm{M} \cdot B_{pt} \geq \sum_{n=1}^{N} C_{npt} \qquad \forall p,t \qquad (3.8)$$

$$\mathrm{M} \cdot A_{dt} \geq \sum_{i=1}^{I}\sum_{p=1}^{P} V_{ipdt} \qquad \forall d,t \qquad (3.9)$$

$$\begin{aligned}
&\sum_{n=1}^{N} E_{y_p} R_{npt} X_{np(P+1)t} - \sum_{n=1}^{N}\sum_{\bar{p}=1}^{P} E_{y_p} X_{n\bar{p}pt} g_{n\bar{p}p} \\
&+ \sum_{i=1}^{I}\sum_{d=1}^{D} V_{ipdt}(E_{y_d} q^1_{id} - E_{y_p} b_{ip}) - \sum_{o=1}^{O}\sum_{j=1}^{J} W_{opjt}(E_{y_o} s_{oj} \\
&+ E_{y_p} tr^1_{opj}) - E_{y_p} B_{pt}(F^1_p + \mathrm{L}_{pt}) - E_{y_p} Z_{pt} G_p - E_{y_p}(B_{p(t-1)} \\
&- B_{pt})(K^1_p + \sum_{\bar{t}=t}^{T} r^{\bar{t}-t} \mathrm{L}_{p\bar{t}}) \geq \mathrm{ERevP}^+_{pt} - \mathrm{ERevP}^-_{pt} \qquad \forall p,t \qquad (3.10)
\end{aligned}$$

$$\begin{aligned}
&\sum_{i=1}^{I}\sum_{p=1}^{P} V_{ipdt}(q^2_{id} - q^1_{id} - tr^2_{ipd}) - A_{dt} F^2_d - (A_{d(t-1)} - A_{dt}) K^2_d \\
&\geq \mathrm{RevD}^+_{dt} - \mathrm{RevD}^-_{dt} \qquad \forall d,t \qquad (3.11)
\end{aligned}$$

$$A_{dt} \geq A_{d(t+1)} \qquad \forall d, t = \{1, \ldots, T-1\} \qquad (3.12)$$

$$B_{pt} \geq B_{p(t+1)} \qquad \forall p, t = \{1, \ldots, T-1\} \qquad (3.13)$$

$$B_{p0} = A_{d0} = 1, \qquad \forall p,d \qquad (3.14)$$

$$\begin{aligned}
&X_{np\bar{p}t}, V_{ipdt}, W_{opjt}, C_{npt} \in \mathbb{N}_0, \\
&\mathrm{ERevP}^+_{pt}, \mathrm{ERevP}^-_{pt}, \mathrm{RevD}^+_{dt}, \mathrm{RevD}^-_{dt} \in \mathbb{R}_+, \\
&Z_{pt}, B_{pt}, A_{dt} \in \{0,1\}. \qquad (3.15)
\end{aligned}$$

The objective (3.1) maximizes the TDNP over the planning horizon. Note that the inclusion of currency exchange and tax rates may play an important role in the network reconfiguration and be a driver for the transfer of PFUs in real-life downsizing applications. Constraint (3.2) requires that the total supply of product i from production centers in period t to distribution center d is no more than the demand of product i at distribution center d in period t. Note that the here described SCDP focuses on surviving financial obstacles. Penalty costs are not charged for intentionally forgoing demands. Constraint (3.3) requires that the total supply of raw material j in period t

to production center p is greater or equal to the demand of material j at production center p in period t. Constraint (3.4) requires that the total demand of raw material j in period t at supplier o cannot be more than the capacity of supplier o. Constraint (3.5) requires that the production volume of products at production center p does not exceed the production capacity of production center p in period t for each PFU type. Constraint (3.6) balances production capacity between periods for each PFU type, while (3.7) forces Z_{pt} to be equal to one when there is any adjustment of assigned PFUs at production center p in period t. Constraint (3.8) forces B_{pt} to be equal to one when there is any PFU located at production center p in period t. Constraint (3.9) forces A_{dt} to be equal to one as long as the distribution center d is supplied with any product in period t. Note that when a production center p in a particular period t is kept open, i.e. $B_{pt} = 1$ and $C_{npt} = 0$, then the facility location is temporary reserved for possible future period use when demand raises. Constraint (3.10) is the revenue (or loss) of production center p in period t in the numeraire country's currency. Constraint (3.11) is the revenue (or loss) of distribution center d in period t in its local currency. Constraint (3.12) (resp. (3.13)) guarantees that distribution (resp. production) centers cannot be reopened after closing. Constraint (3.14) ensures that all production and distribution centers are operating at the beginning of the planning horizon.

3.3 MILP model and new substitution formulation

Downsizing a supply chain often results in unsatisfied demands. While unsatisfied demand can divert and be fulfilled by another similar product in the market, a supply chain of multiple substitutable products may face a shifted demand when it is downsized. Depending on the substitutability among products, the resulted demand is largely influenced by downsizing decisions. In this section, we extend the multi-product downsizing MILP model (3.1)–(3.15) with demand substitution such that the applied downsizing operations will be consistent with the realized demand.

Substitution effects have been recognized and studied for decades. Numerous research topics in supply chain management, logistics, production, operations management, and economics are related to substitution. Among vast literature, demand (or product) substitution has been often considered by assortment problems, lot-sizing problems with substitution, or capacity investment and planning decisions. The assortment problem, as defined by Pentico [2008], involves the selection of the sizes or qualities of the final products. Demands for an unstocked size can be filled with another size which is available, with an associated substitution cost. The substitution cost concerns marginal cost differences and may also contain the conversion cost for transforming available products into products formats that customer desires. Lang [2010] provides an extensive discussion on lot-sizing problems with substitution. The substitution under consideration can refer to the replacement of demands for unstocked finished products or to the flexible bill-of-material related to parts and semi-finished products. On the economics side, capacity investment and planning decisions concern the impacts of demand substitution on product pricing and on the value of production flexibility. For example, Karakul and Chan [2008] provide an analytical study of the influence of product substitutability on the joint pricing and procurement decisions of two different products. Lus and Muriel [2009] study the optimal investment mix in flexible and dedicated capacities and find out that the optimal investment in manufacturing flexibility tends to decrease as products become more substitutable.

Quantitative models like MILP continue to play a very important role for building a more realistic combination of key supply chain network entities like supplier, manufacturing and distribution units, and financial elements such as debt, added costs, tax and currency exchange rates. To the best of our knowledge, Eppen et al. [1989] is the only paper that considers demand substitution for capacity planning using MILP. They present a scenario-based MILP model for GM capacity planning. The MILP model considers applying capacity adjustment while products are substitutable. While assuming that individual demands diverse between substitutable products, the authors require that the replacement rate between any two products is always equal to one and that all diverted demands need to be satisfied. However, in general, unprofitable demands may be disregarded and the replacement rate does not have to be always equal to one. For example, when a 200 grams chocolate pack is unavailable, the demand may be diverted to two 100 grams chocolate packs. In this case, the replacement rate is 2. Such an uneven substitution often happens in commodity market especially when it is combined with promotion events.

The demand quantity of a product is determined by the number of customers and their average purchase quantity. The change of demand quantities caused by demand substitution also depends on the diversion rate of demand from one product to another as well as the replacement rate between these two substitutable products.

Our generalized substitution matrix, $Y \in \mathbb{R}^{I \times I}$, is defined as

$$Y := \begin{pmatrix} S_{11}H_{11} & S_{12}H_{12} & \dots & S_{1I}H_{1I} \\ S_{21}H_{21} & S_{22}H_{22} & \dots & S_{2I}H_{2I} \\ \vdots & \vdots & \ddots & \vdots \\ S_{I1}H_{I1} & S_{I2}H_{I2} & \dots & S_{II}H_{II} \end{pmatrix}, \tag{3.16}$$

where the substitution rate $Y_{ik} := S_{ik}H_{ik}$ specifies the change of demand quantity of product i when demand of one unit of product k is not satisfied. S_{ik} and H_{ik} stand for *the replacement rate* and *the demand diversion rate* from product k to product i respectively. Without loss of generality, we assume that products of the multi-product SCDP under consideration cannot be separated into independent subgroups where substitution only happens inside each subgroup. We define $S := e(e^{-1})^T$, where $e \in \mathbb{R}^I_+$ and $(e^{-1})_i := e_i^{-1}$. Here, e_i stands for the replacement rate of the numeraire product to product i. The matrix S has the following properties:

- $S_{ik} > 0, \qquad \forall i, k \in \{1, \ldots, I\}$
- $S_{ii} = 1, \qquad \forall i \in \{1, \ldots, I\}$
- $S_{ik}S_{ki} = 1, \qquad \forall i, k \in \{1, \ldots, I\}$
- $S_{ik} = S_{il}S_{lk}, \qquad \forall i, k, l \in \{1, \ldots, I\}$.

In the case that there are two or more mutually independent subgroups of substitutable products, each of the group of products can be studied independently.

There may be a list of products that can fulfill the same demand of a customer. Without loss of generality, we assume that in case $H_{ik} > 0$ for some $i, k \in \{1, \ldots, I\}$, the demand diversion rate H_{ik} of unsatisfied customers of product k take product i as their second choice. H has the following properties:

- $H_{ik} \in [0, 1], \qquad \forall i, k \in \{1, \ldots, I\}$
- $H_{ii} = 0, \qquad \forall i \in \{1, \ldots, I\}$
- $\sum_{k=1}^{I} H_{ki} \leq 1, \qquad \forall i \in \{1, \ldots, I\}$.

Note that demands of a group of products can be interdependent, i.e., a group of products may require a combined usage. An unsatisfied demand of one of the products brings down demands of the rest products of the group, and an increased demand of one of them brings up the demands of the rest products of the group. By considering the group of interdependent products as one united product, our proposed formulation can take into account the demand correlation between products.

Let $\nu^+_{idt} \in \mathbb{N}_0$ (resp. $\nu^-_{idt} \in \mathbb{N}_0$) be the unsatisfied demand (resp. the oversupply) of product i at distribution center d in period t, the multi-product downsizing MILP model with demand substitution (downsizing MILPds) can be derived by replacing constraint (3.2) of the downsizing MILP with the following two constraints:

$$\sum_{p=1}^{P} V_{ipdt} + \nu_{idt}^{+} - \nu_{idt}^{-} = Q_{idt} \qquad \forall i, d, t, \tag{3.17}$$

$$\nu_{idt}^{-} \leq \sum_{k=1}^{I} Y_{ik} \nu_{kdt}^{+} \qquad \forall i, d, t. \tag{3.18}$$

Constraint (3.17) allows the total supply of product i to differ from its expected demand at distribution center d in period t. Constraint (3.18) requires that the oversupply of product i is less than or equal to the diverted demand from other products. Note that constraints (3.17) and (3.18) together result with relaxed substitution formulation of that of Eppen et al. [1989] (see page 521), where diverted demands are allowed to be unsatisfied. Depending on the choice of production center and transportation route, profit margins of demands can differ from case to case even for the same product. By allowing unsatisfied demands, a company facing financial difficulty can choose to produce less than demand and serve only profitable demands such that higher profit can be generated with lower costs.

An alternative formulation of downsizing MILPds can be derived following the reallocation of demands among products. Let $\upsilon_{ikdt} \in \mathbb{R}_{+}$ be the shifted demand from product k to product i at distribution center d and period t. Then, we can introduce the following constraints:

$$\sum_{p=1}^{P} V_{ipdt} \leq Q_{idt} + \sum_{k=1}^{I} S_{ik} \upsilon_{ikdt} - \sum_{k=1}^{I} \upsilon_{kidt} \qquad \forall i, d, t, \tag{3.19}$$

$$\upsilon_{ikdt} = H_{ik} \sum_{l=1}^{I} \upsilon_{lkdt} \qquad \forall i, k, d, t. \tag{3.20}$$

Constraint (3.19) balances the shifted demand of each products according to product replacement rates. Constraint (3.20) guarantees that demands are diverted according to demand diversion rates. Here, we do not implement the formulation of downsizing MILPds with constraints (3.19) and (3.20) since it is more computationally demanding than the one that includes (3.17) and (3.18).

Since demand quantities can change after substitution, it is important to show that the total supply of products is bounded. By analyzing constraints (3.17) and (3.18), we conclude the following properties of the downsizing MILPds (3.1), (3.3)–(3.15), (3.17)–(3.18).

Lemma 3.1. *For a feasible point of the downsizing MILPds (3.1), (3.3)–(3.15), (3.17)–(3.18), we have:*

$$\sum_{i=1}^{I}\sum_{p=1}^{P} V_{ipdt} \leq \sum_{i=1}^{I} Q_{idt} + (\sum_{i=1}^{I}\sum_{k=1}^{I} Y_{ik}\nu^{+}_{kdt} - \sum_{i=1}^{I}\nu^{+}_{idt}) \qquad \forall d, t.$$

Proof. Let V^*_{ipdt}, ${\nu^+_{idt}}^*$, ${\nu^-_{idt}}^*$ be feasible for the downsizing MILPds (3.1), (3.3)–(3.15), (3.17)–(3.18). Based on constraints (3.17) and (3.18), we have $\sum_{p=1}^{P} V^*_{ipdt} + {\nu^+_{idt}}^* - {\nu^-_{idt}}^* = Q_{idt}$ and ${\nu^-_{idt}}^* \leq \sum_{k=1}^{I} Y_{ik}{\nu^+_{kdt}}^*$ for all i, d, t, from where it follows the proof. □

For the case that all $S_{ik} = 1$, $\forall i, k \in \{1, \ldots, I\}$, we have the following results.

Lemma 3.2. *Suppose that in the downsizing MILPds (3.1), (3.3)–(3.15), (3.17)–(3.18), the replacement rate $S_{ik} = 1$, $\forall i, k \in \{1, \ldots, I\}$. Then the sum of unsatisfied demands is always larger than or equal to the sum of diverted demands for all d and t.*

Proof. Let ${\nu^+_{idt}}^*$ be feasible for the downsizing MILPds (3.1), (3.3)–(3.15), (3.17)–(3.18). When $S_{ik} = 1$, $\forall i, k \in \{1, \ldots, I\}$, we have $Y = H$. Hence, $\sum_{k=1}^{I} Y_{ki} \leq 1, \forall i \in \{1, \ldots, I\}$, which gives $\sum_{i=1}^{I} {\nu^+_{idt}}^* \geq \sum_{i=1}^{I}\sum_{k=1}^{I} Y_{ik}{\nu^+_{kdt}}^* \; \forall d, t.$ □

Lemma 3.3. *Suppose that in the downsizing MILPds (3.1), (3.3)–(3.15), (3.17)–(3.18), the replacement rate $S_{ik} = 1$, $\forall i, k \in \{1, \ldots, I\}$. Then the total supply of products to distribution center d in period t is less than or equal to its demand in period t.*

Proof. Let V^*_{ipdt} and ${\nu^+_{idt}}^*$ be feasible for the downsizing MILPds (3.1), (3.3)–(3.15), (3.17)–(3.18). From Lemma 3.1 and the fact that $\sum_{i=1}^{I} {\nu^+_{idt}}^* \geq \sum_{i=1}^{I}\sum_{k=1}^{I} Y_{ik}{\nu^+_{kdt}}^*$ for all d and t, it follows $\sum_{i=1}^{I}\sum_{p=1}^{P} V^*_{ipdt} \leq \sum_{i=1}^{I} Q_{idt}$, $\forall d, t$. □

It follows from the previous lemma that the total supply of products to a distribution center is bounded by its demands before substitution.

If there exists $S_{ik} > 1$ for some $i, k \in \{1, \ldots, I\}$, we have the following results.

Proposition 3.4. *Suppose that in the downsizing MILPds (3.1), (3.3)–(3.15), (3.17)–(3.18), the replacement rate $S_{ik} > 1$ for some $i, k \in \{1, \ldots, I\}$. Then*

$$\sum_{i=1}^{I}\sum_{k=1}^{I} Y_{ik}\nu^{+}_{kdt} - \sum_{i=1}^{I}\nu^{+}_{idt} \leq (\alpha - 1)\sum_{i=1}^{I} Q_{idt} \qquad \forall d, t,$$

where $\alpha := e_I e_1^{-1}$ is the largest replacement rate in S, assuming that $e_1 \leq e_2 \leq \ldots \leq e_I$.

Proof. From constraints (3.17) and (3.18), the following is satisfied for all feasible points of the downsizing MILPds (3.1), (3.3)–(3.15), (3.17)–(3.18):

$$\nu^{+}_{idt} \leq Q_{idt} + \sum_{k=1}^{I} Y_{ik}\nu^{+}_{kdt} \qquad \forall i, d, t. \tag{3.21}$$

In order to find the maximum value of $\sum_{i=1}^{I}\sum_{k=1}^{I} Y_{ik}\nu^{+}_{kdt} - \sum_{i=1}^{I}\nu^{+}_{idt}$ for all d and t, subject to (3.21), we formulate the following problem:

$$\begin{aligned}
\text{Maximize} \qquad & \sum_{i=1}^{I}\sum_{k=1}^{I} Y_{ik}\nu^{+}_{kdt} - \sum_{i=1}^{I}\nu^{+}_{idt} \\
\text{s.t.} \quad & \nu^{+}_{idt} - \sum_{k=1}^{I} Y_{ik}\nu^{+}_{kdt} \leq Q_{idt} \qquad \forall i \\
& \nu^{+}_{idt} \in \mathbb{R}_{+}.
\end{aligned}$$

This optimization problem can be reformulated in a vector form as follows:

$$\begin{aligned}
\text{Maximize} \qquad & u^{\mathsf{T}}(Y - \mathcal{I})\nu^{+}_{dt} \\
\text{s.t.} \quad & (\mathcal{I} - Y)\nu^{+}_{dt} \leq Q_{dt} \\
& \nu^{+}_{dt} \in \mathbb{R}^{I}_{+},
\end{aligned} \tag{3.22}$$

where u is an all-one vector, $\mathcal{I}$ the identity matrix, and $\nu^{+}_{dt} = \left(\nu^{+}_{1dt}, \ldots, \nu^{+}_{Idt}\right)^{\mathsf{T}}$, $Q_{dt} = (Q_{1dt}, \ldots, Q_{Idt})^{\mathsf{T}}$. Without loss of generality, we assume that e_i is sorted in an ascending order and the substitution matrix is defined as:

$$Y := \begin{pmatrix}
0 & \frac{e_1}{e_2}H_{12} & \frac{e_1}{e_3}H_{13} & \cdots & \frac{e_1}{e_I}H_{1I} \\
\frac{e_2}{e_1}H_{21} & 0 & \frac{e_2}{e_3}H_{23} & \cdots & \frac{e_2}{e_I}H_{2I} \\
\frac{e_3}{e_1}H_{31} & \frac{e_3}{e_2}H_{32} & 0 & & \vdots \\
\vdots & \vdots & & \ddots & \frac{e_{I-1}}{e_I}H_{(I-1)I} \\
\frac{e_I}{e_1}H_{I1} & \frac{e_I}{e_2}H_{I2} & \cdots & \frac{e_I}{e_{I-1}}H_{I(I-1)} & 0
\end{pmatrix}.$$

Here H_{ik} is the demand diversion rate defined in 3.16. The dual problem of the maximization problem 3.22 is

$$\begin{aligned}
\text{Minimize} \qquad & h^{\mathsf{T}}Q_{dt} \\
\text{s.t.} \quad & (h + u)^{\mathsf{T}}(\mathcal{I} - Y) \geq 0 \\
& h \geq 0.
\end{aligned}$$

It is clear that $h = \left(\frac{e_I}{e_1} - 1, \frac{e_I}{e_2} - 1, \ldots, \frac{e_I}{e_{I-1}} - 1, 0\right)^\intercal$ is a feasible solution of the dual problem, such that

$$(h+u)^\intercal(\mathcal{I} - Y) \geq \begin{pmatrix} \frac{e_I}{e_1} - \sum_{k=1}^{I} \frac{e_I}{e_1} H_{k1} \\ \frac{e_I}{e_2} - \sum_{k=1}^{I} \frac{e_I}{e_2} H_{k2} \\ \vdots \\ \frac{e_I}{e_{I-1}} - \sum_{k=1}^{I} \frac{e_I}{e_{I-1}} H_{k(I-1)} \\ 1 - \sum_{k=1}^{I} H_{kI} \end{pmatrix} \geq 0.$$

Let α be the largest replacement rate of S, i.e., $\alpha = e_I e_1^{-1}$. Based on the duality theorem, we know that for all d and t:

$$\sum_{i=1}^{I}\sum_{k=1}^{I} Y_{ik}\nu_{kdt}^{+} - \sum_{i=1}^{I} \nu_{idt}^{+} \leq \sum_{i=1}^{I} (\frac{e_I}{e_i} - 1) Q_{idt} \leq (\alpha - 1) \sum_{i=1}^{I} Q_{idt}$$

□

Lemma 3.5. *Suppose that in the downsizing MILPds (3.1), (3.3)–(3.15), (3.17)–(3.18), the replacement rate $S_{ik} > 1$ for some $i, k \in \{1, \ldots, I\}$. Then the total supply of products to distribution center d in period t is less than or equal to the product of the largest replacement rate of S and its demand in period t.*

Proof. Let V_{ipdt}^* and $\nu_{idt}^{+\,*}$ be feasible for the downsizing MILPds (3.1), (3.3)–(3.15), (3.17)–(3.18). From Lemma 3.1 and Proposition 3.4, it follows $\sum_{i=1}^{I} \sum_{p=1}^{P} V_{ipdt}^* \leq \alpha \sum_{i=1}^{I} Q_{idt}$, $\forall d, t$. □

It follows from the previous lemma that the constant "M" of the downsizing MILPds should be larger than $\max_{d,t}\{\alpha \sum_{i=1}^{I} Q_{idt}\}$. In the following section, we numerically validate both the downsizing multi-product MILP and MILPds.

3.4 Numerical results

In this section, we test our proposed approach with systematically generated cases and discuss the obtained results. Section 3.4.1 presents the data generation method. Section 3.4.2 and 3.4.3 discuss the obtained test results of the downsizing multi-product MILP and MILPds respectively.

3.4.1 Data generation

All test cases are systematically generated using a realistic value added model in the network, departing from the final product value based on which constructing costs/values added at each echelon. To be specific, we construct each test case for the multi-product SCDP with four steps as follows:

(a) Products generation: First, we define the total number of products, raw materials, and PFU types involved in a multi-product supply chain network. We specify the product-material combination and the product-PFU combination. The former indicates the requirement rates of raw materials for producing one unit of a certain product. The latter indicates the usage rates of PFUs for producing one unit of a certain product. We allocate two randomly generated values to each raw material type. The two values represent value bases of purchasing and transportation costs of a raw material respectively. By summing the purchasing value bases of raw materials according to the product-material combination, we obtain the product value seeds of all product types. For each product type, the value bases of production and transportation costs, product profits, internal transfer and market prices are determined as factors of its product value seed. The value bases define the cost structure of the multi-product supply chain for further generation.

(b) Network specifics generation: We initiate a fixed number of available suppliers, production centers, and distribution centers. By adding a random adjustment to the value base of each parameter, we derive specifics of a multi-product supply chain network. The random adjustment is a value that is randomly drawn from the uniform distribution. In order to avoid the complexity of data generation, we assume that variable labor cost is dominant, and therefore variable production cost is plant dependent only. Furthermore, fixed operation costs, closing penalty costs, and fixed capacity adjustment costs (mainly the costs of changing facilities layout), are defined as factors of the sum of product profit bases. Therefore, their values vary with the number of products involved and are plant dependent only. PFU values and transfer costs are defined as factors of the average of product profit bases, and the factor decreases when the number of PFU types increases. In another words, the more PFU types, the more likely the machine market is under a severe competition, and hence the lower the machine values. This way, PFU values and transfer costs vary with the number of PFU types but are independent of the number of product types. Here, we also generate demand volumes of products at each distribution center, raw material supply limitation of suppliers, exchange rates, and discount rate.

(c) Network determination: An optimization model derived from the multi-product downsizing MILP model is used to select production centers and suppliers, and to determine the optimal production capacity allocation, such that all demands of distribution centers can be satisfied with minimum operation costs. We refer to the corresponding optimization model as the initial multi-product MILP, see (3.23)–(3.34). Given the fact that distributions are treated as demand centers which generate demands, all distribution centers are opened in every generated case.

(d) Demand reduction: Finally, we assume that economic downtrend strikes the market in the second period of the planning horizon and a demand decline is expected to last for the next six periods for each product type. Managers of the optimized supply chain realize this change and would like to downsize the supply chain such that the investment is protected for the remaining nine periods. To reduce the six periods demands of a certain product at a distribution center, a fraction is randomly drawn from the uniform distribution $U(0, 0.9)$. By doing so we obtain a downsizing case with a planning horizon of nine periods. We refer to the remaining nine periods as the downsizing periods.

The initial multi-product MILP model, derived from the multi-product downsizing MILP model (3.1)–(3.15), looks for the optimal initial capacity allocation between potential production centers. Its formulation follows the same cost assumptions as the multi-product downsizing MILP, and uses following redefined parameters and variables:

Costs and prices

$$R_{np} = R_{np1} \quad \text{the purchasing cost of one PFU of type } n$$

Decision variables

$C_{np} \in \mathbb{N}_0$ the number of PFU of type n assigned to production center p

$$B_p = \begin{cases} 1, & \text{if the production center } p \text{ is open} \\ 0, & \text{otherwise.} \end{cases}$$

The initial multi-product MILP model is formulated as follows:

$$\begin{aligned}\text{Maximize} \sum_{t=1}^{T} r^{t-1} \Big\{ &\sum_{p=1}^{P} [(1-\text{tax}_p^1)\text{ERevP}_{pt}^{+} - \text{ERevP}_{pt}^{-}] \\ &+ \sum_{d=1}^{D} E_{y_d}[(1-\text{tax}_d^2)\text{RevD}_{dt}^{+} - \text{RevD}_{dt}^{-}] \Big\} \end{aligned} \tag{3.23}$$

Subject to:

$$\sum_{p=1}^{P} V_{ipdt} = Q_{idt} \qquad \forall i,d,t \in \{2,\dots,T\} \tag{3.24}$$

$$\sum_{p=1}^{P} V_{ipdt} \le Q_{idt} \qquad \forall i,d,t=1 \tag{3.25}$$

$$\sum_{o=1}^{O} W_{opjt} \ge \sum_{i=1}^{I}\sum_{d=1}^{D} m_{ij} V_{ipdt} \qquad \forall p,j,t \tag{3.26}$$

$$\sum_{p=1}^{P} W_{opjt} \le S_{oj} \qquad \forall o,j,t \tag{3.27}$$

$$\sum_{i=1}^{I}\sum_{d=1}^{D} u_{in} V_{ipdt} \le C_{np} \qquad \forall n,p,t \in \{2,\dots,T\} \tag{3.28}$$

$$\sum_{i=1}^{I}\sum_{d=1}^{D} u_{in} V_{ipdt} \le (1-\sigma) C_{np} \qquad \forall n,p,t=1 \tag{3.29}$$

$$\text{M} \cdot B_p \ge \sum_{n=1}^{N} C_{np} \qquad \forall p \tag{3.30}$$

$$\begin{aligned}&\sum_{i=1}^{I}\sum_{d=1}^{D} V_{ipdt}(E_{y_d} q_{id}^1 - E_{y_p} b_{ip}) - \sum_{o=1}^{O}\sum_{j=1}^{J} W_{opjt}(E_{y_o} s_{oj} + E_{y_p} tr_{opj}^1) \\ &-E_{y_p} B_p F_p^1 \ge \text{ERevP}_{pt}^{+} - \text{ERevP}_{pt}^{-} \qquad \forall p, t \in \{2,\dots,T\}\end{aligned} \tag{3.31}$$

$$\begin{aligned}&\sum_{i=1}^{I}\sum_{d=1}^{D} V_{ipdt}(E_{y_d} q_{id}^1 - E_{y_p} b_{ip}) - \sum_{o=1}^{O}\sum_{j=1}^{J} W_{opjt}(E_{y_o} s_{oj} + E_{y_p} tr_{opj}^1) \\ &-E_{y_p} B_p F_p^1 - E_{y_p}(\sum_{n=1}^{N} C_{np} R_{np} + B_p G_p) \ge \text{ERevP}_{pt}^{+} - \text{ERevP}_{pt}^{-} \qquad \forall p, t=1\end{aligned} \tag{3.32}$$

$$\sum_{i=1}^{I}\sum_{p=1}^{P} V_{ipdt}(q_{id}^2 - q_{id}^1 - tr_{ipd}^2) - F_d^2 \ge \text{RevD}_{dt}^{+} - \text{RevD}_{dt}^{-} \qquad \forall d,t \tag{3.33}$$

$$\begin{aligned}&V_{ipdt}, W_{opjt}, C_{np} \in \mathbb{N}_0, \\ &\text{ERevP}_{pt}^{+}, \text{ERevP}_{pt}^{-}, \text{RevD}_{dt}^{+}, \text{RevD}_{dt}^{-} \in \mathbb{R}_{+}, \\ &B_p \in \{0,1\}.\end{aligned} \tag{3.34}$$

The objective (3.23) maximizes the TDNP over the planning horizon. Constraint (3.24) requires that total supply of product i to distribution center d is equal to its demand in period $t = 2, \ldots, T$, while (3.25) allows less supply of product i than demand at distribution center d in period $t = 1$. We assume that the lead time and installation of machines takes a fixed portion of the time unit and suggests insufficient production capacity in the first period. Constraint (3.26) requires that the total supply of material j to production center p is greater or equal to the demand of material j at production center p in period t, while (3.27) requires that the supply of material j from supplier o should not exceed its capacity. Constraint (3.28) and (3.29) require that the production volume of products at production center p in period t should not exceed its production capacity for each PFU type. Constraint (3.30) forces B_p to be equal to one when there is any PFU assigned to production center p. Constraint (3.31) (resp. (3.32)) is the revenue (or loss) of production center p in period $t = 2, \ldots, T$ (resp. $t = 1$) in the numeraire country's currency. Note that we consider the PFU purchasing and capacity adjustment costs in the first period for the opening of a production center. Constraint (3.33) is the revenue (or loss) of distribution center d in period t in its local currency.

3.4.2 Numerical results of multi-product downsizing MILP

We test the multi-product downsizing MILP model (3.1)–(3.15) with 48 generated downsizing cases. All downsizing cases are solved by CPLEX using AIMMS interface, running on a PC with Intel Core2 Quad CPU, 2.66GHz, and 3.21GB of memory. The computation results are listed in Table 3.1. While most of the downsizing operations are planned in the first downsizing period, we present the value after a "+" sign to indicate that downsizing operations are planned in a later downsizing period. The number in parentheses provides the period when the downsizing operations take place.

The columns two to five of Table 3.1 specify the following features of downsizing cases: the number of PFU types, the number of product types, the number of current PFUs, and the number of current production centers, respectively. The column six provides the computation time for solving the multi-product downsizing MILP model. The columns seven to ten specify the downsizing results: the number of PFUs sold, the number of PFUs moved, the number of production centers closed, the number of distribution centers closed, and the increase of TDNP (in percentage) relative to that obtained when no downsizing operation is applied, respectively.

Based on Table 3.1, we have the following remarks:

TABLE 3.1: Results for 48 downsizing cases.

Case	♯ of PFU types	♯ of prod. types	♯ of PFUs	♯ of prod. centers	Comp. time (s)	Downsizing MILP results				
						♯ PFUs sold	♯ PFUs moved	♯ prod. centers closed	♯ dist. centers closed	TDNP increase (%)
3.1	1	1	18	7	8	5	0	1	+4(8)	3.5
3.2	1	1	17	3	0.67	7	0	1	1+7(8)	97.6
3.3	1	1	12	6	0.39	0	0	0	0	0
3.4	1	1	16	5	8	7	1	1	+8(8)	11.7
3.5	1	2	26	6	11	12	0	0	0	9.1
3.6	1	2	25	5	2	12	0	0	0	9.3
3.7	1	2	32	5	4	14	0	0	0	14.8
3.8	1	2	32	6	15	15	0	1	0	13.6
3.9	1	3	51	6	47	22	0	1	+1(8)	44.4
3.10	1	3	40	6	5	21	0	1	0	26.4
3.11	1	3	38	6	10	10	0	0	0	3.1
3.12	1	3	40	7	20	21	0	2	1	375.7
3.13	2	2	30	5	11	13	0	1	1	25.5
3.14	2	2	30	5	2	1	0	0	0	0.1
3.15	2	2	33	7	812	1	0	0	0	0.1
3.16	2	2	42	5	19	7	0	0	0	1
3.17	2	4	63	7	24	3	0	0	0	0.4
3.18	2	4	67	6	403	29	0	0	0	9.3
3.19	2	4	102	6	40	15	0	0	0	0.9
3.20	2	4	71	7	1806	31	0	0	0	6
3.21	2	6	123	6	42	35	0	0	0	3
3.22	2	6	112	6	54	45	0	0	0	5.2
3.23	2	6	114	7	61	53	0	0	0	42
3.24	2	6	117	6	72	53	0	0	0	5.4
3.25	3	3	82	6	1624	18	0	0	+1(8)	3.3
3.26	3	3	75	7	4612	11	0	1	0	0.6
3.27	3	3	75	7	1465	11	1	1	0	0.8
3.28	3	3	43	7	6	2	0	0	0	0.3
3.29	3	6	129	7	516	6	0	0	0	0.1
3.30	3	6	129	7	1097	31	0	0	0	1.5
3.31	3	6	128	6	54	27	0	0	0	2.3
3.32	3	6	149	7	594	65	1	1	0	4.3
3.33	3	9	193	7	4639	2	0	0	0	0.005
3.34	3	9	202	7	1112	58	0	0	0	2.8
3.35	3	9	245	7	319	90	0	0	0	5.5
3.36	3	9	198	6	65	7	0	0	0	0.1
3.37	4	4	125	4	1447	24	1	0	0	1.2
3.38	4	4	108	9	1930	17	1	1	0	4.7
3.39	4	4	114	6	455	4	0	0	0	0.1
3.40	4	4	127	6	5601	67	4	1	+1(8)	549.4
3.41	4	8	195	5	134	25	0	0	0	0.3
3.42	4	8	206	6	1780	18	0	0	0	0.3
3.43	4	8	187	7	5063	5	0	0	0	0.05
3.44	4	8	255	6	395	55	0	0	0	1.1
3.45	4	12	272	5	123	3	0	0	0	0.03
3.46	4	12	322	7	274	9	0	0	0	0.1
3.47	4	12	392	8	1581	115	0	1	0	1.6
3.48	4	12	262	8	1626	13	0	0	0	0.1

- All cases are suggested to downsize except Case 3.3. We refer to Case 3.3 as the insignificant downsizing case, meaning that downsizing strategy cannot help improving the profitability of the supply chain in this case.

- Downsizing solutions can help significantly improving the profitability of the downsized company in some cases. Ten test cases generate more than 10% increase of the TDNP, while the largest improvement is more than five times of the TDNP obtained in the case that no downsizing operation is applied.

- All selling of PFUs are planned in the first downsizing period. Note that a PFU is redundant when its revenue contribution is less than its market value. Since market value of PFUs decreases when it gets old, redundant PFUs are sold as soon as possible.

- The portion of PFUs sold decreases when the number of product and PFU types increases (see Figure 3.2). This suggests that retained PFUs are often flexible machines and are required for manufacturing certain products even after downsizing. Therefore, we do not see drastic reduction of PFUs.

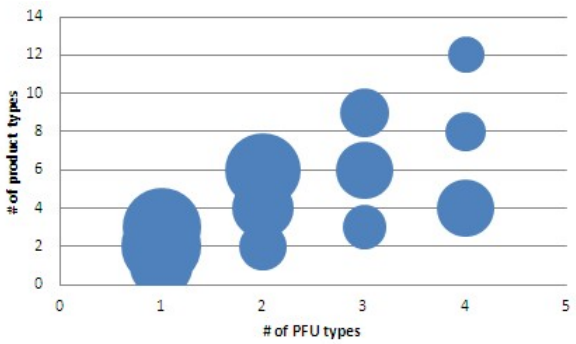


Figure 3.2: Average portion of PFUs sold.

- PFUs are seldom moved. Note that the here generated cases are for studying the impact of demand reductions on the optimal production setting of a supply chain network. The transfer of PFUs is a rare event, which happens only to gain a profit, i.e., saving fixed operation costs, promoting extra PFU sales, saving tax payments, etc.

- Production and distribution centers are seldom closed when the number of product types is large. Since the data generation procedure assigns arbitrary demand volume to each product type, the total demand increases along with the rising number of products types involved. Therefore, when the number of product types is large, both production and distribution centers expect sufficient demands after downsizing for sustaining their daily operation.

- Often, there are distribution centers closed in the eighth period. Note that demands recover in the last three downsizing periods. Given the remaining available production capacities, the multi-product downsizing MILP model reassigns available PFUs to serve more profitable demands with less cost. Less profitable demands, however, are intentionally given up, and as such corresponding distribution centers are closed when their demands cannot be met.

- The computation time tends to increases along with the number of PFU and product types.

3.4.3 Numerical results of demand substitution

Demand substitution contributes to production flexibility and allows company to shift demand across products so that the company can satisfy more customers and earn more without incurring the cost of extra capacity. Depending on PFU requirement rates for producing different products, demand substitution impacts supply chain downsizing operations through the choice of product portfolio. Hence, also affects the profitability of the downsized company. In this section, we discuss test results of the downsizing MILPds (3.1), (3.3)–(3.15), (3.17)–(3.18).

3.4.3.1 Numerical results of demand substitution when the replacement rate equals to one

We tested our downsizing MILPds on five cases, Case 3.9, 3.17, 3.24, 3.31, and 3.39 from Table 3.1. For each case, we arbitrarily select three products denoted by “A”, “B”, “C” and run the test with seven different substitution matrices, where we gradually increase the substitution rates. The seven substitution matrices (along with substation graphs) are provided in Appendix A, 1 to 7. Substitution matrices (SuMs) 1 to 3 represent chain substitutions, where none of the products is mutually substitutable with another product. SuMs 4, 6, and 7 represent loop substitutions, where any two of the products are substitutable with each other. SuM 5 represents a situation where both chain and loop substitution exist. For illustration purposes, we explain the substitution relationship represented by substitution matrix (SuM) 5. It suggests that unsatisfied demands of product B are equally divided and diverted to product A and C, and unsatisfied demands of product A are diverted to product B, while unsatisfied demands of product C are lost. Since network configuration and flows determine the profitability of each product, in order to identify the profitability ranking of the three products of each case, we test pairwise equal substitutions of the three products, i.e., every time we allow two of them to be fully substitutable with each other. Based on the direction of the major demand shifts, we determine their profit trade-offs. The profit trade-offs of the three products are given in Table 3.2 for each case, which are later used for validating test results.

Test results are listed in Tables 3.3 to 3.6. Each table presents the test results of a case, and each row of the table presents the results obtained with one SuM. In the following, we elaborate our discussion of test results with Case 3.24 (see Table 3.4), while findings

Table 3.2: Profitability of products.

Case	Profit trade-off		
	high	medium	low
3.9	A	C	B
3.17	A	B	C
3.24	A	C	B
3.31	B	A	C
3.39	C	A	B

from other cases are summarized as remarks at the end of this section. The columns 2 to 8 of Table 3.4 present the downsizing solution of Case 3.24. Since not all PFU types are used for manufacturing the three substitutable products, we only indicate the changes of PFU types which are affected by the demand substitution in the columns 2 to 6. There are two PFU types involved in Case 3.24 (see Table 3.1), one PFU type is used for producing B and C, while the other one is used for producing A, B, and C. We categorize the first PFU type as dedicated PFU, and the second PFU type as flexible PFU. PFU types of other cases are similarly categorized depending on their ability to produce the three products. The last three columns of Table 3.4 present the demand fulfillment rates (in percentage) of the three products relative to their original demand. Based on the demand fulfillment rate, we can identify where demands are diverted to. The downsizing solution considering no demand substitution, listed in row 1 of Table 3.4, indicates that there are 23 of the 58 flexible PFUs sold and 30 of the 59 dedicated PFUs sold, while no PFUs are moved. As to demand fulfillment rate, all demands of product A are satisfied, while only 52% demands of product B and 82% demands of product C are satisfied. The test results of SuM 1 and 2 suggest the same downsizing plan as if no demand can be substituted. As we know from Table 3.2, profit trade-offs of the three products of Case 3.24 follow a preference of A to C, and C to B. Hence, by allowing demand shift from product A to B, SuMs 1 and 2 do not benefit the company. On the contrary, SuMs 3 and 4 both allow demand shift from product B to A, which contributes a higher profit. Comparing rows 4 and 5 with row 1, we can see that only the production volume of A increases and is almost doubled, while the production of B is terminated. This suggests that all demands of product B shift to product A. With SuM 5, the unsatisfied demand of product B is equally divided between product A and C. Since the company gain extra profit no matter whether demands is shifting to A or to C, the test results suggest terminating production of B. The test results of SuMs 6 and 7 both suggest the same downsizing plan, where production of B and C are both terminated and all demands shift to product A. While this downsizing plan generates the highest profit, we can spot a clear difference of PFU reallocation when comparing with the downsizing plans which does not explore the demand substitution. There is a significant increase of selling of dedicated PFUs from 30 to 43. The selling of flexible PFUs, however, decreases from 23 to 14, while the number of flexible PFUs moved increases from 0 to 2. This suggests that flexible PFUs are more likely to be reserved after downsizing when products become more substitutable.

Table 3.3: Test results of Case 3.9

Tests	♯ PFUs sold		♯ PFUs moved		♯ prod. centers closed	♯ dist. centers closed	TDNP	Demand fulfillment(%)		
	Flex.	Dedi.	Flex.	Dedi.				A	B	C
Origin	22/51	0	0	0	1	+1(8)	187169	97	63	80
SuM 1	22/51	0	0	0	1	+1(8)	187169	97	63	80
SuM 2	22/51	0	0	0	1	+1(8)	187169	97	63	80
SuM 3	19/51	0	0	0	0	+3(8)	318710	200	0	57
SuM 4	19/51	0	0	0	0	+3(8)	318710	200	0	57
SuM 5	20/51	0	0	0	1	+2(8)	275495	146	0	105
SuM 6	17/51	0	0	0	1	+8(8)	394602	278	0	3
SuM 7	17/51	0	0	0	1	+8(8)	394602	278	0	3

Table 3.4: Test results of Case 3.24

Tests	♯ PFUs sold		♯ PFUs moved		♯ prod. centers closed	♯ dist. centers closed	TDNP	Demand fulfillment(%)		
	Flex.	Dedi.	Flex.	Dedi.				A	B	C
No sub.	23/58	30/59	0	0	0	0	3752942	100	52	82
SuM 1	23/58	30/59	0	0	0	0	3752942	100	52	82
SuM 2	23/58	30/59	0	0	0	0	3752942	100	52	82
SuM 3	19/58	37/59	0	0	0	0	5175832	186	0	69
SuM 4	19/58	37/59	0	0	0	0	5175832	186	0	69
SuM 5	21/58	34/59	0	0	0	0	4490662	143	0	98
SuM 6	14/58	43/59	2/58	0	0	0	6697216	284	0	0
SuM 7	14/58	43/59	2/58	0	0	0	6697216	284	0	0
SuM 8–13	14/58	43/59	2/58	0	0	0	6697216	284	0	0

Table 3.5: Test results of Case 3.31

Tests	♯ PFUs sold		♯ PFUs moved		♯ prod. centers closed	♯ dist. centers closed	TDNP	Demand fulfillment(%)		
	Flex.	Dedi.	Flex.	Dedi.				A	B	C
No sub.	13/75	8/18	0	0	0	0	1804192	95	100	81
SuM 1	19/75	8/18	0	0	0	0	1874917	9	139	80
SuM 2	14/75	8/18	0	0	0	0	2061689	0	185	81
SuM 3	13/75	8/18	0	0	0	0	1804192	95	100	81
SuM 4	14/75	8/18	0	0	0	0	2061689	0	185	81
SuM 5	14/75	8/18	0	0	0	0	2061689	0	185	81
SuM 6	15/75	18/18	0	0	0	0	2421812	0	291	0
SuM 7	15/75	18/18	0	0	0	0	2421812	0	291	0

Table 3.6: Test results of Case 3.36

Tests	♯ PFUs sold		♯ PFUs moved		♯ prod. centers closed	♯ dist. centers closed	TDNP	Demand fulfillment(%)		
	Flex.	Dedi.	Flex.	Dedi.				A	B	C
No sub.	5/138	2/60	0	0	0	0	1908074	98	100	100
SuM 1	8/138	2/60	0	0	0	0	1911335	87	106	100
SuM 2	14/138	4/60	0	0	0	0	1921111	68	130	100
SuM 3	0/138	5/60	0	0	0	0	1965380	160	38	100
SuM 4	5/138	2/60	0	0	0	0	1980817	136	65	100
SuM 5	33/138	0/60	2/138	2/60	0	0	2351609	0	4	269
SuM 6	32/138	0/60	2/138	2/60	0	0	2352190	0	7	266
SuM 7	32/138	0/60	2/138	2/60	0	0	2352190	0	7	266

The substitution relationship of a group of products forms a substitution circle when satisfying the following two conditions:

a. fully substitutable: there is no demand diverted to the outside of the group of products.

b. loop substitution: any two products in the group are substitutable with each other.

In the presence of a substitution circle, any substitution relationship within the group results in the same optimal downsizing solution, and companies always try to divert all demands to the most-profitable product in the group. We can see that SuMs 6 and 7 produce the same downsizing results in all cases, and demands always divert to the most-profitable product as long as there is enough production capacity. To investigate this situation further, Case 3.24 is tested with six other substitution matrices which represent substitution circles. The substitution matrices are listed in Appendix A, 8 to 13. All tests again result in the same downsizing solution as that of SuMs 6 and 7 (see SuMs 8 to 13 of Table 3.4). This property of demand substitution provide an intuition for product portfolio management: as long as a group of products forms an substitution circle, it is very likely for the company to gain more profit by only producing the most-profitable product.

Note that the value of ν^+_{idt} can be larger than Q_{idt} for some i, d, t following our MILPds formulation. For example, the test results of Case 3.24 with SuM 7 suggest shifting all demands from B to C, and then from C to A. If we denote the demand of product A, B, and C as Q_{Adt}, Q_{Bdt}, and Q_{Cdt} respectively for some d and t, it is clear that $\nu^+_{Bdt} = Q_{Bdt}$, $\nu^+_{Cdt} = Q_{Bdt} + Q_{Cdt}$, and $\nu^+_{Adt} = 0$, where the value of ν^+_{Cdt} is larger than Q_{Cdt}. However, when marketing manager requires the unsatisfied demand to be bounded, we may introduce a bound to the value of ν^+_{idt} such that $\nu^+_{idt} \leq \beta Q_{idt}$ for all i, d, t, and $\beta \in (0, 1]$. The restricted downsizing MILPds results in a formulation which allows only one time substitution, i.e., a demand can only shift from a product to another neighbor product on the substitution graph. We extend our tests of Case 3.24 with SuMs 8 to 13 requiring $\nu^+_{idt} \leq Q_{idt}$ for all i, d, t, where $\beta = 1$, and list the test results in Table 3.7.

Comparing the obtained results with those of no bounding on the value of ν^+_{idt}, we have the following observations: (a) Most of the solutions are different in Table 3.7, which means that the detailed substitution relationships between products of a substitution circle does matter in case of one time substitution. (b) Only SuM 12 produces the same downsizing solution as that of no restriction on ν^+_{idt}, where demands of product B and C

Table 3.7: Bounding tests of Case 3.24

Tests	♯ PFUs sold		♯ PFUs moved		♯ prod. centers closed	♯ dist. centers closed	TDNP	Demand fulfillment(%)		
	Flex.	Dedi.	Flex.	Dedi.				A	B	C
SuM 8	22/58	34/59	0	0	0	0	4527866	149	51	45
SuM 9	21/58	39/59	0	0	0	0	5350288	199	12	39
SuM 10	21/58	34/59	0	0	0	0	4494425	143	4	93
SuM 11	22/58	34/59	0	0	0	0	4527866	149	51	45
SuM 12	14/58	43/59	2/58	0	0	0	6697216	284	0	0
SuM 13	19/58	37/59	0	0	0	0	5197936	192	34	31

are allowed to directly shift to the most-profitable product A at a replacement rate of 1. (c) All the rest tests result in less profitable downsizing plans. Note that the one time substitution with $\beta = 1$ represents the immediate demand shift after downsizing. The obtained downsizing solution does not fully explore the substitution possibilities and the gap sometime can be quite large. For example, the company of Case 3.24 with SuM 9 would expect a profit of 5350288 in case they try to explore only the immediate demand shift after downsizing, or the company can expect a profit about 20% higher when they take into account the further shifts of demands.

Based on our observations of test results of all cases, we make the following remarks:

- The profitability of a demand diversion depends on two factors: (a) the profitability of the substitute (alternative) products and (b) the corresponding substitution rates. For example, the diversion from more-profitable product A to less-profitable product B in Case 3.9 and 3.24 is not profitable (see SuMs 1 and 2 of Tables 3.3 and 3.4), while the diversion of demands from product A to product B becomes profitable when the substitution rate increases from 0.5 to 1 in Case 3.17 (see SuMs 1 and 2 of Table 3.8). Therefore, whether a diversion of demands is profitable depends on the weighted average profit of substitute products.

Table 3.8: Test results of Case 3.17

Tests	♯ PFUs sold		♯ PFUs moved		♯ prod. centers closed	♯ dist. centers closed	TDNP	Demand fulfillment(%)		
	Flex.	Dedi.	Flex.	Dedi.				A	B	C
No sub.	2/44	1/19	0	0	0	0	590551	100	100	99
SuM 1	2/44	1/19	0	0	0	0	590551	100	100	99
SuM 2	1/44	1/19	0	0	0	0	603434	77	122	99
SuM 3	9/44	1/19	0	0	0	0	652504	181	23	99
SuM 4	8/44	1/19	0	0	0	0	665226	159	44	99
SuM 5	7/44	0/19	0	0	0	0	618035	102	64	125
SuM 6	0	16/19	6/44	0	0	0	784051	240	50	19
SuM 7	0	16/19	6/44	0	0	0	784051	240	50	19

- Since the production process of the substitute product can be interrupted and stopped when production resources, such as, raw material supply capacity and production capacity, reach their limits, a profitable diversion of demands might not be complete. For example, in Case 3.17 with SuMs 6 and 7, the diversion of demands from product B and C to product A cannot be complete because the flexible PFUs reach the capacity limits (see SuMs 6 and 7 of Table 3.8), or when with SuM 5, the diversion from product B to A and C cannot be complete because the dedicated PFUs reach the capacity limits (see SuM 5 of Table 3.8).

- Dedicated PFUs are likely to be sold when demands are increasingly substitutable, while flexible PFUs are more likely to be transferred rather than be sold. Case 3.9, 3.17, and 3.24 all demonstrate the same tendency of PFU reallocation (see Tables 3.3, 3.4, and 3.8). This is not only because that the flexible PFUs are more likely to be occupied by the substitute products, but also because that more demands are reserved rather than downsized after substitution.

3.4.3.2 Numerical results of demand substitution when the replacement rate differs from one

SuMs 1 to 7 in Appendix A adopt replacement rate $S_{ik} = 1$ for all products $i, k \in \{1, \ldots, I\}$. In this section, we extend our test of Case 3.24 with general substitution matrices, where the replacement rates between products are:

$$S = \begin{pmatrix} 1 & 2 & 2 \\ 0.5 & 1 & 1 \\ 0.5 & 1 & 1 \end{pmatrix}.$$

This means that $e = (1, 0.5, 0.5)^{\intercal}$, and an unsatisfied customer who need one unit of product B or C will demand for two units of product A for exchange. By adopting the same diversion matrix H of SuMs 1 to 7, we obtain a set of general substitution matrices. We list the general substitution matrices in Appendix A, 14 to 19, while test results are listed in Table 3.9.

TABLE 3.9: Test results of Case 3.24 with general SuM

Tests	♯ PFUs sold		♯ PFUs moved		♯ prod. centers closed	♯ dist. centers closed	TDNP	Demand fulfillment(%)			Largest SBR
	Flex.	Dedi.	Flex.	Dedi.				A	B	C	
No sub.	23/58	30/59	0	0	0	0	3752942	100	52	82	0
SuM 14	23/58	30/59	0	0	0	0	3752942	100	52	82	0
SuM 15	23/58	30/59	0	0	0	0	3752942	100	52	82	0
SuM 16	9/58	37/59	3/58	0	0	0	6792871	271	0	69	0.7
SuM 17	9/58	37/59	3/58	0	0	0	6792871	271	0	69	0.7
SuM 18	16/58	34/59	0	0	0	0	5300103	186	0	98	0.35
SuM 19	0	45/59	7/58	0	0	0	10195210	469	0	0	0.9
SuM 20	0	45/59	7/58	0	0	0	10195210	469	0	0	0.9

Note that A is the most profitable product. By increasing the replacement rate from B and C to A, we do not change the preference order of the three products. Comparing Table 3.9 with Table 3.4, we have the following observations:

- Unprofitable diversions are still unprofitable. SuMs 14 and 15 in Table 3.9 suggest the same downsizing results as that of SuMs 1 and 2 in Table 3.4.

- Profitable diversions are still profitable. SuMs 16 to 20 in Table 3.9 suggest the same demand diversions as that of SuMs 3 to 7 in Table 3.4. When comparing test results with the results of no demand substitution, the differences of demand fulfillment of product A are always doubled in Table 3.9, while the demand fulfillment of product C remains the same in both tables because of the replacement rate of 1 between product B and C.

- An increased number of flexible PFUs are reserved and an increased number of dedicated PFUs are sold in Table 3.9 when substitution rates increase. SuMs 19 and 20 suggest no selling of flexible PFUs, while the selling of dedicated PFUs increases for 2 units when comparing with SuMs 6 and 7 in Table 3.9.

- We define substitution balance ratio (SBR) of distribution center d in period t as:

$$\mathrm{SBR}_{dt} = \frac{\sum_{i=1}^{I}\sum_{k=1}^{I} Y_{ik}\nu_{kdt}^{+} - \sum_{i=1}^{I}\nu_{idt}^{+}}{(\alpha - 1)\sum_{i=1}^{I} Q_{idt}}.$$

  There are $d \cdot t$ SBRs of each test. According to Proposition 3.4, SBRs should always be less than 1, and the higher the value of SBR the more intensive the substitution activities are in each case. We list the largest SBR in the column 12 of Table 3.9 for each test.

3.5 Summary

Business growth, stagnation, and decline periodically occur in cycles. During the uptrend, companies clearly segment market and deliver each targeted group with customized products. When economy downtrend starts, the sharp demand decline and raised costs make the extended product lines too expensive to sustain. The multi-product SCDP under bankruptcy in this chapter addresses in such a difficult time and considers reducing product types and the size of supply chain network. While the multi-product downsizing MILP optimizes the supply chain network configuration in accordance with forecast demand contraction, the further development of downsizing MILPds take into account demand adjustments in case of demand substitution. The novel formulation of demand substitution relates substitution rate to demand diversion and replacement rate, and enables the downsizing MILPds to consider uneven substitution for network design. Numerical results confirm the validity of our proposed approach in assisting companies to reshape their supply chain network and to target a more sustainable market that constantly generate stable and profitable demands.

Although financial difficulties are presumed for the development of the SCDP under bankruptcy, the application of the downsizing models in this chapter is not restricted for only survival purpose. While current downsizing decisions are mainly determined based on manager's instinct and knowledge of market growth, our downsizing models can support managers with more precise analysis of business circumstance and decision making. Many fast-clockspeed industries (see Fine [2000]) can benefit from the approach we provide in this chapter. Nokia, one of the largest mobile phone manufacturers, recently initiated a series of downsizing operations including job cut, factory closure, and R&D reduction, which represents one downsizing example in electronics industry. Its products feature high substitutability and short life cycle. Once a new model is launched, earlier models would become obsolete. Based on our test results of chain substitutions, we can easily understand why Nokia migrates its cell phone operating system from "Symbian" to "Windows phone". Nissan recently cut back its domestic production capacity because of the Yan's appreciation and the decline of oversee sales, representing one downsizing example in automobile industry. With here proposed downsizing models, managers can search for alternative locations of production centers and target markets that weaken the impact of currency fluctuation. Other downsizing examples can also be easily found from internet service, commodity, fashion, and pharmaceutical industries. Comparing with current substitution formulations which mainly focus on special substitution structures, e.g., downward substitution (see Hsu and Bassok [1999]), one-step substitution, or even substitution where replacement rates are always equal to one, our substitution formulation provides a more realistic approximation of consumer behavior of demand substitution. The insightful definition of the substitution matrix specifies the properties of each of its elements, which is valuable for data analysis and help ruling out low-quality survey data. The SBR defined in Section 3.4.3.2 can also be adopted for measuring the intensity of substitution.

It is worth mentioning that the implementation of the downsizing models proposed in Chapter 2 and 3 requires extensive use of aggregated data. The preparation of the aggregated data involves the collection of operation costs from different interest groups, the forecast of demand and policy influence on tax, interest rates, and currency exchange rates, and the survey of customer preferences on products. In particular, the determination of demand volumes requires not only rational analysis but also subjective judgment. Combining the foreseen trend of market development (e.g., technology, government policy, customer preference) with the promotion method that marketing department may adopt, a company can expect significantly varied demand turnouts. The systematic data generators presented in Chapter 2 and 3 support the development of fine and fair test cases, fostering our numerical results with interesting observations of downsizing impacts on the performance of supply chains. The generators permit further a focal company fearing down- or up-stream bankruptcy to investigate the bankruptcy propagation impacts of any member without direct involvement of other parties and strategize an approach toward suppliers and/or customers to manage future risks. A comprehensive understanding of the effects of different downsizing strategies can only be achieved by conducting statistical analysis of results obtained from the proposed downsizing models using a large set of experiments generated with the available data generators.

Chapter 2 and 3 concern the strategic level decision-making for downsizing manufacturing supply chain networks, the aim of which is to better align core business operations and resources with financial strategies. Hence, the focus is on the forward network flows, through which service is delivered to customers. However, in order to achieve the overall cost control of a supply chain network, operations on the reverse network flows for after-sale service and tactical level decisions regarding production process design and inventory management cannot be ignored from decision-making. In the next chapter, we consider to reconfigure a closed-loop supply chain network from the cost-efficiency perspective. The take-back of returned products, recovery operations, and inventory replenishments are at the focus for achieving the efficient operations of a warranty distribution network.

Chapter 4

The Optimal Design of A Warranty Distribution Network

4.1 Introduction

Nowadays, product purchase often implies warranty agreements. Depending on the agreements, a customer may be entitled to a refund, replacement, or repair of a product in the case that the purchased product defects. A supply chain network that provides warranty service to customers is called here a *warranty distribution network* (WDN). Our WDN is an arrangement of storage facilities and transportation systems of an third party logistics (3PL) provider that handles the outsourced aftersales service activities of a large international semiconductor company. A distribution network usually resembles a closed-loop supply chain network. The combination of forward flows that deliver new and refurbished (no defect found or successfully repaired) products to the end users, and reverse flows that collect used products from the end users, makes the warranty distribution network a closed-loop supply chain network. Furthermore, inspection and recovery of returned products is often performed on the reverse flows to reduce warranty service costs. The goal of warranty service is to be responsive and cost efficient, see e.g., Murthy et al. [2004]. A few companies today are paying enough attention to their warranty distribution network capabilities. Mostly, companies outsource the entire operation. Therefore, warranty service provided by international 3PLs is a growing business globally. Considering that a 3PL network might not be optimal to handle and manage, a WDN demands optimizing such an activity. This also produces substantial benefits for 3PL in offering better service at lower costs, and releasing resources capacity (storage and transport) for new business opportunities.

The core interrelated management decisions of WDN are inventory management, order fulfillment, distribution, transportation and reverse logistics. The inventory aspect has been extensively discussed in the literature under spare part inventory management. The transportation issue together with inventory has also been studied, but mostly at one or two echelons. Among these research works we can refer to Kutanoglu and Lohiya [2008]. They optimize an integrated inventory and transportation mode for a single-echelon, multi-facility service parts logistics system with time-based service level constraints. When the location-allocation is included, the problem falls under closed-loop/reserve logistics category of problems in supply chain management. While the design of reverse logistics and closed-loop supply chain networks has been extensively studied in the last two decades, the WDN is rarely addressed in the literature. Fleischmann et al. [1997] provide a systematic overview of the issues arising in the context of reverse logistics and report the lack of research investigating the integration of forward and reverse distribution. Four years later, Fleischmann et al. [2001] present a generic facility location model that optimizes both, the forward and the return flow of products simultaneously. They also identify a great impact of product recovery on the logistics network design, and emphasize importance of optimizing both, forward and return networks. Thereafter, a research on a closed-loop supply chain network design has been developed in many aspects. We select below a few relevant research results. Krikke et al. [2003] propose a mathematical model to support both; the design of a product and a closed-loop logistic network. Their model also takes into account the environment impact of logistics operations by measuring the energy use and the residual waste stream. Ko and Evans [2007] present a nonlinear programming model for the design of the forward-reverse logistics network of third party logistics providers. Their model takes into account the multi-period planning of capacity expansion at warehouses and repair centers. A genetic algorithm-based heuristics is developed for solving their problem. Pishvaee et al. [2010] present a bi-objective mixed integer programming model for minimizing total costs and maximizing the responsiveness of a closed-loop logistics network. They develop a multi-objective memetic algorithm that exploits a dynamic search strategy in order to find the set of non-dominated solutions. El-Sayed et al. [2010] present a stochastic mixed integer linear programming model for designing a multi-period forward-reverse logistics network, where demands are stochastic. Pishvaee et al. [2011] adopt robust optimization techniques for designing a robust closed-loop supply chain network. The uncertainties under their consideration are from demands, returns, and transportation costs. Ashayeri and Tuzkaya [2011] propose a multi-criteria optimization model to design a responsive network for after-sale services of high-tech products. The model optimizes the location of return and repair facilities to increase network responsiveness, however it does not account for inventory of forward and refurbished flows. A similar approach is also used by Hassanzadeh Amin and Zhang [2014], they integrate forward and reverse channels in closed-loop supply chain networks using a mixed-integer linear programming model. Their network includes multiple products, plants, recovery technologies, demand markets, and collection centers. The model does not consider different formats of repair and does not consider the inventory issues related to forward and reverse flows. For a general overview on closed-loop supply chains, interested readers might read Guide and Van Wassenhove [2009]. For a recent review on closed-loop supply chains, interested reader might read Souza [2013].

In WDN, returned products are often subject to different damages (if there is any). Therefore, refurbished products can often be obtained from different processes. For example, a returned product with no defect can be identified as a good product after functional testing. Thus, the WDN design problem should also consider the following issues:

The differentiable recovery costs of returned products: Because of different operations involved in recovering of returned products, refurbished products in inventory are obtained with various operation costs.

Diverse sources for inventory replenishment: Depending on the location of each recovery process, it may be profitable to send the refurbished products to different warehouses.

The intentional adaptation of the recovery processes for cost saving: Depending on the location of recovery processes and the quality of returned products, the performance of a recovery process may generate more costs than saving. Eliminating such a process may be profitable.

Almost all literature on a closed-loop supply chain network design has been implicitly assuming that returned products can only be turned into usable products by performing the same recovery processes. However, few papers that might come close to this work do not consider optimization of the network; rather simulate different configuration alternatives to measure the performance. For example Fritzsche and Lasch [2012] simulate an integrated logistics model of spare parts maintenance planning within the aviation industry. Their model uses a combination of analytical measures and neural network based simulation. Therefore, a model that can handle effective recovery process and location, inventory control policy for coordinating forward new product flows, and refurbished product flows while optimizing a multi-echelon location-allocation network and associated transportation flows does not exist in any research that addresses the WDN modeling. To the best of our knowledge, Özkır and Başlıgıl [2012] is the only paper on a closed-loop supply chain network design that considers different recovery processes of returned products. Namely, besides repairing returned products, the authors also consider possible reuse of materials and components of non-repairable returned products as inputs for constructing new products. A mixed integer linear programming model is proposed for solving their problem. Recovery facilities are assumed to be geographically separated, and material flows between recovery facilities are explicitly formulated in the model.

Here, we consider different recovery processes of returned products in order to design a closed-loop supply chain network problem. In particular, we are interested in designing a WDN where returned products are of various qualities and the reuse of returned products requires a careful control of recovery processes. Unlike the problem addressed by Özkır and Başlıgıl [2012], the here described problem has two special features, which result in a nonlinear and nonconvex optimization problem. These features are:

- **The potential hybrid use of distribution centers:** In our case the warehouses are hybrid storage/repair centers. Recovery or repair facilities can be allocated to each of the distribution centers. Depending on which recovery facilities are available to a distribution center, different recovery processes may be performed by the distribution center. The joint decision on both recovery facility allocation and product flows results in nonlinear constraints.

- **The impact of inventory replenishment policy:** The inventory replenishment decisions at distribution centers generate a considerable amount of costs, and requires careful planning. The reason is twofold. Firstly, the distribution network operates transnationally. Custom duties, tariffs, and government incentives are important consideration in configuring the WDN. Sometime, a large amount of custom fee is charged every time a flow of materials cross a country border where bonded warehousing is not practiced, which in turn increases considerably the inventory ordering cost and holding costs. Secondly, the financial asset that is locked in inventories cannot be used for alternative investments. The loss of its potential gain is referred as the opportunity cost, representing the inventory holding cost. Depending on whether the inventory is replenished with new or refurbished products inventory holding costs can be greatly influenced. Because the costs of refurbished products is lower than new products as it mainly includes the recovery costs and the return costs. Considering the replenishment policy impacts on holding and ordering costs of inventory, and the number of inventory replenishments per time unit makes the problem nonlinear.

By incorporating the above mentioned features, we develop a nonlinear mixed integer programming (NLMIP) model for the WDN. Our model optimizes both, the design of the closed-loop distribution network and the assignment of recovery facilities among distribution centers. By assigning recovery facilities among distribution centers according to the predefined possible geographical separations of recovery processes, the here proposed model provides a cost-effective closed-loop supply chain network and corresponding recovery processes at each distribution center. To approximately solve the NLMIP model, we (piecewise) linearize nonlinear constraints and objective and obtain a high-quality feasible solution.

The rest of the chapter is organized as follows. Section 4.2 describes the warranty distribution network design problem encountered by the semiconductor company. Section 4.3 presents the NLMIP model for designing the closed-loop warranty distribution network. The linearized NLMIP model is presented in Section 4.4. Numerical results are discussed in Section 4.5 and concluding remarks are given in Section 4.6.

4.2 Problem description

As an effort for improving after-sale service and customer satisfaction, the warranty program of FTL[1], a semiconductor company, provides its customers with warranty contract. With the warranty contract, customers can claim for a replacement when a product defects. The returned product needs to be sent back for inspection. In the case that the claim is credited, a good product will be sent to the customer. FTL manufactures many different types of products. The recovery processes of returned, defected products may differ depending on the product type. For the ease of demonstration, the here presented case study considers only one product type i.e., motherboard. According to historical data, the claims for defected motherboards account for more than 60% of all transactions.

The complete recovery processes of returned motherboards consists of visual inspection, functional testing, and repair (see Figure 4.1). Warranty and recovery process tracks several measures and these are reported on monthly basis by the third party logistics service provider. This information is used to quantify the process. After receiving returned products, say from customer i, visual inspection is performed. During the visual inspection, an inspector goes through an exception list in order to make preliminary judgment on whether customer i should be responsible for the defect. In the case of customer induced defects, no further warranty service will be provided to that customer. Since visual inspection is important to be performed right after receiving a returned product, visual inspection is always conducted at the distribution center where the after-sale service is provided. After visual inspection, some customers are found to be responsible

[1]Fictive name. The authors are not allowed to disclose details of the industrial partners.

for the defect and for those warranty claim does not apply and are not counted in our study. However, for the remaining customers the probability that the visual inspected product will be scrapped is P_i^0, and the probability that such a product will be sent to functional testing for further tests is P_i^1, where $P_i^0 + P_i^1 = 1$. The functional testing is a necessary step for detecting the malfunctioning parts of a returned product, and it is always performed before repair. After functional testing, the probability that the functional tested product will be scrapped is P_i^{10}, the probability that no defect is found and such product will be sent directly to inventory as a good product is P_i^{11}, and the probability that such product will be sent to repair is P_i^2, where $P_i^{10} + P_i^{11} + P_i^2 = 1$. The probability that a product sent to repair will be repaired is P_i^{21}. However, the probability that such product will be scrapped is $P_i^{20} = 1 - P_i^{21}$. The functional testing and repair can be performed at any distribution center. This suggests that a returned product may be visual inspected at one distribution center and have its functional testing and repair conducted at another distribution center.

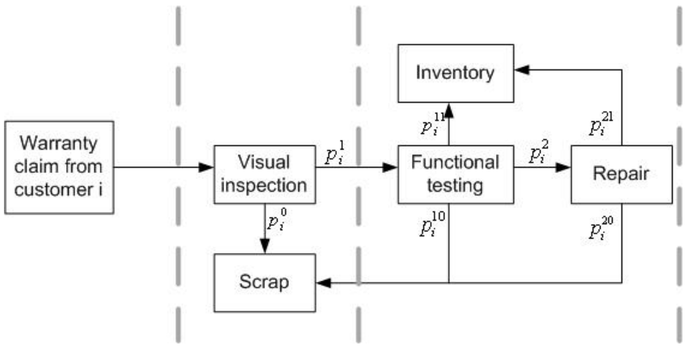


FIGURE 4.1: The complete recovery processes of returned products.

In practice, for the cost-saving purpose, not all distribution centers can perform all operations. Depending on a distribution center to which a returned product is sent after visual inspection, the returned product may sometimes go through different recovery processes than previously described. For example, a returned product may be sent to a distribution center where only functional testing can be performed. In such case, the returned product cannot be repaired even if it is required, and the probability that it will be scrapped after functional testing is $P_i^2 + P_i^{10}$, see Figure 4.2.

The FTL warranty program currently operates on a transnational distribution network consisting of one production center and two levels of distribution centers (see Figure 4.3). The distribution network is operated by an outsourced logistics service provider who is responsible for the storage, the forward flow of new and refurbished products and the reverse flow of returned products. Service to customers of different regions is assigned among distribution centers of service provider. With the forward distribution, the network supplies all customer regions with new and refurbished products such

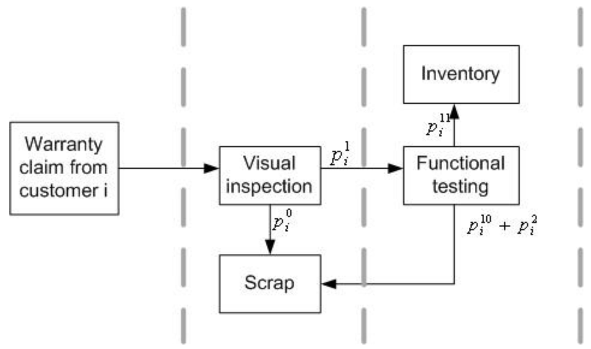


FIGURE 4.2: Alternative recovery processes without repair.

that customer service can be completed within the response time specified by warranty contract. The inventory of the first-level distribution center is replenished from the production center and from recovery processes, while that of the second-level distribution centers is mainly replenished from the first-level distribution center. With the reverse distribution, the network collects defected products from customers and conducts recovery processes if it is necessary. In the current situation, the regional warehouse one (RW 1) performs visual inspection and functional testing to returned products, and all defected products are scrapped without repair (see Figure 4.2 for the recovery processes at RW 1). Similarly, RW 2 only performs visual inspection to returned products, and all returned products are scrapped after visual inspection. RW 3 performs visual inspection to returned products, and then sends not-scrapped products to the central warehouse for functional testing and repair. The central warehouse, unlike RWs, performs the complete recovery processes to returned (not-scrapped) products. According to a management judgment, it is not economical to transfer refurbished products between warehouses. Therefore, refurbished products that are resulted from functional testing or repair only contribute to the inventory of the warehouse where the operation is conducted.

The joint decision of warehouses locations and deployment of inventory is vital for WDN. The warranty stock management problem here is a bit complicated by the high service requirements placed at the central warehouse due to external and internal customers. The central warehouse must simultaneously set aside enough inventories to satisfy external customers' demands and to provide the RWs with enough product on hand to satisfy the RW's customers' demands. Another problem is to synchronize the replenishment activities of new and refurbished products between the two echelons to minimize inventory and to balance costs of orders handled between central distribution and RWs. Failure to adequately tackle these challenges will lead to increased inventory costs and potential service failures.

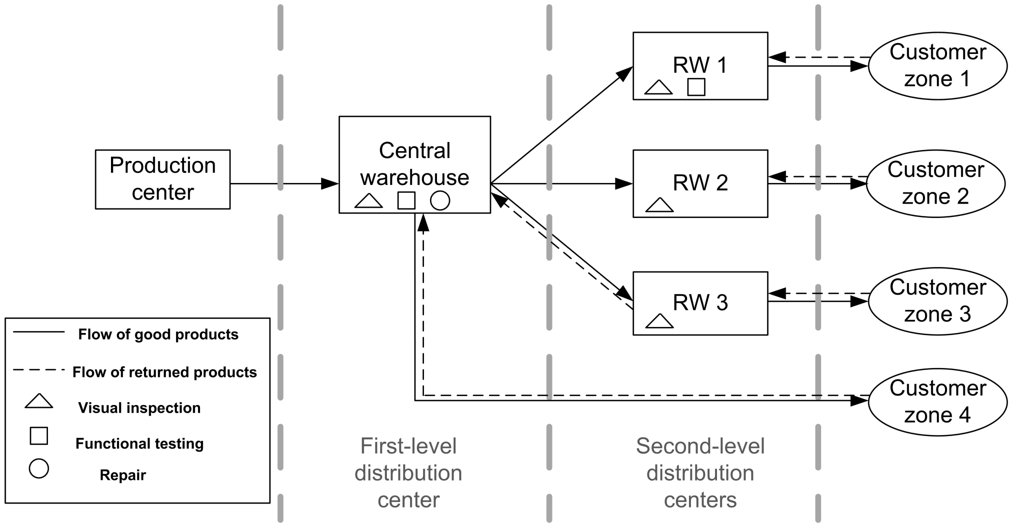


FIGURE 4.3: The current warranty distribution network of FTL.

FTL together with the 3PL service provider would like to redesign the distribution network of FTL warranty program, such that operation costs are reduced while after-sale service can still be conducted within required response time. In particular, FTL considers the following network adjustments:

- reassigning customers among distribution centers for after-sale service
- adjusting the forward and reverse flow of products
- adjusting the inventory replenishment frequency at distribution centers
- reassigning visual inspection, functional testing, and repair tasks among distribution centers
- closing some of the distribution centers.

Besides, a first-level distribution center may become a second-level distribution center, and vice versa. Note that for visual inspection is not required specialized equipment. Therefore, all distribution centers have the potential to visually inspect returned products without any setup or fixed operation cost.

4.3 The NLMIP model

In this section, we introduce a nonlinear mixed integer programming model for the redesign of the warranty distribution network of FTL. The index sets, cost parameters, and decision variables of the NLMIP model are as follows:

Index sets

$i \in \{1, \ldots, I\}$	the index of a customer
$j, k \in \{1, \ldots, J\}$	the index of a distribution center

Costs and prices

c_j^1 the cost for functional testing of one returned product at distribution center j

c_j^2 the repair cost for one returned product at distribution center j

f_j^1 the fixed operation cost of distribution center j

f_j^2 the fixed cost of distribution center j for functional testing

f_j^3 the fixed cost of distribution center j for repair

h_j the holding (opportunity) cost rate at distribution center j

n_j the penalty cost for closing distribution center j

o_j the ordering cost at distribution center j

tr_j^1 the cost for supplying one new product from production center of FTL to the first-level distribution center j

tr_{kj}^2 the cost for delivering one product from distribution center k to distribution center j ($tr_{kk}^2 = 0, \forall k$)

tr_{ij}^3 the cost of distribution center j for processing one returned product from customer i (including service and visual inspection costs)

u the production cost of a new product at FTL production center

Other parameters

l_{ij} the lead time of distribution center j for serving customer i

M_1 a constant is larger than $\sum_{i=1}^{I} \lambda_i$

P_i^1 the probability that a product returned from customer i will be sent to functional testing after visual inspection

P_i^{11} the probability that a product returned from customer i is is sent to inventory

P_i^2 the probability that a product returned from customer i will be sent to repair after functional testing

P_i^{21} the probability that a product returned from customer i is repaired

r_i the response time specified by the warranty contract with customer i

λ_i the number of warranty claims received from customer i per time unit

Decision variables

$$X_{ij} = \begin{cases} 1, & \text{if customer } i \text{ is served by distribution center } j \\ 0, & \text{otherwise} \end{cases}$$

$$Z_j^1 = \begin{cases} 1, & \text{if distribution center } j \text{ remains open} \\ 0, & \text{otherwise} \end{cases}$$

$$Z_j^2 = \begin{cases} 1, & \text{if distribution center } j \text{ can perform functional testing} \\ 0, & \text{otherwise} \end{cases}$$

$$Z_j^3 = \begin{cases} 1, & \text{if distribution center } j \text{ can perform repair} \\ 0, & \text{otherwise} \end{cases}$$

$R_j \in \mathbb{R}_+$ the number of inventory replenishments at distribution center j per time unit

$V_{ij} \in \mathbb{R}_+^0$ the number of returned products from customer i, which are repaired at distribution center j

$T_{ij} \in \mathbb{R}_+^0$ the total expenditure on the returned products from customer i, which are successfully repaired at distribution center j

$W_{ikj} \in \mathbb{R}_+^0$ the number of returned products from customer i that are received at distribution center k and tested for functionality at distribution center j, if functional testing is required (when $W_{ikk} > 0$ for some k, returned products from customer i are visual inspected and tested for functionality at the distribution center k)

$Y_{kj} \in \mathbb{R}_+^0$ the number of new products at distribution center j that are replenished by the distribution center k (when $Y_{kk} > 0$ for some k, the distribution center k is a first-level distribution center, and Y_{kk} of new products are supplied to distribution center k from the FTL production center)

where $\mathbb{R}_+^0 = \{x \in \mathbb{R} : x \geq 0\}$ and $\mathbb{R}_+ = \{x \in \mathbb{R} : x > 0\}$.

The NLMIP model minimizes the total operation cost of the WDN. Operation costs considered by objective (4.3) (see below) include the cost for replenishing inventory at distribution centers, the cost of customer service, inventory holding and ordering costs, visual inspection, functional testing and repair costs of returned products, fixed operation costs, and closing penalty costs. In particular, the cost for replenishing inventory with new products is given by

$$\sum_{j=1}^{J}(u + tr_j^1)Y_{jj} + \sum_{j,k=1,k\neq j}^{J} tr_{kj}^2 Y_{kj}.$$

The cost for customer service and visual inspection is given by

$$\sum_{i=1}^{I}\sum_{j=1}^{J}\lambda_i tr_{ij}^3 X_{ij}.$$

The inventory holding cost of new products and returned products at distribution center j reflect the opportunity cost of investments locked in inventory, and are given by

$$\frac{h_j}{2R_j}\left(\sum_{k=1}^{J}(u + tr_{kj}^2 + tr_k^1)Y_{kj} + \sum_{i=1}^{I}\sum_{k=1}^{J}(c_j^1 + tr_{kj}^2 + tr_{ik}^3)P_i^1 P_i^{11} W_{ikj} + T_{ij}\right). \tag{4.1}$$

Note that every item of inventory at a distribution center is expected to hold for a period of $1/(2R_j)$. The investment of a new product includes the production and transportation costs, while the investment of a refurbished product includes the cost for conducting recovery processes and the transportation costs. The complete inventory ordering cost is given by

$$\sum_{j=1}^{J} o_j R_j Z_j^1. \tag{4.2}$$

The total cost for conducting functional testing and repair is given by

$$\sum_{i=1}^{I}\sum_{j=1}^{J}\left[\sum_{k=1}^{J}(c_j^1 + tr_{kj}^2)P_i^1 W_{ikj}\right] + c_j^2 V_{ij}.$$

The sum of all fixed costs is given by

$$\sum_{j=1}^{J}(f_j^1 Z_j^1 + f_j^2 Z_j^2 + f_j^3 Z_j^3).$$

Here we consider the fixed operation costs of distribution centers, and the fixed costs for keeping functional testing and repair functions at distribution centers. Penalty costs for closing distribution centers are given by

$$\sum_{j=1}^{J} n_j(1 - Z_j^1).$$

The objective function of the NLMIP model is:

$$\begin{aligned}
\min \quad & \sum_{j=1}^{J}(u+tr_j^1)Y_{jj} + \sum_{j,k=1,k\neq j}^{J} tr_{kj}^2 Y_{kj} + \sum_{i=1}^{I}\sum_{j=1}^{J}\lambda_i tr_{ij}^3 X_{ij} + \sum_{j=1}^{J}\Bigg[o_j Z_j^1 R_j \\
& + \frac{h_j}{2R_j}\Bigg(\sum_{k=1}^{J}(u+tr_{kj}^2+tr_k^1)Y_{kj} + \sum_{i=1}^{I}\sum_{k=1}^{J}(c_j^1+tr_{kj}^2+tr_{ik}^3)P_i^1P_i^{11}W_{ikj} + T_{ij}\Bigg)\Bigg] \\
& + \sum_{j=1}^{J}\Bigg[\sum_{i=1}^{I}\sum_{k=1}^{J}(c_j^1+tr_{kj}^2)P_i^1 W_{ikj} + c_j^2 V_{ij}\Bigg] + \sum_{j=1}^{J}(f_j^1 Z_j^1 + f_j^2 Z_j^2 + f_j^3 Z_j^3 \\
& + n_j(1-Z_j^1))
\end{aligned} \tag{4.3}$$

The NLMIP model subjects to the following constraints:
Constraint (4.4) ensures that the outbound flow at a distribution center equals to the inbound flow. The inbound flow consists of the supply of inventory from new and returned products, and the outbound flow consists of the demand from customers and other distribution centers.

$$\sum_{k=1,\,k\neq j}^{J} Y_{jk} + \sum_{i=1}^{I}\lambda_i X_{ij} = \sum_{k=1}^{J} Y_{kj} + \sum_{i=1}^{I}\Big(\sum_{k=1}^{J} P_i^1 P_i^{11} W_{ikj} + P_i^{21} V_{ij}\Big) \qquad \forall j \tag{4.4}$$

Constraint (4.5) requires that the total number of new products transferred out of distribution center j is less than or equal to the number of new products purchased at distribution center j. Hence, the here proposed NLMIP model allows only two levels of distribution centers for the forward flow of new products.

$$\sum_{k=1,\,k\neq j}^{J} Y_{jk} \leq Y_{jj} \quad \forall j \tag{4.5}$$

Note that constraint (4.5) also ensures that $\sum_{k=1}^{J} Y_{kj} - \sum_{k=1,\,k\neq j}^{J} Y_{jk}$ is nonnegative in constraint (4.4). This nonnegative number equals to the number of new products used for serving customers of distribution center j. Constraint (4.6) ensures that each customer is served by one distribution center.

$$\sum_{j=1}^{J} X_{ij} = 1 \quad \forall i \tag{4.6}$$

Constraint (4.7) requires that the number of products that are sent to functional testing is less than or equal to the total number returned products from customer i. This constraint also ensures that if distribution center j provides after-sale service to customer i, the returned products from customer i are transferred via distribution center j to a distribution center k for functional testing.

$$\lambda_i X_{ij} \geq \sum_{k=1}^{J} W_{ijk} \qquad \forall i, j \tag{4.7}$$

Constraint (4.8) ensures that the variable V_{ij} (for all i, j) equals to the number of products that are sent to repair.

$$P_i^1 P_i^2 Z_j^3 \sum_{k=1}^{J} W_{ikj} = V_{ij} \qquad \forall i, j \tag{4.8}$$

Constraint (4.9) ensures that the variable T_{ij} (for all i, j) equals to the total expenditure on the returned products of customer i, which are successfully repaired at distribution center j.

$$P_i^1 P_i^2 P_i^{21} Z_j^3 \sum_{k=1}^{J} (c_j^1 + tr_{kj}^2 + tr_{ik}^3 + c_j^2) W_{ikj} = T_{ij} \qquad \forall i, j \tag{4.9}$$

Constraint (4.10) forces Z_j^1 to be equal to one when there is any inbound flow at distribution center j.

$$\mathrm{M}_1 \cdot Z_j^1 \geq \sum_{k=1}^{J} Y_{kj} + \sum_{i=1}^{I} \sum_{k=1}^{J} W_{ikj} \qquad \forall j, \tag{4.10}$$

where M_1 is a large constant. Constraint (4.11) (resp. (4.12)) forces Z_j^2 (resp. Z_j^3) to be equal to one when the distribution center j provides functional testing (resp. repairing).

$$\mathrm{M}_1 \cdot Z_j^2 \geq W_{ikj} \qquad \forall i, k, j \tag{4.11}$$

$$\mathrm{M}_1 \cdot Z_j^3 \geq V_{ij} \qquad \forall i, j \tag{4.12}$$

In order to avoid the unstable performance of Big M formulations, constraints (4.10)–(4.12) are implemented as indicator constraints in AIMMS. Constraint (4.13) requires that every customer is assigned to a close-by distribution center such that the after-sale service can be finished within the promised response time.

$$\sum_{j=1}^{J} l_{ij} X_{ij} \leq r_i \qquad \forall i \tag{4.13}$$

Finally, we specify model variables, i.e.,

$$\begin{aligned} & R_j \in \mathbb{R}_+, \ W_{ikj}, V_{ij}, Y_{kj}, T_{ij} \in \mathbb{R}_+^0, \\ & X_{ij}, Z_j^1, Z_j^2, Z_j^3 \in \{0, 1\}, \qquad \forall i, j, k. \end{aligned} \tag{4.14}$$

Our NLMIP model has the objective function (4.3) and constraints (4.4)-(4.14).

4.4 On linearizing nonlinear model

The nonlinear formulation of inventory holding cost (4.1), ordering cost (4.2), and constraints (4.8), (4.9) make the proposed model (4.3)-(4.14) a nonlinear nonconvex optimization problem. It is well known that such a problem is hard to solve and obtaining its global optimal solution is, in general, intractable. Therefore, deriving a tight linear approximation of the NLMIP model (4.3)-(4.14) is essential for obtaining a high-quality solution of the distribution network redesign problem of FTL. In this section, we linearize constraints (4.2), (4.8), and (4.9) by introducing additional variables and constraints. We also piecewise linearize the inventory holding cost (4.1) by adopting the approach from D'Ambrosio et al. [2010]. For more information about piecewise linear approximation, interested reader might read Vielma et al. [2010] and Geißler et al. [2012]. We elaborate the detailed procedures of linearization and approximation in the rest of the section.

In order to derive a linear reformulation of (4.2), we introduce for each $j \in \{1, \ldots, J\}$ a new variable B_j that represents the inventory ordering costs at distribution center j. Assuming that

$$0 < \underline{R}_j \leq R_j \leq \bar{R}_j, \tag{4.15}$$

where $\bar{R}_j$ (resp. $\underline{R}_j$) is the maximum (resp. minimum) number of replenishments at distribution center j in a time unit, we ensure that $B_j = o_j Z_j^1 R_j$, $\forall j$ with the following constraints:

$$B_j \leq o_j Z_j^1 \bar{R}_j \qquad \forall j \tag{4.16}$$

$$B_j \leq o_j R_j \qquad \forall j \tag{4.17}$$

$$B_j \geq o_j R_j - o_j \bar{R}_j (1 - Z_j^1) \qquad \forall j \tag{4.18}$$

$$B_j \geq 0. \qquad \forall j \tag{4.19}$$

Finally, by replacing the complete inventory ordering cost (4.2) with $\sum_j B_j$ in the objective function (4.3) and adding constraints (4.16)–(4.19) for each j, we linearize (4.2).

Similarly, we can replace (4.8) with the following linear constraints:

$$V_{ij} \leq P_i^1 P_i^2 \lambda_i Z_j^3 \qquad \forall i, j \qquad (4.20)$$

$$V_{ij} \leq P_i^1 P_i^2 \sum_{k=1}^{J} W_{ikj} \qquad \forall i, j \qquad (4.21)$$

$$V_{ij} \geq P_i^1 P_i^2 \sum_{k=1}^{J} W_{ikj} - P_i^1 P_i^2 \lambda_i (1 - Z_j^3) \qquad \forall i, j. \qquad (4.22)$$

Here, we exploit that for fixed i, j, $0 \leq \sum_{k=1}^{J} W_{ikj} \leq \lambda_i$ is satisfied. Note that it is also required $V_{ij} \geq 0$ for all i, j, see (4.14). Furthermore, since (4.20) provides in general a tighter restriction on V_{ij} than (4.12), constraint (4.12) can be omitted from the linearized model formulation in the presence of (4.20).

For fixed i, j, we define the maximum expenditure for repairing a returned product, i.e.,

$$\mathrm{M}_2 := \max_k \{c_j^1 + tr_{kj}^2 + tr_{ik}^3 + c_j^2\}.$$

Since $0 \leq \sum_{k=1}^{J} (c_j^1 + tr_{kj}^2 + tr_{ik}^3 + c_j^2) W_{ikj} \leq \mathrm{M}_2 \lambda_i$, we can replace constraints in (4.9) with the following linear constraints:

$$P_i^1 P_i^2 P_i^{21} \sum_{k=1}^{J} (c_j^1 + tr_{kj}^2 + tr_{ik}^3 + c_j^2) W_{ikj} - P_i^1 P_i^2 P_i^{21} \mathrm{M}_2 \lambda_i (1 - Z_j^3) \leq T_{ij}, \quad \forall i, j. \quad (4.23)$$

Constraint (4.23) is implemented as an indicator constraint in AIMMS. Note that since the objective function (4.3) minimizes the total operation costs, constraints similar to (4.20) and (4.21) for bounding the value of T_{ij} from above can be omitted. The same argument is not true for omitting constraints (4.20) and (4.21), since increasing V_{ij} may results in cost reduction.

The inventory holding cost (4.1) at distribution center j is a nonlinear function that can not be simply replaced by a set of linear constraints. Therefore, we approximate (4.1) by using a piecewise linear approximation. For the ease of notation, we define a new variable H_j representing the value of investments that are locked in the inventory at distribution center j, i.e.,

$$H_j := \sum_{k=1}^{J} (u + tr_{kj}^2 + tr_k^1) Y_{kj} + \sum_{i=1}^{I} \Big(\sum_{k=1}^{J} (c_j^1 + tr_{kj}^2 + tr_{ik}^3) P_i^1 P_i^{11} W_{ikj} + T_{ij} \Big).$$

Therefore, the inventory holding cost at distribution center j may be written as

$$F^j(R_j, H_j) = \frac{h_j H_j}{2R_j}. \qquad (4.24)$$

Now, for each distribution center j, we take S samples of R_j which are denoted by $\{R_j^s|\ s = 1,\dots,S\}$. While the values R_j^1 and R_j^S are equal to $\underline{R}_j$ and $\bar{R}_j$ respectively, see (4.15), the remaining samples are selected from the interval $[\underline{R}_j, \bar{R}_j]$ with equal distances between consecutive samples. For any given value $\hat{R}_j \in [R_j^s, R_j^{s+1})$, $s \in \{1,\dots,S-1\}$, the approximate function value of $F^j(\hat{R}_j, H_j)$ is given by $F^j(R_j^s, H_j)$, which is the function value at the left extreme of the sample interval containing $\hat{R}_j$. To be more specific, by defining a binary variable $\beta_j^s \in \{0,1\}$ to be equal to one when $R_j^s \le R_j < R_j^{s+1}$ and zero otherwise, we approximate the value of $F^j(R_j, H_j)$, $\forall j$ with the following constraints:

$$\sum_{s=1}^{S-1} \beta_j^s = 1 \qquad \forall j \tag{4.25}$$

$$R_j \ge \sum_{s=1}^{S-1} \beta_j^s R_j^s \qquad \forall j \tag{4.26}$$

$$R_j < \sum_{s=1}^{S-1} \beta_j^s R_j^{s+1} \qquad \forall j \tag{4.27}$$

$$F^j(R_j, H_j) \le F^j(R_j^s, H_j) + (1-\beta_j^s)\mathrm{M}_3 \qquad \forall j, s = 1,\dots,S-1 \tag{4.28}$$

$$F^j(R_j, H_j) \ge F^j(R_j^s, H_j) - (1-\beta_j^s)\mathrm{M}_3 \qquad \forall j, s = 1,\dots,S-1, \tag{4.29}$$

where M_3 is a constant that is larger than $\max_j F^j(\bar{R}_j\underline{R}_j/(\bar{R}_j - \underline{R}_j), \bar{H})$. Here, $\bar{H}$ is the total market value of products that are requested by customers in a time unit. Note that $F^j(\bar{R}_j\underline{R}_j/(\bar{R}_j - \underline{R}_j), \bar{H}) = F^j(\underline{R}_j, \bar{H}) - F^j(\bar{R}_j, \bar{H})$, represents the maximum variation of inventory holding cost when R_j changes. Constraints (4.28) and (4.29) ensure that $F^j(R_j, H_j) = F^j(R_j^s, H_j)$ when $\beta_j^s = 1$ for any $s \in \{1,\dots,S-1\}$. Since $F^j(R_j^s, H_j)$ is linear in H_j for the fixed R_j^s, the here described approximation approach is a simplified approach from D'Ambrosio et al. [2010], where sampling of the second variable is also required.

After replacing the cost terms (4.1) and (4.2) with $F^j(R_j, H_j)$ and B_j, respectively, in objective function (4.3) the linearized objective function is:

$$\begin{aligned}&\sum_{j=1}^{J}(u + tr_j^1)Y_{jj} + \sum_{j=1}^{J}\sum_{k=1}^{J} tr_{kj}^2 Y_{kj} + \sum_{i=1}^{I}\sum_{j=1}^{J} \lambda_i tr_{ij}^3 X_{ij} + \sum_{j=1}^{J}(B_j + F^j(R_j, H_j))\\ &+ \sum_{j=1}^{J}\left[\sum_{i=1}^{I}\sum_{k=1}^{J}(c_j^1 + tr_{kj}^2)P_i^1 W_{ikj} + c_j^2 V_{ij}\right] + \sum_{j=1}^{J}(f_j^1 Z_j^1 + f_j^2 Z_j^2 + f_j^3 Z_j^3 + n_j(1 - Z_j^1))\end{aligned} \tag{4.30}$$

In addition, constraint (4.14) is extended for specifying new variables H_j, B_j, β_j^s, and F^j as follows:

$$R_j \in \mathbb{R}_+, W_{ikj}, V_{ij}, Y_{kj}, T_{ij}, H_j, B_j, F^j \in \mathbb{R}_+^0,$$
$$X_{ij}, Z_j^1, Z_j^2, Z_j^3, \beta_j^s \in \{0, 1\}. \tag{4.31}$$

Finally, the linearized NLMIP has objective function (4.30) and constraints (4.4)–(4.7), (4.10), (4.11), (4.13), (4.16)–(4.23), (4.25)–(4.29), (4.31). We refer to the linearized NLMIP model as the LMIP model. Note that the complexity of the LMIP model with respect to the number of variables and constraints is $O(IJ^2 + SJ)$.

Since the LMIP model is obtained from the NLMIP model by adding additional variables and constraints and replacing variable R_j with a sample in the objective, the solution of the LMIP model is also a feasible solution of the NLMIP model. Furthermore, note that R_j is involved in constraints (4.17), (4.18), (4.26), and (4.27). Constraints (4.26) and (4.27) require $R_j^s \le R_j < R_j^{s+1}$ and $F^j(R_j, H_j) = F^j(R_j^s, H_j)$ when $\beta_j^s = 1$. Constraints (4.17) and (4.18) ensure that $R_j = R_j^s$ in the optimal solution of the LMIP model when $R_j^s \le R_j < R_j^{s+1}$ and $Z_j^1 = 1$. It suggests that in the optimal solution both $R_j = R_j^s$ and $F^j(R_j, H_j) = F^j(R_j^s, H_j)$ are ensured for any operating distribution center j. Therefore, if the optimal solution of the LMIP model is entered into the NLMIP model, the objectives of the NLMIP model and the LMIP model will be the same. In the next section, we present the test results of the LMIP model and discuss its performance.

4.5 Numerical results

The LMIP model is used for redesigning the warranty distribution network of FTL. In this section, we first present the computation results of the LMIP model and the improved design of the warranty distribution network. Then we discuss the results of a sensitivity analysis regarding the uncertainties of the number of warranty claims, transportation costs, and probabilities that appear in the recovery model. All problems in Section 4.5 are solved by CPLEX using AIMMS interface, running on a PC with Intel Core2 Quad CPU, 2.66GHz, and 3.21GB of memory.

4.5.1 Computation results

The implementation of the LMIP model requires a preselection of S, the number of samples of R_j. On the one hand, a larger value of S results in a tighter approximation of $F^j(R_j, H_j)$, see (4.24). On the other hand, larger S results in a larger number of variables and constraints, hence, higher computational cost. Here, we test the LMIP model by a gradually increasing value of S. To be specific, we set for S the following values 21, 51, 101, 201, 301, and 401. Computational details and results are summarized in Table 4.1. The columns two to six specify the following features of each test: the value of S, the number of variables, the number of constraints, the computational time in seconds, and the objective value, respectively.

TABLE 4.1: Computation results of the LMIP model

Tests	S	♯ of variables	♯ of constraints	Computational time (Sec.)	Total cost[a]
1	21	1584	2137	3	113382.84
2	51	1705	2377	10	113224.63
3	101	1905	2777	77	113224.11
4	201	2305	3577	771	113219.25
5	301	2705	4377	3700	113217.19
6	401	3105	5177	7562	113216.34

[a]Cost figures are masked.

Along with the increasing value of S, the computational time increases and the objective value decreases. While the improvement in the objective from test one to test two is about 158 Euros, there is a difference of only about 8 Euros between tests six and two, which accounts a minor improvement of less than 0.01%.

Although the solution of LMIP model varies with the choice of S, the results of tests 2–6 suggest the same warranty distribution network (see Figure 4.4). By comparing Figure 4.4 with Figure 4.3, we identify the following network allocation and flow differences:

- Network allocation differences:
  - The complete recovery processes are established at RW 1 and 2.
  - RW 3 is closed.
- Network flow differences:
  - Customer zone three which was served by RW 3 is now served by the central warehouse.
  - Central warehouse supplies RW 2 with returned products instead of new products.

The new design of the warranty distribution network suggests that the recovery of returned products should always be performed whenever it is possible. While recovering returned products of customer zones one and two is suggested to be performed at the closest-by regional warehouses, the returned products of customer zone three and four are suggested to be recovered at the central warehouse. Test results suggest that the

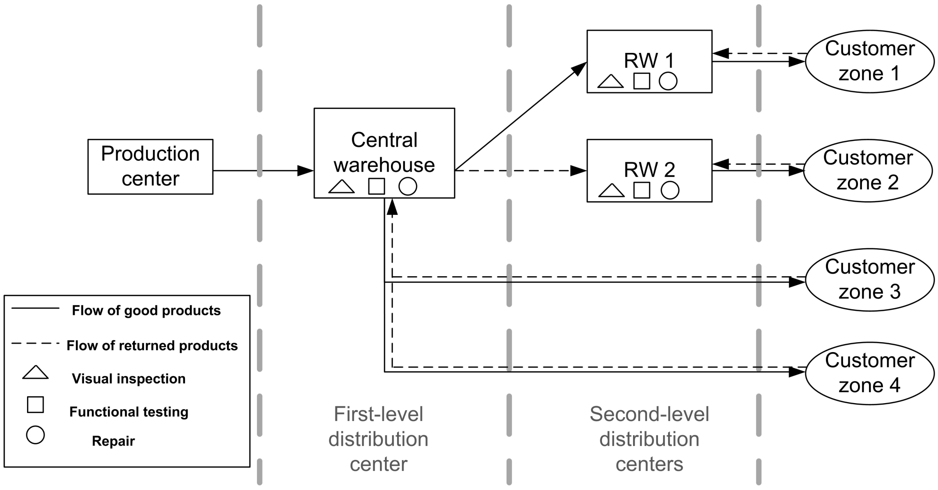


FIGURE 4.4: The new warranty distribution network of FTL.

new warranty distribution network reduces the total cost for 3.4%, which is a reasonable extra margin for one product line only. Also, that is a sustainable saving in the current economic environment.

4.5.2 Sensitivity analysis

Warranty distribution networks are exposed to uncertainties. Increasing visibility and traceability of returns and recovery supply chain velocity would ease the uncertainties. However, it will not remove them altogether. Therefore, the network design must be checked under stress conditions. In recent years, the robust optimization approach is used to deal with supply chain uncertainties, see e.g., Bertsimas and Thiele [2004], Pishvaee et al. [2011]. However, the robust design of the here described warranty distribution network would be extremely difficult due to the nonlinearities of the NLMIP model itself. Therefore, we perform a sensitivity analysis in order to identify the impact of uncertainties on the solution of the problem under investigation.

Since most of the uncertainties of a closed-loop supply chain come from demand, transportation, and recovering process, we perform a sensitivity analysis on the following parameters: λ, tr^1, tr^3, P^{11}, and P^{21}. In the sensitivity analysis we change values of the above mentioned parameters one, by one and set at 10% or 20% higher or lower values from their original ones. Considering the periodical introduction of new product configurations, the 10% and 20% variation of parameter values are reasonable for the here considered electronic industry. In order to obtain keen observations while keeping computation manageable, all tests of the sensitivity analysis are conducted with 201 samples of R_j. The column two to eight of Table 4.2 specify the following features of the obtained test results: parameter changes, the total number of refurbished products, the total number of purchased new products, the total value of products in inventory, the total number of replenishments per time unit, the total inventory cost, and the objective value, respectively.

TABLE 4.2: Sensitivity analysis of the LMIP model

Tests	Scenarios	♯ of refurb. products	♯ of new products	Inventory value	♯ of replenishments	Inventory cost	Total cost[a]
4	Base case	695	310	61199.78	10.72	2271.73	113219.25
7	λ 20% $\downarrow$	556	249	56919.54	10.62	2446.75	98082.64
8	λ 10% $\downarrow$	628	280	61355.63	10.77	2325.60	106009.28
9	λ 10% $\uparrow$	765	342	67315.04	10.77	2376.29	120747.49
10	λ 20% $\uparrow$	833	372	73303.00	10.82	2494.72	128110.01
11	tr^1 20% $\downarrow$	695	310	61059.18	10.72	2270.00	113089.07
12	tr^1 10% $\downarrow$	695	310	61129.48	10.72	2270.87	113154.16
13	tr^1 10% $\uparrow$	695	310	61270.08	10.72	2272.60	113284.35
14	tr^1 20% $\uparrow$	695	310	61340.38	10.72	2273.47	113349.44
15	tr^3 20% $\downarrow$	695	310	54175.82	10.52	2011.51	106377.05
16	tr^3 10% $\downarrow$	695	310	58873.58	10.72	2217.16	109799.52
17	tr^3 10% $\uparrow$	695	310	63525.98	10.77	2323.40	116636.08
18	tr^3 20% $\uparrow$	695	310	65852.17	10.77	2374.80	120052.63
19	P^{11}, P^{21} 20% $\downarrow$	451	554	79725.65	10.92	2786.95	135353.82
20	P^{11}, P^{21} 10% $\downarrow$	582	423	66432.66	10.77	2335.05	123579.11
21	P^{11}, P^{21} 10% $\uparrow$	788	217	55045.96	10.57	2120.35	104461.02
22	P^{11}, P^{21} 20% $\uparrow$	862	143	51856.69	10.22	2101.26	97336.57
23	P^{11}, P^{21} 30% $\downarrow$	0	1005	94036.91	10.92	2858.87	146237.30

[a] Cost figures are masked.

There are several conclusions that arise from our sensitivity analysis. We list our these as follows:

- Results of tests seven, eight, and 19 provide different network allocations and flows from the warranty distribution network shown in Figure 4.4. The results of test eight suggest that RW 1 only perform visual inspection to returned products. All returned products from customer zone one are collected by RW 1, and then sent to the central warehouse for functional testing and repair. Therefore, we can conclude that RW 1 loses the economy of scale for performing functional testing and repair when the number of warranty claims reduces by 10%. Similarly, when the number of warranty claims or probabilities for recovering returned products reduces by 20%, the results of test seven and 19 suggest that both RW 1 and 2 lose the economy of scale for performing functional testing and repair. All returned products of customer zone one and two are visually inspected at RW 1 and 2 and then sent to the central warehouse for functional testing and repair.

- Results of tests 15, 21, and 22 provide different network flows from the warranty distribution network shown in Figure 4.4. The central warehouse is suggested to supply RW 1 with returned products instead of new products. Note that replenishing inventory with returned products instead of new products results in reduced inventory holding costs but increased transportation costs among distribution centers. The reduction of tr^3 in test 15 suggests reduced inventory values of returned products, strengthening the reduction of inventory holding costs. The increase of P^{11} and P^{21} in tests 21 and 22 suggests a reduced number of returned products that are needed for generating refurbished products at RW 1, weakening the increase of transportation costs among distribution centers. Therefore, both the reduction of tr^3 and the increase of P^{11} and P^{21} support replenishing RW 1 with returned products.

- The warranty claims received by FTL represent not only the demand of well-functioning products but also the supply of returned products. Since the number of refurbished products is proportional to the number of returned products, an increase (resp. decrease) of λ suggests an increased (resp. decreased) number of refurbished products and an increased (resp. decreased) demand for new products.

- An increase (resp. decrease) of P^{11} and P^{21} results in an increased (resp. decreased) number of refurbished products. In order to serve the same number of warranty claims, a reduced (resp. increased) number of new products are purchased. Therefore, the variation of P^{11} and P^{21} influences the proportion of refurbished products to new products in inventory. Furthermore, recovering returned products may become unprofitable when P^{11} and P^{21} further decrease (see test 23). Accurate estimations of P^{11} and P^{21} are essential for the success of warranty distribution network redesign.

- The total number of replenishments per time unit, the total inventory cost, and the total cost are positively correlated with the total inventory value. Note that an increase of the inventory value may result from the following three reasons:

  - an increased number of warranty claims (e.g. tests 9 and 10)
  - an increased proportion of new products to refurbished products in inventory (e.g. tests 19 and 20)
  - increased operation costs (e.g. tests 13, 14, 17, and 18).

- The variation of both tr^1 and tr^3 shows no significant influence on the number of new products purchased and the number of products refurbished, not even when the variation increases to 50% or 100% (see tests 24-31 in Table 4.3). Note that according to the warranty service agreements of FTL, all warranty claims need to be inspected, suggesting that tr^3 cannot be avoided. Although the variation of tr^3 significantly influences the total cost of the warranty distribution network, serving customers with refurbished products remains relatively cheap. Hence, the variation of tr^3 does not affect the number of new products purchased and the number of products refurbished. The insignificant influence of tr^1 variation, however, is caused by the low transportation cost between the center warehouse and the production center. The cost is too low to influence the cost advantage of serving customers with refurbished products. The test results suggest that tr^1 has no significant influence on the number of new products purchased and the number of products refurbished even when the variation increases to 100%.

TABLE 4.3: Extended sensitivity analysis of the LMIP model

Tests	Scenarios	♯ of refurb. products	♯ of new products	Inventory value	♯ of replenishments	Inventory cost	Total cost[a]
24	tr^1 50% ↓	695	310	60848.275	10.719	2267.408	112893.784
25	tr^1 50% ↑	695	310	61551.275	10.719	2276.062	113544.724
26	tr^1 100% ↓	695	310	58828.099	10.819	2561.957	111593.407
27	tr^1 100% ↑	695	310	61902.776	10.719	2280.389	113870.195
28	tr^3 50% ↓	695	310	47197.221	9.870	1800.394	96070.460
29	tr^3 50% ↑	695	310	72830.774	10.819	2522.431	130295.740
30	tr^3 100% ↓	695	310	36823.243	7.862	1962.281	67560.865
31	tr^3 100% ↑	695	310	94288.945	10.919	2860.135	147237.053

[a] Cost figures are masked.

4.6 Summary

Effective warranty distribution network design and management is still not on the radar maps of most companies. Many have outsourced the entire process, like the case under study, and expect only to receive the promised service at lowest costs by the logistics provider. In order to increase warranty service performance, the activity should not be looked at as a cost center, but as a source of value for both the Original Equipment Manufacturer (OEM) company and the respective 3PL service provider. Efficient warranty distribution network should not be simply considered as closed loop supply chain, it should also include repair service options of returned products. Depending on the involved recovery processes at possibly geographically separated recovery facilities, the associated costs for recovering returned products may vary considerably. Therefore, to obtain an optimal design of a warranty distribution network one needs to optimize both, a closed-loop distribution network and recovery processes of returned products.

In this chapter, we propose a nonlinear, nonconvex mixed integer programming model for the design of a warranty distribution network of a semiconductor company. Our model optimizes a design of recovery processes of returned products and inventory locations of refurbished products, as well as the forward flow of new products. Based on evidence from the literature, most papers on closed-loop supply chain network design assume returned products can only be turned into usable products by performing the same recovery processes at a fixed location. We consider here different recovery processes of returned products, which could be performed at alternative echelons, which results in nonlinearities in the model. In order to obtain a solution of the nonlinear and nonconvex optimization problem, we derive a piecewise-linear model as a tight linear approximation of the NLMIP model. The solution quality and the computation complexity of the linearized model depends on the preselected number of samples of one of the model variables. Our approach results with an improved design of the warranty distribution network.

The model can be easily implemented for various large e-commerce businesses or OEMs like automotive or aircraft manufacturers, or other electronic companies similar to the case under study. For example, car companies have usually an extensive network of workshops (garages) where warranty services are offered. The model can be also used by logistics service providers to reduce own costs and pass on part of saving to clients and release warehousing and transportation capacities for new business opportunities. As our experience in this case suggests, the opportunity gains may be potentially very large. A service provider with such an optimization model in hand, has a tool to improve own performance and that of the clients.

It is worth mentioning that although the here presented NLMIP model is for the design of a particular warranty distribution network, it can also be used for analyzing outsourcing options of recovery operations to certified repair vendors, or for evaluating service contract with third party logistics providers. With certain modifications, the here proposed approach can take into account even more complicated recovery processes and reuse options of returned products, and provides valuable insights for the design of warranty distribution networks with multiple product types and warranty service types. Multiple product returns makes WDN much more challenging, as products may be dispatched to different repair vendors from different echelons of the distribution network. Without an optimization model, like the one proposed here, system cost gradually increases and service will decrease.

Supply chain network (re-)design problems concern the resource deployment issues where production facility units need to be (re-)allocated. We discuss in Chapter 2 and 3 about selling and relocating of facilities for improving the financial performance of supply chain networks. In Chapter 4, the reallocation of facilities is addressed for improving the cost efficiency of a warranty distribution network. In these cases, the operations of facility units are always assumed to be predetermined and fixed. However, the operation at facility unit level is responsible for the day-to-day business performance and it is the key for achieving fast responsiveness and high production throughput. In the next chapter, we look into an optimization problem for improving the throughput of a facility unit, where two operational level decisions need to be determined simultaneously.

Chapter 5

An Aggregated Optimization Model for Multi-head SMD Placements

5.1 Introduction

The multi-head SMD (see Ayob and Kendall [2008]) is one of the most popular auto-assembly machines due to its relative high speed in mounting components on PCB and low price. The optimization problem for improving the throughput of its operations, however, is shown to be highly complex. McGinnis et al. [1992] summarize optimization problems for a SMD as arrangement of component feeders and sequencing of placement operations. To be specific, the major optimization problems of a multi-head SMD production planning consist of feeder arrangement, component and nozzle assignment to each placement head, as well as sequence of component placements on PCB. In addition to these problems, in this chapter, we are also interested in improving the traveling speed of the robot arm, which is a function of component delivery nozzles mounted on the robot placement heads. We specify this as a HC. Namely, some nozzles are better in handling certain component type and allow higher traveling speed of robot arm. Therefore, HC is implicitly determined as a result of component and nozzle assignment to the placement heads. Hence extra attention in component and nozzle assignment is needed in order to guarantee optimal HC. The HC problem or the traveling speed problem addressed in this chapter, to the best of our knowledge, has been for the first time incorporated in an optimization model.

Among the major problems of a SMD production planning, feeder arrangement is one of the crucial problems impacting PCB assembly throughput time. Lee et al. [2000]

develop a model solved by dynamic programming for determining the feeder assignment of a multi-head SMD and provide a method for reducing the computation time. Ayob and Kendall [2005] focus on improving the feeder setup of a sequential pick and place machine in order to minimize the robot assembly time, the feeder movements and PCB table movement. Li et al. [2008] studied an application of genetic algorithm for obtaining a feeder assignment of a turret-type SMD. Duman and Or [2007] search among specific algorithms reflecting implementation of taboo search, simulated annealing and genetic algorithm-type metaheuristics in order to identify the well performing heuristic procedures for solving the quadratic assignment problem of feeder assignment. The authors in Duman and Or [2007] conclude that the performance of a heuristic highly depends on the problem specifications.

The feeder arrangement for our assembly problem is formulated before conducting of the here proposed research. Therefore, we assume that the planning solution to the feeder assignment is known and focus on the remaining major problems of a multi-head SMD production planning. We refer to the remaining major problems, which consist of component and nozzle assignment to each placement head, improving HC, and sequence of component placements on PCB, as our multi-head SMD placement optimization problem. Very few literature has the same problem setting as ours because of the diversity of the machine type and the range of complexity problems involved. Burke et al. [1999, 2000, 2001] formulate a generalized traveling salesman problem model based on hypertours for a SMD which has the similar feature as ours. Their formulation includes the considerations of component type assignment to feeder slots, tool assignment to placement locations, and component placement sequence. A constructive and local search heuristics is provided in order to reduce computation time and determine locally optimal solutions. Lee et al. [2000] develop a hierarchical approach considering following three subproblems: construction of feeder reel-groups, assignment of those feeder reel-groups, and sequencing of pick-and-place movements, each of which is solved by a heuristics. The proposed method can be applied to SMD with any number of heads. Knuutila et al. [2007] proposed a greedy heuristic under the multi-head SMD environment for nozzle selection with the aim of minimizing the number of pickups when the sequence of component placements is given. This heuristic produces optimal solution under restricted assumptions. One observation from the literature review is that almost every kind of mathematical formulations related to the multi-head SMD placement optimization problem turn to be a large scale problem that cannot be solved in a reasonable time frame. Therefore, methods like TSP heuristic (see Lee et al. [2000], Zeng et al. [2004]), local search (see Ayob and Kendall [2003], Burke et al. [1999, 2000, 2001]), and genetic algorithms (see Hardas et al. [2008], Li et al. [2008], Sun et al. [2005]) are frequently applied.

As an effort in pursuing high quality solution, we present a way of deriving a tractable mathematical model for solving the multi-head SMD placement optimization problem. In this chapter, we develop a multi-objective MILP model for the multi-head SMD placement optimization problem based on batches of components along with a heuristic placing algorithm. The idea is to determine the optimal sequence of batches of components to the placement heads in the first stage by solving the MILP, and then to determine the sequence of components with a heuristic method in the second stage. These two steps together assure a feasible solution produced in reasonable time.

The rest of the chapter is organized as follows. In Section 5.2, we describe the main features of an auto-assembly process of a multi-head SMD. The MILP model is presented in Section 5.3, and the heuristic method for determining the final sequence of components is discussed in Section 5.4. In Section 5.5 we present the numerical results for the proposed approach with 15 real-life data sets.

5.2 SMD auto assembly problem

In this chapter we are interested in the multi-head SMD of the type AX2.01, see Figure 5.1, which is developed by Assembléon, formerly known as Philips Electronic Technology. It is a high accurate mounting device which is specialized for placing large number of components on a PCB. It is equipped with a fix PCB table, one feeder bank close to a corner of the PCB table, a single 4-head robot arm, one automatic nozzle changer (ANC) and two extra cameras for alignment. In each pick-and-place cycle, the robot arm moves from feeder banks first to the cameras and then to the PCB table where the mounting operation is taken place. The alignment at the cameras is required for providing high accuracy of the mounting operation, and components are first scanned and rotated if it is necessary for adjusting the positions in order to have components pointed at the planned directions. The cameras can align at most two components at a time. After leaving the PCB table, the robot arm then first visits ANC for exchanging nozzles before going to the feeder banks if there is one or more components in the next pick-and-place cycle requiring a nozzle different than those that are currently in use. The nozzle exchanges are normally very time consuming.

Without loss of generality, following assumptions are made:

1. We assume that each PCB of a certain type is processed one after another by the SMD.
2. The SMD is equipped with a fixed PCB table, one fixed feeder bank placed at low-left corner of the PCB table, an ANC, a robot arm, and a pair of cameras.

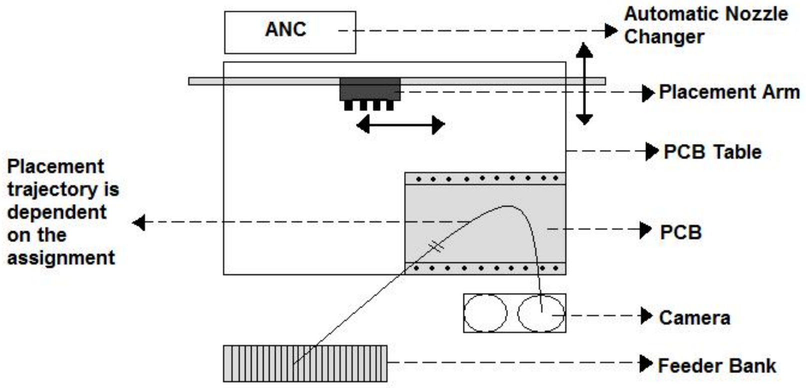


FIGURE 5.1: Layout of AX2.01

3. The robot arm has four placement heads and can carry at most four components in one pick-and-place cycle. Note that it is also possible to carry less than four components in one pick-and-place cycle.

4. The pair of cameras take a fixed time for scanning all components carried in one pick-and-place cycle.

5. The robot arm travels from camera to PCB for placing components, then travels to ANC first if nozzle-change is necessary, and then goes to the feeder bank for picking up components in each pick-and-place cycle.

6. The time needed for traveling in between the PCB table, the feeder bank, and camera is assumed to be fixed. Note that the traveling time between the PCB table and the feeder bank is assumed to be identical no matter wether ANC is visited by the robot arm in a pick-and-place cycle or not.

7. Powered by two separate motors, the robot arm travels simultaneously in the horizontal and vertical directions. Note that the separate motors may generate different traveling speeds in the horizontal and vertical directions. In this setting, the traveling time between two points on the PCB table is considered as the maximum of the horizontal and vertical traveling times. We refer to this type of movement as a Chebyshev traveling movement. (According to Abello et al. [2002], the Chebyshev distance is a metric defined on a vector space where the distance between two vectors is the greatest of their differences along any coordinate dimension.)

8. The HC specifies for each component the preferred delivery nozzles and the corresponding traveling speeds for different component-nozzle matchs. There are possibly more than one nozzles that can pick up a certain component.

9. The arm traveling speed is defined by the highest HC among four placement heads. We assume the lower the HC the higher the traveling speed, and the higher the HC the slower the traveling speed.

10. The time for picking up components at the feeder bank is assumed to be identical in every pick-and-place cycle.

11. Nozzles of the same type can be assigned to the placement heads simultaneously.

12. Every placement head is capable of visiting all places on the PCB table.

The main purpose of this research is to minimize the total processing time for mounting a PCB, which includes following four objectives: minimizing the number of nozzle exchanges, balancing workload among four placement heads, maximizing the traveling speed, and minimizing the traveling distance. The hierarchical procedure we propose splits the previously mentioned four objectives into two stages. In the first stage, we formulate a multi-objective MILP problem that includes optimizing the first three above mentioned objectives. In the second stage, we implement a heuristic that is based on the results obtained from the first stage, in order to determine the final sequencing by minimizing the traveling distance.

The main reasons for this partitioning are:

- The first three objectives are highly correlated with each other. Component assignment limits the possible nozzle selection, and the nozzle selection determines the HC and hence the traveling speed.

- The production processing time can be reduced most significantly by reducing the number of nozzle exchanges and the number of pick-and-place cycles, and increasing the average traveling speed. The traveling distance minimization, however, offers the least improvement on reducing the processing time.

- The exclusion of minimizing travel distance from first stage allows MILP formulation based on batches of components instead of single component, which results with reduced complexity.

- The MILP formulation based on batches of components defines the characteristics of the batches assigned to placement heads, such as the batch size, the component type, and the order of placements, but not the allocation of each individual component. Hence, by determining the component-wise placement order and allowing components exchange between batches of the same component type, the optimization in the second stage can still greatly explore the opportunity of refinement.

We believe that this hierarchical procedure is the best optimization approach in terms of reducing the complexity while maintaining optimization as much as possible. We present the inputs and the desired outputs of the hierarchical procedure in the sequel.

The inputs to the hierarchical procedure include:

- Component classification: A table with information on different component types.
- Handling Class: A matrix which specifies the HC for each pair of component type-nozzle match.
- Component location: The x-y coordinates of all components on a PCB.

As a result of the hierarchical procedure, the following information is obtained and a combination of these information is referred to as "chargelist".

- The components assignment to each of the placement heads.
- The placement sequences of the components.
- The nozzle selection for handling each of these components.

5.3 First stage: the MILP model

In this section, we derive the MILP model that solves the first stage of the problem. Variables in our MILP model are based on batches of components. By aggregating variables to the batches, we obtain a model with reduced number of assignment variables. This approach provides a unique alternative paradigm for typical assignment problem in electronic/semi-conductor industries. A batch is defined as a set of identical components that needs to be placed on a PCB by a certain placement head. The total number of identical components can be divided into few batches, if it is justified by the optimization.

Below parameters are used in the model formulation:

I	the number of component types
J	the number of nozzle types
$k \in \{1,2,3,4\}$	the set of placement heads
L	the maximum number of batch levels $L \leq I+1$
comp_i	the number of identical components of type i
M	a given large number (that is larger than $\max_{i \in I}\{\text{comp}_i\}$)
H_{ij}	the HC when component of type i is handled by nozzle type j

Variables in the model are:

X_{ijk} the number of components of type i that are placed by nozzle type j on placement head k
N_k the total number of nozzle exchanges on placement head k
H_l the worst HC of all batches on level l
WL the largest workload of four placement heads

$$Z_{ijlk} = \begin{cases} 1, & \text{if batch } X_{ijk} \text{ is placed on level } l \\ 0, & \text{otherwise,} \end{cases}$$

$$D_{lk} = \begin{cases} 1, & \text{if there is a change of nozzle in the level } l+1 \text{ on placement head } k \\ 0.5, & \text{if there are no batches placed on levels higher than } l \\ 0, & \text{otherwise.} \end{cases}$$

Our MILP model is formulated in the sequel:

$$\text{Minimize} \qquad a \cdot WL + b \cdot \sum_{k=1}^{4} N_k + c \cdot \sum_{l=1}^{L} H_l \tag{5.1}$$

Subject to:

$$\sum_{j=1}^{J}\sum_{k=1}^{4} X_{ijk} = \text{comp}_i \qquad \forall i \tag{5.2}$$

$$\sum_{j=1}^{J}\sum_{i=1}^{I} X_{ijk} \leq WL \qquad \forall k \tag{5.3}$$

$$X_{ijk} \leq \text{M} \cdot \sum_{l=1}^{L} Z_{ijlk} \qquad \forall i, j, k \tag{5.4}$$

$$\sum_{l=1}^{L} Z_{ijlk} \leq 1 \qquad \forall i, j, k \tag{5.5}$$

$$\sum_{l=1}^{L} Z_{ijlk} \leq X_{ijk} \qquad \forall i, j, k \tag{5.6}$$

$$\sum_{j=1}^{J}\sum_{i=1}^{I} Z_{ijlk} \geq \sum_{j=1}^{J}\sum_{i=1}^{I} Z_{ij(l+1)k} \qquad \forall k, l \tag{5.7}$$

$$\sum_{i=1}^{I}\sum_{j=1}^{J} Z_{ijlk} \leq 1 \qquad \forall l, k \tag{5.8}$$

$$D_{lk} = \frac{1}{2} \cdot \sum_{j=1}^{J} \Big| \sum_{i=1}^{I} Z_{ijlk} - \sum_{i=1}^{I} Z_{ij(l+1)k} \Big| \qquad \forall k, l \tag{5.9}$$

$$N_k = \sum_{l=1}^{L} D_{lk} - 0.5 \qquad \forall k \tag{5.10}$$

$$H_l \geq \sum_{i=1}^{I} \sum_{j=1}^{J} H_{ij} \cdot Z_{ijlk} \qquad \forall l, k \tag{5.11}$$

$$Z_{ijlk} \in \{0,1\},\ D_{lk} \in [0,1],$$

$$X_{ijk} \in \mathbb{N}_0,\ N_k \in \mathbb{N}_0,\ H_l \in \mathbb{R}_+. \tag{5.12}$$

Where a, b, c are real numbers, whose values are determined as described in Section 5.5.

Constraint (5.2) guarantees that the sum of the different batch sizes of component type i is equal to the predetermined size of component type i. Constraint (5.3) calculates the largest workload among placement heads. Constraint (5.4) ensures that batch X_{ijk} always has a place when its size is greater than zero. Constraint (5.5) guarantees that batch X_{ijk} can be assigned at most to one place. Constraint (5.6) ensures that there are no assigned locations for batches of size zero. Constraint (5.7) ensures that the batches have to be located at lower level l before being located to the higher level $l+1$. Constraint (5.8) ensures that each place can be used to allocate at most one batch. The introduction of constraint (5.9) is intended to count for each level of batches whether there is a nozzle exchange. D_{lk} is equal to one when there is an exchange in the next level, and is equal to zero if there is no exchange. Since, based on our formulation, every nozzle exchange will be counted once for each of the nozzle types on different level, the actual counted number is doubled. That is why we multiply 0.5 to the counted value. However, this implementation results in a extra output value of 0.5 for D_{lk} when Z_{ijlk} for some i and j is the last batch assigned to placement head k, i.e., when there are no more batches assigned to higher levels than l. This constraint can be further formulated as below:

$$\sum_{i=1}^{I} Z_{ijlk} - \sum_{i=1}^{I} Z_{ij(l+1)k} = D^+_{ljk} - D^-_{ljk} \qquad \forall l, j, k$$

$$D_{lk} = \frac{1}{2} \cdot \sum_{j=1}^{J} (D^+_{ljk} + D^-_{ljk}) \qquad \forall k, l$$

$$D^+_{ljk}, D^-_{ljk} \geq 0 \qquad \forall l, j, k.$$

Constraint (5.10) counts the total number of nozzle exchanges on one placement head. Under the assumption of repetitive production, the planned placement order of batches is processed reversely between sequential PCBs, during which the last batch level of the on-processing PCB are processed as the first batch level of the next PCB. Hence, there is no nozzle exchange after processing the last-level batches, and the counted 0.5 times of nozzle exchange at the last batch level can be removed from calculation. Constraint (5.11) determines the worst HC for each batch level.

From the solution of the optimization problem (5.1) - (5.12) we obtain the batch size, the batch location, the nozzle assignment for each batch, as well as the workload on each placement head, the number of nozzle exchanges, and the HC for each pick-and-place cycle. The complexity of this model with respect to the number of variables and constraints is presented below. The complexity depends on the number of component types I, the number of nozzle types J, as well as the maximum number of levels for batches L.

$$\text{Number of Variables} = \begin{cases} I \cdot J \cdot 4 & \text{for} \quad X_{ijk} \\ I \cdot J \cdot 4 \cdot L & \text{for} \quad Z_{ijlk} \\ L \cdot 4 & \text{for} \quad D_{lk} \\ 4 & \text{for} \quad N_k \\ L & \text{for} \quad H_l \\ 1 & \text{for} \quad WL \end{cases} = (4L+4) \cdot I \cdot J + 5 \cdot L + 5$$

$$\text{Number of Constraints} = \begin{cases} I & \text{for (5.2)} \\ 4 & \text{for (5.3)} \\ I \cdot J \cdot 4 & \text{for (5.4)} \\ I \cdot J \cdot 4 & \text{for (5.5)} \\ I \cdot J \cdot 4 & \text{for (5.6)} \\ 4 \cdot L & \text{for (5.7)} \\ 4 \cdot L & \text{for (5.8)} \\ 4 \cdot L & \text{for (5.9)} \\ 4 & \text{for (5.10)} \\ 4 \cdot L & \text{for (5.11)} \end{cases} = 12 \cdot I \cdot J + 16 \cdot L + I + 8$$

Note that the complexity of the model is greatly influenced by the number of component types rather than the number of components. More precisely, the complexity of MILP model (5.1) - (5.12) w.r.t. the number of variables and constraints is $O(I^2 J)$, where I is the number of component types.

When a model for the multi-head SMD placement optimization problem is formulated based on single components, then the complexity of the corresponding single component based model is $O(n^2 J)$, where n is the number of components. We have here in mind a reformulation of problem (5.1) - (5.12) where the size of each batch is one, i.e. a batch is a component. Note that for $n \gg I$, the single component based model becomes intractable while our proposed model remains tractable. Following the same argument, the complexity of the aggregated model is never larger than the single based one, since the number of component types is at least the number of components.

5.4 Second stage: the heuristic method

From the solution of MILP model, we obtain the component type of each batch, the batch sizes, and the order of the batches assigned to each placement head. These information can be presented in a bar chart as Figure 5.2. Data presented in Figure 5.2 is the solution of MILP model of the Case 5.1 from Table 5.2. The different bars represent the workload on placement heads. The different shaded areas on the bars represent different batches. The hight of each shaded area represents the batch size. The order of batches on a bar indicates the placement order on a certain placement head.

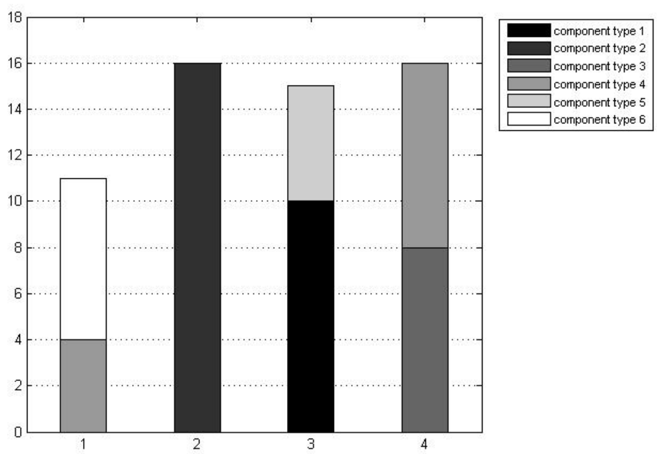


Figure 5.2: Output of MILP

In the second stage, a heuristic is used to determine a placement sequence based on the previously mentioned batch information. The heuristic determines which components need to be grouped into one pick-and-place cycle, the order of pick-and-place cycles, and the placement sequence of components in each pick-and-place cycle. This problem is a special case of the traveling salesman problem which is complicated by the Chebyshev traveling feature of the robot arm and the classification of the component type. The traveling problem of Chebyshev feature is well known as the Chebyshev Traveling Salesman Problem (CTSP). As mentioned in Bozer et al. [1990], many heuristic procedures based on geometric concepts have been developed for the CTSP. However, none of the heuristic procedures mentioned in Bozer et al. [1990] deal with the CTSP combined with the classification of vertices needed to be visited, which in our case refers to the classification of the components. Note that grouping components into one pick-and-place cycle and determining the order of pick-and-place cycles is equivalent to the determination of the specific components composing the different batches on the placement heads (shaded areas on each bar in Figure 5.2) and the placement order of these components in each batch. Instead of formulating another MILP or adapting an existing heuristic to determine the optimal solution, a greedy heuristic named as *level placing algorithm* is developed in order to provide a good feasible solution for our problem.

Our level placing algorithm consists of a selection process and an optimization process. The selection process is for grouping components into each pick-and-place cycle such that the selected components can fill in the batches on the placement heads level by level with correct component types. In the selection process, our algorithm selects components from each component type based on the smallest possible y-axis scheme, i.e., the components of the lowest y-coordinate among valid components of different component types are selected first. The optimization procedure determines the best placement sequence of these selected components with respect to the minimum Chebyshev traveling distance. We present our level placing algorithm for the final sequencing in Figure 5.3.

Notations used in the algorithm:

- C_{n_i} stands for the n_i-th component which is of component type i.
- $Y_k^{i_k}$ stands for the number of components of type i_k which are going to be assigned to placement head k in the following pick-and-place cycles.

Combining the results of MILP model and this heuristic method, we complete the placement optimization problem of multi-head surface mounting device. The numerical results are presented in the following section.

5.5 Numerical results

The MILP model is solved by CPLEX using AIMMS interface, running on a PC with PENTIUM 4, 2.4GHz and 1.5GB of memory. Our heuristic algorithm is implemented by MATLAB 2007b on the same machine.

The a, b, c coefficients of MILP model are determined as $1, 6, 1$ respectively based on the following management judgment: 1 additional minute for one extra pick-and-place cycle, 6 additional minutes for one extra nozzle exchange, and 1 additional minutes for one HC increase. These values are also verified by the factorial design that is described as follows. A factorial design of 27 scenarios with 3 levels for each of the coefficients is conducted based on the data of Case 5.1 of Table 5.2. The performance of MILP model is tested for these scenarios and the outputs of the MILP models of these scenarios can be classified into three different categories. We present these three categories in Table 5.1 in terms of their outputs of MILP models: workload, nozzle exchange, and HC. The last column of Table 5.1 indicates the number of scenarios which are classified into the same category. More than half of the scenarios fall into the first category. We may note that the MILP model with the proposed combination of coefficients of objective terms $1, 6, 1$ provides the same outputs as in the first category. Hence, the management judgment is rather moderate. The closeness of the outputs of MILP models of these categories also indicates a sufficient efficiency of MILP model in terms of high tolerance of a, b, c estimation errors.

Table 5.1: Factorial design results

Category	Workload	Nozzle exchange	HC	$\sharp$ of scenarios with same outputs
1	16	0	1 and 5	14
2	15	1	1 and 5	9
3	15	0	1 and 8	4

In Table 5.2, we present the numerical results of 15 real-life data sets based on the above coefficient estimation. Note that the data set of Case 5.1 is created for the demonstration and analysis purpose. In first three columns of Table 5.2, characteristics of each of the cases are specified. This includes the number of component types, the number of components, and the lowest and highest possible HC. In "case complexity", the number of variables and the number of constraints are specified for each case. These two values determine the complexity of the corresponding computation. The test results from the first stage and the second stage are listed in "result of first stage" and "result of second stage" respectively, which include the computation time, the final workload, the number of nozzle exchanges, the lowest and highest HC in chargelist, and the final traveling distance. Based on the results, there are few observations we would like to highlight in the rest of this section.

- Our method indeed provides a good solution in terms of balancing the workload, minimizing the number of nozzle exchanges and improving HC in the final chargelist.

  1. In Case 5.2, 5.3, 5.4, 5.9, and 5.12, all the components are assigned onto 4 placement heads optimally. The workloads are balanced optimally.
  2. The nozzle exchanges are almost always avoided except in Case 5.11, 5.12 and 5.16. The number of nozzle exchanges is effectively minimized.
  3. The HC are improved clearly in Case 5.1, 5.4, 5.15. The highest HC is reduced from 8 to 5 in Case 5.1, from 4 to 2.7 in Case 5.4 and from 8 to 2 in Case 5.15. Note that we only present and examine the highest HC reduction in Table 5.2, although the results do not explicitly indicate improvements for the rest cases, the actual improvements are significant for most cases.

Table 5.2: Basic results

	Case Characteristics			Case Complexity		Result of 1st Stage				Result of 2nd Stage
case	♯ comp. type	♯ comp.	L/H HC	♯ var.	♯ of constr.	Comput. time(s)	WL	Nozzle exch.	L/H HC	Total dist.(m)
5.1	6	58	1/8	477	338	5.87	16	0	1/5	5.5632
5.2	1	80	2/2	64	85	0.00	20	0	2/2	7.6139
5.3	1	40	2/2	81	105	0.00	10	0	2/2	3.7145
5.4	4	16	2/4	285	224	0.00	4	0	2/3	1.6588
5.5	7	21	2/2	738	451	0.25	6	0	2/2	2.0100
5.6	7	12	2/2	427	295	10.91	6	0	2/2	1.0096
5.7	8	9	2/3	359	260	4.63	3	0	2/3	0.9899
5.8	8	15	2/8	859	488	61.34	5	0	2/8	1.1273
5.9	9	43	2/4	1149	725	28.73	11	0	2/4	4.0568
5.10	11	13	2/4	1341	635	46.63	4	0	2/4	1.6928
5.11	13	600	2/8	1205	581	23589.73	150	1	2/8	56.9631
5.12	13	64	2/2	1772	769	1076.16	16	1	2/2	5.9389
5.13	14	22	4/8	1435	634	286.28	8	0	4/8	2.6632
5.14	19	27	2/8	2568	943	8506.16	8	0	2/8	3.5121
5.15	24	54	2/8	5660	1584	22955.02	15	0	2/2	7.9704
5.16	28	80	2/8	5076	1516	$> 10^6$	24	3	2/8	11.0438

Table 5.3: Batch size of basic results

Case	5.1	5.2	5.3	5.4	5.5	5.6	5.7	5.8	5.9	5.10	5.11	5.12	5.13	5.14	5.15	5.16
Largest/Smallest Batch Size	10/10	20/20	1/8	1/10	2/12	4/4	1/8	1/2	3/3	1/4	1/2	1/5	1/5	3/114	1/3	3/16

- The computation time of the first stage increases as the number of variables and constraints increase. Note that the number of variables increases along with the number of component types rather than the number of components. When the number of variables are below 300, the computation time is less than one second, like in Case 5.2, 5.3, and 5.4. When the number of variables does not exceed 1000, the computation time is in a range of few seconds. When the number of variables increases to a range between 1000 and 2000, the computation is still manageable, and the computation time may vary from 1 minute to few hours. When the number of variables exceed 2000, the computation time may increase to days and even weeks when there are over 5000 variables.

- The number of components does not influence heavily the computation time of a problem. As for an example when comparing Case 5.2 and Case 5.4, although Case 5.2 has more than four times as many components than Case 5.4, there is hardly any increase in the computation time of Case 5.2. Case 5.11 with 600 components experiences a rather long computation time which is caused by the substantially enlarged feasible region (see constraint (5.2) of page 117).

- The computation time of the second stage is negligible. Even when the component number increase to 600 in Case 5.11, the computation time is only about 2 seconds.

- The total traveling distance as an output of the second stage is the sum of Chebyshev distances of sequentially movements of the robot arm. We may see that total traveling distance increases as the number of components increases. The total traveling distance can be rescaled into total traveling time by dividing the sequential Chebyshev distances with the corresponding traveling speeds on those directions.

- We observe that the batch sizes could vary greatly from only one component to almost 114 components (see Table 5.3), which are not constrained in our formulation.

In order to further validate our proposed method, we compare its results with those of the current optimization approach of AX2.01. The placement optimization of AX2.01 is currently conducted based on a heuristic, referred as Assembléon Quick Estimator (AQE). It determines the operating chargelist by first minimizing the number of placement cycles and then reducing the number of nozzle exchanges. Based on the data that are available to us, Table 5.4 summarizes the results obtained from AQE. The columns two to four of the table indicate the workload, the number of nozzle exchanges, and the total traveling distance (in meters) of each case. The value in parentheses in the fourth column indicates the improvement of traveling distance in percentage when comparing the result of our method with that of AQE. The results show that our method always results in solutions with shorter traveling distances. In four out of 12 cases, the improvements of traveling distance are more than 50% (see Case 5.6, 5.8, 5.12, and 5.16). By comparing Table 5.4 with Table 5.2, we can see that the number of placement cycles and the number of nozzle exchanges might be also reduced by our approach. In particular in Case 5.4, not only the traveling distance is reduced by 15%, but also the three nozzle exchanges are removed by our solution. Also in Case 5.12, in addition to the reduction of traveling distance for about 50%, one placement cycle and two nozzle exchanges are reduced by our solution. It is clear that our proposed method outperforms the AQE and is a more effective approach for solving the multi-head SMD placement optimization problem.

TABLE 5.4: Results from Assembléon Quick Estimator

Case	WL	Nozzle exchange	Total distance
5.2	20	0	8.006(5%)
5.3	10	0	7.261(49%)
5.4	4	3	1.941(15%)
5.6	3	1	2.669(62%)
5.7	3	0	1.304(24%)
5.8	4	0	2.414(53%)
5.9	11	0	7.187(44%)
5.10	4	0	2.729(40%)
5.12	17	3	12.019(51%)
5.14	8	1	6.517(46%)
5.15	14	0	12.977(39%)
5.16	21	3	22.520(51%)

5.6 Summary

The focus of this chapter is to explore the use of aggregate modeling in assigning and sequencing of batches of components to a multi-head SMD.

We propose a hierarchical approach of two stages for solving the PCB component placement problem. The MILP model is based on variables of batches of components rather than individual components. This way of modeling turns to be valuable for developing a tractable mathematical programming model in terms of reducing the computation time and shows a great effectiveness in balancing the workload, minimizing the number of nozzle exchanges, and improving HC. The numerical results indicate that this MILP model is most efficient for PCB types which has large number of components but limited number component types. The computation time needed for level placing algorithm providing the final sequencing is negligible.

Algorithm

Input:
the number of components on PCB: N
the number of component types: I
the number of components of type i: N_i, $\forall i \in \{1,2,3,\ldots,I\}$
component C_{n_i} with coordinates (x_{n_i}, y_{n_i}), $\forall n_i \in \{1,2,\ldots,N_i\}$
output from MILP: X_{ijk}, Z_{ijlk}, $\forall i,j,l,k$
 	
the number of batches on each placement head k, $L_k = \sum_i \sum_j \sum_l Z_{ijlk}, \forall k = 1,2,3,4$
available components of type i, $A_i = \{C_{n_i} \mid n_i \text{ is of type } i\}$, $\forall i \in \{1,2,3,\ldots,I\}$
Sort C_{n_i} in A_i nondecreasingly w.r.t. y_{n_i}, $\forall i$ **End Sort**
$l_k \leftarrow 1$, $\forall k = \{1,2,3,4\}$
$Y_k^{i_k} \leftarrow \sum_i \sum_j Z_{ijl_kk} X_{ijk}$, $\forall k = \{1,2,3,4\}$
Total Chebyshev Travel Distance: $TCTD \leftarrow 0$
While $Y_k^{i_k}$ is larger than zero for at least one $k \in \{1,2,3,4\}$
[P1] choose and remove the first components from corresponding available component sets A_{i_k} and set $Y_k^{i_k} \leftarrow Y_k^{i_k} - 1$, $\forall k \in \{k \mid Y_k^{i_k} > 0\}$
[P2] calculate the Chebyshev travel distance d_s for every possible placing sequence s of these chosen components (24 alternatives when 4 components are chosen)
[P3] travel distance $d_{min} = \min_s d_s$ and set the total Chebyshev travel distance $TCTD \leftarrow TCTD + d_{min}$
If $Y_k^{i_k}$ equal to zero for one or more k and $l_k < L_k$
[P4] $l_k \leftarrow l_k + 1$ and set $Y_k^{i_k} \leftarrow \sum_i \sum_j Z_{ijl_kk} X_{ijk}$, $\forall k \in \{k \mid Y_k^{i_k} = 0\}$
End If
End While
 	
Output
$TCTD_{optimal} = TCTD$

FIGURE 5.3: Level placing algorithm

Chapter 6

Conclusion and future research

The scopes of the supply chain network and operations design problems have extended into management of dynamic global supply chain and focused on managing uncertainties at different levels of aggregation. In this research, we investigated four interrelated supply chain network and operations design problems, each of which characterize a contemporary supply chain management issue. Our research results demonstrate how these supply chain management issues can be efficiently integrated into a hierarchical approach and solved by optimization models, which provides valuable insights for assisting the decision-making of management team.

We begin our research with two research questions concerning supply chain network downsizing problems. The SCDP under bankruptcy defined in Chapter 2 is inspired by the downsizing application of GM when they face financial difficulties, that is our first research question. The problem addresses the necessity of ensuring financial robustness when downsizing a transnational supply chain network. Special attention needs to be paid for ensuring successful debt payments, and stabilizing the return on investment when uncertainties are involved. Our proposed approach adopts robust optimization techniques and illustrates how downsizing operations can protect a supply chain network from demand and exchange rate uncertainties. The proposed downsizing MIP model and its robust counterparts can help downsizing managers with detailed downsizing plans, which leads to higher and sustainable economic value of an existing supply chain network. Our second research question extends the SCDP under bankruptcy into a multi-product case in Chapter 3. Special attentions are paid to the selection of the optimal product portfolio when products are substitutable. Note that downsizing operations may impact the actual demands of a downsized supply chain network. We propose to incorporate the multi-product downsizing MIP model with a new general formulation of demand substitution, which allows the downsizing solutions to be generated anticipating possible demand shifts. In another word, the new general formulation of demand substitution enables our downsizing model to actively reselect the most profitable product portfolio, rather than passively react on demand contraction.

Our third research question looks into the design of a transnational warranty distribution network, where both recovery process design and inventory management are crucial for the efficient operation of the warranty distribution network. In Chapter 4, we proposed to integrate the warranty distribution network design with the recovery processes design and inventory replenishment decisions. The resulted warranty network design model is a nonlinear and nonconvex optimization problem. A tight linear approximation of the problem is developed based on linearization and piecewise linear approximation for generating network design solutions. While the linearized mixed integer programming model represents a comprehensive warranty distribution network design model, its solution quality and computation complexity can be adjusted by changing the pre-selected number of samples of decision variable R_j (the number of replenishments at distribution center j). Building this comprehensive warranty distribution network design model is crucial for the efficient operations of transnational after-sales service. It is worth mentioning that although the here present nonlinear warranty network design model and its linear approximation are for the design of a particular warranty distribution network, they can also be used for analyzing outsourcing options of recovery operations to certified repair vendors, or for evaluating service contract with third party logistics providers. With certain modifications, the here proposed approach can take into account more complicated recovery processes and reuse options of returned products, and provides valuable insights for the design of warranty distribution networks with multiple product types and warranty service types.

While the concerns on the efficient reuse and relocation of production facilities have been repeatedly addressed in Chapter 2, 3, and 4 for improving supply chain efficiency, our last research question focuses on optimizing the operation at facility unit level, a multi-head SMD. The optimization problem integrates decisions for component and nozzle assignment to each placement head and sequence of component placements on PCB. In Chapter 5, we propose a two-stage optimization approach. The approach optimizes the assignment of batches of components to placement heads in the first stage, which balances workload among placement heads, reduces the number of nozzle changes, and increases the traveling speed of robot arm. The level placing algorithm is then adopted in the second stage to minimize travel distance and determine the final chargelist from the output of the first stage. Based on this hierarchical approach, feasible solutions can be derived in a reasonable time frame. The outputs of this approach can be used in industry as a high quality solution of an on-line optimization, which can be further tested and improved by on-line optimization techniques.

While our proposed optimization models in this thesis provide valid analyzing frameworks of downsizing decision process, warranty distribution network design, and optimization of facility unit operations, the techniques and methods that we adopt for treating supply chain uncertainties and demand substitution effects, integrating recovery process design, and improving operation efficiency are not mutually exclusive. Therefore, more integrative approach feeding higher level by the results of lower level is an area for future study. Our research can be further extended in some distinct ways as outlined below.

In Chapter 2 and 3, our current research on supply chain network downsizing assumes that demands are generated by individual customers and the supply of end products can take any integer value less than the total demand. However, demands can also be generated by the contracted orders from few clients. In this case, the resources of a supply chain network are grouped into batches and failing to satisfying the demand of a client by certain target threshold would result in extra cost, huge amount of fine, or even withdraw of the client. Therefore, how production resources can be wisely deployed in accordance with reduced batch demands can be an interesting future research of supply chain network downsizing.

The solution to the SCDP under bankruptcy is a multi-period transformation plan. While some of the transformation decisions need to be determined here and now, other decisions, such as detailed production and transportation plans, can be decided when the true data is revealed. A solution can be of great help if advices on possible adjustments to future decisions are also provided by the optimization model. Therefore, developing an adjustable robust counterpart of the downsizing model by expressing future decisions as functions of uncertain parameters can further improves the robustness of the downsized supply chain network. Furthermore, demand substitution effects reflect consumer preference and are intrinsically uncertain. Hence, future research can also include developing a tractable robust counterpart of the downsizing model to deal with substitution uncertainties.

Another important avenue of research on supply chain network downsizing is to consider the possible unreliability of the downsized supply chain network, which can be important when much capacity is consolidated at few locations. Note that disruptions caused by nature disasters can easily destroy the operation system of a supply chain if a main operation center cannot produce, get supply, or transport out finished products. Extra attentions need to be paid for preventing too much consolidation by balancing workload on different plants, such that an agile supply chain network can be obtained from downsizing operations. Also, suppliers play a crucial role for the stability of supply chain operation. Extending our current work to consider contract issues with suppliers and the possibilities of re-insourcing subcontracted works may further improve the stability of the downsized supply chain network.

In Chapter 4, we assume negligible lead time and do not consider safety stocks at distribution centers when redesigning the warranty distribution network of FTL. Note that the supply of new and refurbished products may experience different lead times and capacity constraints. Strategically planning and relating safety stock level of a distribution center to its mixed use of new and refurbished products for inventory replenishments is important for preventing stock-out and maintaining warranty service level. Furthermore, the uncertainties of the number of claims and the quality of returned products can be aggregated at different distribution centers. Note that the variation of the number of claims causes uncertain demands for well-functioning products at after-sales service centers, and the variation of the quality of returned products causes uncertain supplies of refurbished products. Depending on the allocation of customer service and the location of recovery processes, uncertainties brought by the same group of customers can impact the operations at different distribution centers. Therefore, extending our current warranty distribution network design model to evaluate both safety stock levels and the impacts of uncertainties can further contribute to customer satisfaction.

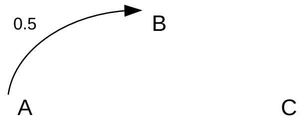
Appendix A

Sample Substitution Matrices of The MIPds Model

- $S_{ik} = 1, \forall i, k \in \{1, \ldots, I\}$

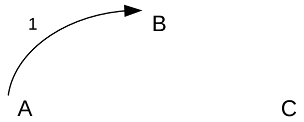
Substitution matrix 1

$$Y = \begin{bmatrix} 0 & 0 & 0 \\ 0.5 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$



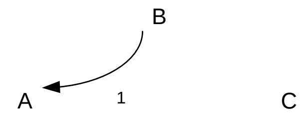
Substitution matrix 2

$$Y = \begin{bmatrix} 0 & 0 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$



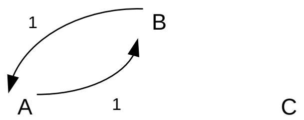
Substitution matrix 3

$$Y = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$



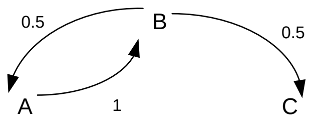
Substitution matrix 4

$$Y = \begin{bmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$



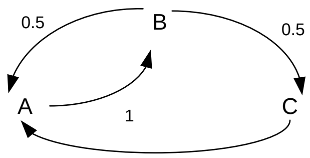
Substitution matrix 5

$$Y = \begin{bmatrix} 0 & 0.5 & 0 \\ 1 & 0 & 0 \\ 0 & 0.5 & 0 \end{bmatrix}$$



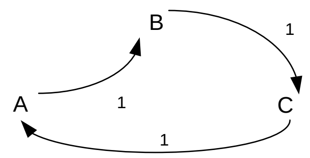
Substitution matrix 6

$$Y = \begin{bmatrix} 0 & 0.5 & 1 \\ 1 & 0 & 0 \\ 0 & 0.5 & 0 \end{bmatrix}$$



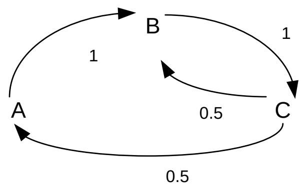
Substitution matrix 7

$$Y = \begin{bmatrix} 0 & 0 & 1 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix}$$



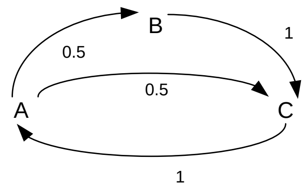
Substitution matrix 8

$$Y = \begin{bmatrix} 0 & 0 & 0.5 \\ 1 & 0 & 0.5 \\ 0 & 1 & 0 \end{bmatrix}$$



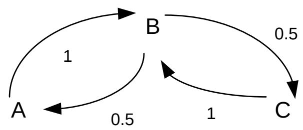
Substitution matrix 9

$$Y = \begin{bmatrix} 0 & 0 & 1 \\ 0.5 & 0 & 0 \\ 0.5 & 1 & 0 \end{bmatrix}$$



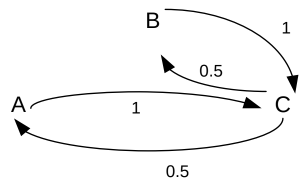
Substitution matrix 10

$$Y = \begin{bmatrix} 0 & 0.5 & 0 \\ 1 & 0 & 1 \\ 0 & 0.5 & 0 \end{bmatrix}$$



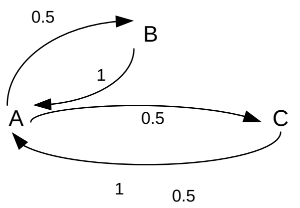
Substitution matrix 11

$$Y = \begin{bmatrix} 0 & 0 & 0.5 \\ 0 & 0 & 0.5 \\ 1 & 1 & 0 \end{bmatrix}$$



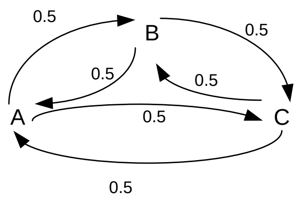
Substitution matrix 12

$$Y = \begin{bmatrix} 0 & 1 & 1 \\ 0.5 & 0 & 0 \\ 0.5 & 0 & 0 \end{bmatrix}$$



Substitution matrix 13

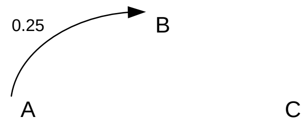
$$Y = \begin{bmatrix} 0 & 0.5 & 0.5 \\ 0.5 & 0 & 0.5 \\ 0.5 & 0.5 & 0 \end{bmatrix}$$



- $S_{ik} \neq 1$ for some $i, k \in \{1, \ldots, I\}$

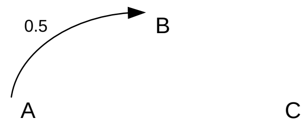
Substitution matrix 14

$$Y = \begin{bmatrix} 0 & 0 & 0 \\ 0.25 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$



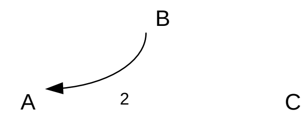
Substitution matrix 15

$$Y = \begin{bmatrix} 0 & 0 & 0 \\ 0.5 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$



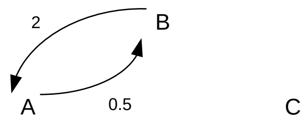
Substitution matrix 16

$$Y = \begin{bmatrix} 0 & 2 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$



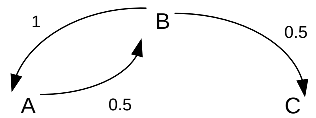
Substitution matrix 17

$$Y = \begin{bmatrix} 0 & 2 & 0 \\ 0.5 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$



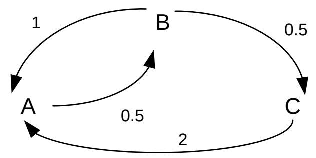
Substitution matrix 18

$$Y = \begin{bmatrix} 0 & 1 & 0 \\ 0.5 & 0 & 0 \\ 0 & 0.5 & 0 \end{bmatrix}$$



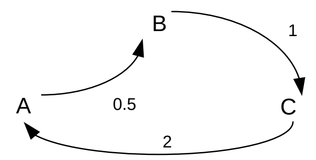
Substitution matrix 19

$$Y = \begin{bmatrix} 0 & 1 & 2 \\ 0.5 & 0 & 0 \\ 0 & 0.5 & 0 \end{bmatrix}$$



Substitution matrix 20

$$Y = \begin{bmatrix} 0 & 0 & 2 \\ 0.5 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix}$$



Bibliography

Abello, J., Pardalos, P., Resende, M., 2002. *Handbook of Massive Data Sets*. Springer.

Ahmadi, J., Ahmadi, R., Matsuo, H., Tirupati, D., 1995. Component fixture positioning/sequencing for printed circuit board assembly with concurrent operations. *Operations Research* 43, 444 – 457.

Appelbaum, S.H., Everard, A., Hung, L.T.S., 1999. Strategic downsizing: Critical success factors. *Management Decision* 37, 535–552.

Ashayeri, J., Ma, N., Sotirov, R., 2010. Creating sustainability through robust optimization of supply chain downsizing, in: *Proceedings of the International Conference on Value Chain Sustainability*, Edited by Carlos Andrés Romano, 15-17 November, 2010, Universidad Politécnica de Valencia, Spain. pp. 159 – 165. ISBN:978-84-15080-01-5.

Ashayeri, J., Tuzkaya, G., 2011. Design of demand driven return supply chain for high-tech products. *Journal of Industrial Engineering and Management* 4, 481 – 503.

Ayob, M., Kendall, G., 2003. Real-time scheduling for multi headed placement machine, in: *Proceedings of the IEEE International Symposium on Assembly and Task Planning* (ISATP2003), pp. 128 – 133.

Ayob, M., Kendall, G., 2005. A triple objective function with a Chebychev dynamic pick-and-place point specification approach to optimise the surface mount pacement machine. *European Journal of Operational Research* 164, 609 – 626.

Ayob, M., Kendall, G., 2008. A survey of surface mount device placement machine optimisation: Machine classification. *European Journal of Operational Research* 186, 893 – 914.

Barratt, M., Barratt, R., 2011. Exploring internal and external supply chain linkages: evidence from the field. *Journal of Operations Management* 29, 514–528.

Barratt, M., Oke, A., 2007. Antecedents of supply chain visibility in retail supply chains: a resource-based theory perspective. *Journal of Operations Management* 25, 1217–1233.

Basten, R., van der Heijden, M., Schutten, J., 2011. A minimum cost flow model for level of repair analysis. *International Journal of Production Economics* 133, 233 – 242.

Basten, R., Schutten, J., Heijden, M., 2009. An efficient model formulation for level of repair analysis. *Annals of Operations Research* 172, 119 – 142.

Ben-Tal, A., Ghaoui, L., Nemirovski, A., 2009. *Robust Optimization.* Princeton Series in Applied Mathematics, Princeton University Press.

Ben-Tal, A., Golany, B., Nemirovski, A., Vial, J.P., 2005. Retailer-supplier flexible commitments contracts: a robust optimization approach. *Manufacturing and Service Operations Management* 7, 248 – 271.

Ben-Tal, A., Nemirovski, A., 1998. Robust convex optimization. *Mathematics of Operations Research* 23, 769 – 805.

Ben-Tal, A., Nemirovski, A., 1999. Robust solutions of uncertain linear programs. *Operations Research Letters* 25, 1 – 13.

Ben-Tal, A., Nemirovski, A., 2000. Robust solutions of linear programming problems contaminated with uncertain data. *Mathematical Programming* 88, 411 – 424.

Bertsimas, D., Sim, M., 2004. The price of robustness. *Operations Research* 52, 35 – 53.

Bertsimas, D., Thiele, A., 2004. A robust optimization approach to supply chain management, in: Bienstock, D., Nemhauser, G. (Eds.), *PCO 2004*, Springer-Verlag Berlin Heidelberg. pp. 86 –100.

Bertsimas, D., Thiele, A., 2006. A robust optimization approach to inventory theory. *Operations Research* 54, 150–168.

Bozer, Y., Schorn, E., Sharp, G., 1990. Geometric approaches to solve the Chebyshev traveling salesman problem. *IIE Transactions* 22, 238 – 254.

Brick, E.S., Uchoa, E., 2009. A facility location and installation of resources model for level of repair analysis. *European Journal of Operational Research* 192, 479 – 486.

Bruccoleri, M., Pasek, J.Z., Koren, Y., 2006. Operation management in reconfigurable manufacturing systems: Reconfiguration for error handling. *International Journal of Production Economics* 100, 87–100.

Burke, E.K., Cowling, P.I., Keuthen, R., 1999. New models and heuristics for component placement in printed circuit board assembly, in: *Proceedings of the 1999 IEEE International Conference on Information, Intelligence and Systems* (ICIIS1999), pp. 133 – 140.

Burke, E.K., Cowling, P.I., Keuthen, R., 2000. Effective heuristic and metaheuristic approaches to optimize component placement in printed circuit board assembly, in: *Proceedings of the Congress on Evolutionary Computation* (CEC2000), IEEE Computer Society Press. pp. 301 – 308.

Burke, E.K., Cowling, P.I., Keuthen, R., 2001. The printed circuit board assembly problem: Heuristic approaches for multi-headed placement machinery, in: *Proceedings of the International Conference on Artificial Intelligence* (ICAI2001), Las Vegas, CSREA Press, pp. 1456 – 1462.

Camm, J.D., Chorman, T.E., Dill, F.A., Evans, J.R., Sweeney, D.J., Wegryn, G.W., 1997. Blending OR/MS, judgment, and GIS: Restructuring P&G's supply chain. *Interfaces* 27, 128 – 142.

Canel, C., Khumawala, B., 1997. Multi-period international facilities location: An algorithm and application. *International Journal of Production Research* 35, 1891 – 1910.

Capron, L., Mitchell, W., Swaminathan, A., 2001. Asset divestiture following horizontal acquisitions: a dynamic view. *Strategic Management Journal* 22, 817 – 844.

Cohen, M.A., Lee, H.L., 1989. Resource deployment analysis of global manufacturing and sitribution networks. *Journal of Manufacturing and Operations Management* 2, 81 – 104.

Csaszar, P., Nelson, P., Rajbhandari, R., Tirpak, T., 2000a. Optimization of automated high-speed modular placement machines using knowledge-based systems. *IEEE Transactions on Systems, Man, and Cybernetics, Part C: Applications and Reviews* 30, 408 – 417.

Csaszar, P., Tirpak, T., Nelson, P., 2000b. Optimization of a high-speed placement machine using tabu search algorithms. *Annals of Operations Research* 96, 125 – 147.

D'Ambrosio, C., Lodi, A., Martello, S., 2010. Piecewise linear approximation of functions of two variables in MILP models. *Operations Research Letters* 38, 39 – 46.

Das, K., Chowdhury, A.H., 2012. Designing a reverse logistics network for optimal collection, recovery and quality-based product-mix planning. *International Journal of Production Economics* 135, 209 – 221.

Duman, E., Or, I., 2007. The quadratic assignment problem in the context of the printed circuit board assembly process. *Computers and Operations Research* 34, 163 – 179.

El-Sayed, M., Afia, N., El-Kharbotly, A., 2010. A stochastic model for forward-reverse logistics network design under risk. *Computers and Industrial Engineering* 58, 423 – 431.

Eppen, G.D., Martin, R.K., Schrage, L., 1989. A scenario approach to capacity planning. *Operations Research* 37, 517 – 527.

Fine, C.H., 2000. Clockspeed-based strategies for supply chain design. *Production and Operations Management* 9, 213 – 221.

Fleischmann, B., Ferber, S., Henrich, P., 2006. Strategic planning of BMW's global production network. *Interfaces* 36, 194 – 208.

Fleischmann, M., Beullens, P., Bloemhof-Ruwaard, J.M., Van Wassenhove, L.N., 2001. The impact of product recovery on logistics network design. *Production and Operations Management* 10, 156 – 173.

Fleischmann, M., Bloemhof-Ruwaard, J.M., Dekker, R., van der Laan, E., van Nunen, J.A., Wassenhove, L.N.V., 1997. Quantitative models for reverse logistics: A review. *European Journal of Operational Research* 103, 1 – 17.

Fluck, Z., Lynch, A., 1999. Why do firms merge and then divest? A theory of financial synergy. *Journal of Business* 73, 319 – 346.

Freeman, S.J., Cameron, K.S., 1993. Organizational downsizing: A convergence and reorientation framework. *Organization Science* 4, 10 – 29.

Fritzsche, R., Lasch, R., 2012. An integrated logistics model of spare parts maintenance planning within the aviation industry. *World Academy of Science, Engineering and Technology* 6, 1 – 10.

Geißler, B., Martin, A., Morsi, A., Schewe, L., 2012. Using piecewise linear functions for solving MINLPs. In Lee, J. and Leyffer, S., editors, *Mixed Integer Nonlinear Programming*, volume 154 of *The IMA Volumes in Mathematics and its Applications*. Springer New York, pp. 287 - 314.

Ghaoui, L.E., Lebret, H., 1997. Robust solutions to least-squares problems with uncertain data. *SIAM Journal on Matrix Analysis and Applications* 18, 1035 – 1064.

Ghaoui, L.E., Oustry, F., Lebret, H., 1998. Robust solutions to uncertain semidefinite programs. *SIAM Journal on Optimization* 9, 33 – 52.

Goetschalckx, M., Fleischmann, B., 2008. Strategic network design, in: *Supply Chain Management and Advanced Planning*. Springer Berlin Heidelberg, pp. 117 – 132.

Goetschalckx, M., Vidal, C.J., Dogan, K., 2002. Modeling and design of global logistics systems: A review of integrated strategic and tactical models and design algorithms. *European Journal of Operational Research* 143, 1 – 18.

Grunow, M., Günther, H.O., Schleusener, M., Yilmaz, I.O., 2004. Operations planning for collect-and-place machines in PCB assembly. *Computers and Industrial Engineering* 47, 409 – 429.

Guide, V.D.R., Van Wassenhove, L.N., 2009. The evolution of closed-loop supply chain research. *Operations Research* 57, 10 – 18.

Hamilton, R.T., Chow, Y.K., 1993. Why managers divest - evidence from New Zealand's largest companies. *Strategic Management Journal* 14, 479 – 484.

Hardas, C., Doolen, T., Jensen, D., 2008. Development of a genetic algorithm for component placement sequence optimization in printed circuit board assembly. *Computers and Industrial Engineering* 555, 165 – 182.

Hassanzadeh Amin, S., Zhang, G., 2014. Closed loop supply chain network configuration by a multiobjective mathematical model. *International Journal of Business Performance and Supply Chain Modelling* 6, 1 – 15.

Ho, W., Ji, P., 2003. Component scheduling for chip shooter machines: a hybrid genetic algorithm approach. *Computers and Operations Research* 30, 2175 – 2189.

Ho, W., Ji, P., 2010. Integrated component scheduling models for chip shooter machines. *International Journal of Production Economics* 123, 31 – 41.

Hodder, J.E., Dincer, M.C., 1986. A multifactor model for international plant location and financing under uncertainty. *Computers and Operations Research* 13, 601 – 609.

Hsu, A., Bassok, Y., 1999. Random yield and random demand in a production system with downward substitution. *Operations Research* 47, 277 – 290.

Huang, G.Q., Zhang, A., Liu, X., 2013. A supply chain configuration model for reassessing global manufacturing in china. *Journal of Manufacturing Technology* 24, 669–687.

Karakul, M., Chan, L., 2008. Analytical and managerial implications of integrating product substitutability in the joint pricing and procurement problem. *European Journal of Operational Research* 190, 179 – 204.

Klibi, W., Martel, A., Guitouni, A., 2010. The design of robust value-creating supply chain networks: A critical review. *European Journal of Operational Research* 203, 283 – 293.

Klomp, C., van de Klundert, J., Spieksma, F.C., Voogt, S., 2000. The feeder rack assignment problem in PCB assembly: A case study. *International Journal of Production Economics* 64, 399 – 407.

Knuutila, T., Pyöttiälä, S., Nevalainen, O.S., 2007. Minimizing the number of pickups on a multi-head placement machine. *The Journal of the Operational Research Society* 58, 115 – 121.

Ko, H.J., Evans, G.W., 2007. A genetic algorithm-based heuristic for the dynamic integrated forward/reverse logistics network for 3PLs. *Computers and Operations Research* 34, 346 – 366.

Koren, Y., Heisel, U., Jovane, F., Moriwaki, T., Pritschow, G., Ulsoy, G., Van Brussel, H., 1999. Reconfigurable manufacturing systems. Keynote paper. *Annals of the CIRP* 48, 6 – 12.

Kouvelis, P., Chambers, C., Wang, H., 2006. Supply chain management research and production and operations management: Review, trends, and opportunities. *Production and Operations Management* 15, 449 – 469.

Krikke, H., Bloemhof-Ruwaard, J., Van Wassenhove, L.N., 2003. Concurrent product and closed-loop supply chain design with an application to refrigerators. *International Journal of Production Research* 41, 3689 – 3719.

Kusumastuti, R.D., Piplani, R., Lim, G.H., 2008. Redesigning closed-loop service network at a computer manufacturer: A case study. *International Journal of Production Economics* 111, 244 – 260.

Kutanoglu, E., Lohiya, D., 2008. Integrated inventory and transportation mode selection: A service parts logistics system. *Transportation Research Part E: Logistics and Transportation Review* 44, 665 – 683.

Landeghem, H.V., Vanmaele, H., 2002. Robust planning: a new paradigm for demand chain planning. *Journal of Operations Management* 20, 769 – 783.

Lang, J.C., 2010. *Production and Inventory Management with Substitutions.* Springer.

Laval, C., Feyhl, M., Kakouros, S., 2005. Hewlett-Packard combined OR and expert knowledge to design its supply chains. *Interfaces* 35, 238 – 247.

Lee, S., Lee, B., Park, T., 2000. A hierarchical method to improve the productivity of multi-head surface mounting machines. *Intelligent Automation and Soft Computing* 6, 291 – 301.

Leipälä, T., Nevalainen, O., 1989. Optimization of the movements of a component placement machine. *European Journal of Operational Research* 38, 167 – 177.

Li, S., Hu, C., Tian, F., 2008. Enhancing optimal feeder assignment of the multi-head surface mounting machine using genetic algorithms. *Applied Soft Computing* 8, 522 – 529.

Lin, C.C., 2004. A weighted max-min model for fuzzy goal programming. *Fuzzy Sets and Systems* 142, 407 – 420.

Lin, J., Chen, T.L., Chu, H.C., Yang, C.H., 2009. A capacity planning model for TFT-LCD production networks, in: *Proceedings of 16th International Conference on Industrial Engineering and Engineering Management, 2009.* (ICIEEM2009), pp. 1663 – 1668.

Listeş, O., Dekker, R., 2005. A stochastic approach to a case study for product recovery network design. *European Journal of Operational Research* 160, 268 – 287.

Lus, B., Muriel, A., 2009. Measuring the impact of increased product substitution on pricing and capacity decisions under linear demand models. *Production and Operations Management* 18, 95 – 113.

Ma, N., 2011. A robust approach to supply chain downsizing problem, in: *Proceedings of the International Conference on Value Chain Sustainability*, 14-16 November, 2011, Katholieke Universiteit Leuven, Center of Industrial Management, Belgium. pp. 208 – 214. ISBN:978-94-6018-478-9.

McGinnis, L., Ammons, J., Carlyle, M., Cranmer, L., Depuy, G., Ellis, K., Tovey, C., Xu, H., 1992. Automated process planning for printed circuit card assembly. *IIE Transactions* 24, 18 – 30.

McIntyre, D.A., 2011,Dec,7. The biggest corporate layoffs of all time. Retrieved August 8, 2013, from http://jobs.aol.com/articles/2011/12/07/the-biggest-corporate-layoffs-of-all-time/.

Meixell, M.J., Gargeya, V.B., 2005. Global supply chain design: A literature review and critique. *Transportation Research Part E: Logistics and Transportation Review* 41, 531 – 550.

Melachrinoudis, E., Messac, A., Min, H., 2005. Consolidating a warehouse network: A physical programming approach. *International Journal of Production Economics* 97, 1 – 17.

Melo, M., Nickel, S., da Gama, F.S., 2005. Dynamic multi-commodity capacitated facility location: a mathematical modeling framework for strategic supply chain planning. *Computers and Operations Research* 33, 181 – 208.

Melo, M., Nickel, S., da Gama, F.S., 2009. Facility location and supply chain management – a review. *European Journal of Operational Research* 196, 401 – 412.

Mieghem, J.A.V., 2003. Commissioned paper capacity management, investment, and hedging: Review and recent developments. *Manufacturing and Service Operations Management* 5, 269 – 302.

Min, H., Zhou, G., 2002. Supply chain modeling: past, present and future. *Computers and Industrial Engineering* 43, 231 – 249.

Moschieri, C., Mair, J., 2005. Research on corporate unbundling: a synthesis. IESE Business School - University of Navarra, Spain, WP 592. http://www.iese.edu/research/pdfs/DI-0592-E.pdf.

Murthy, D., Solem, O., Roren, T., 2004. Product warranty logistics: Issues and challenges. *European Journal of Operational Research* 156, 110 – 126.

Mutha, A., Pokharel, S., 2009. Strategic network design for reverse logistics and remanufacturing using new and old product modules. *Computers and Industrial Engineering* 56, 334 – 346.

Özkır, V., Başlıgıl, H., 2012. Modelling product-recovery processes in closed-loop supply-chain network design. *International Journal of Production Research* 50, 2218 – 2233.

Papageorgiou, L.G., Rotstein, G.E., Shah, N., 2001. Strategic supply chain optimization for the pharmaceutical industries. *Industrial and Engineering Chemistry Research* 40, 275 – 286.

Pentico, D.W., 2008. The assortment problem: A survey. *European Journal of Operational Research* 190, 295 – 309.

Piplani, R., Saraswat, A., 2012. Robust optimisation approach to the design of service networks for reverse logistics. *International Journal of Production Research* 50, 1424 – 1437.

Pishvaee, M.S., Farahani, R.Z., Dullaert, W., 2010. A memetic algorithm for bi-objective integrated forward/reverse logistics network design. *Computers and Operations Research* 37, 1100 – 1112.

Pishvaee, M.S., Rabbani, M., Torabi, S.A., 2011. A robust optimization approach to closed-loop supply chain network design under uncertainty. *Applied Mathematical Modelling* 35, 637 – 649.

Quadir, G.A., Azid, I.A., Parthiban, A., Seetharamu, K.N., Jeevan, K., 2002. Optimization of PCB component placement using genetic algorithms. *Journal of Electronics Manufacturing* 11, 69 – 79.

Renna, P., 2011. Multi-agent based scheduling in manufacturing cells in a dynamic environment. *International Journal of Production Research]*, volume = 49, number = 5, pages = 1285–1301 .

Renna, P., Argoneto, P., 2011. Capacity sharing in the network of independent factories: a cooperative game theory approach. *Robotics and Computer-Integrated Manufacturing* 27, 405 – 417.

Roodman, G.M., Schwarz, L.B., 1975. Optimal and heuristic facility phase-out strategies. *AIIE Transactions* 7, 177 – 184.

Saaty, T.L., 1996. *Decision Making with Dependence and Feedback: The Analytic Network Process*. RWS Publications.

Safai, F., 1996. Cycle time improvement for Fuji IP2 pick-and-place machines. *Hewlett-Packard Journal* 47, 80 – 86.

Salema, M.I.G., Barbosa-Povoa, A.P., Novais, A.Q., 2007. An optimization model for the design of a capacitated multi-product reverse logistics network with uncertainty. *European Journal of Operational Research* 179, 1063 – 1077.

Santoso, T., Ahmed, S., Goetschalckx, M., Shapiro, A., 2005. A stochastic programming approach for supply chain network design under uncertainty. *European Journal of Operational Research* 167, 96 – 115.

Shukla, A., Lalit, V.A., Venkatasubramanian, V., 2011. Optimizing efficiency-robustness trade-offs in supply chain design under uncertainty due to disruptions. *International Journal of Physical Distribution & Logistics Management* 41, 623–647.

Siegfried, J.J., Evans, L.B., 1994. Empirical studies of entry and exit: a survey of the evidence. *Review of Industrial Organization* 9, 121 – 155.

Souza, G.C., 2013. Closed-loop supply chains: a critical review, and future research. *Decision Sciences* 44, 7 – 38.

Strain, M., Media, D., (n.d.). Examples of downsizing in the business world. Retrieved July 29, 2013, from http://smallbusiness.chron.com/examples-downsizing-business-world-22506.html.

Sun, D., Lee, T., Kim, K., 2005. Component allocation and feeder arrangement for a dual-gantry multi-head surface mounting placement tool. *International Journal of Production Economics* 95, 245 – 264.

Surana, A., Kumara, S., Greaves, M., Raghavan, U.N., 2005. Supply-chain networks: a complex adaptive systems perspective. *International Journal of Production Research* 43, 4235–4265.

Tang, C., Tomlin, B., 2008. The power of flexibility for mitigating supply chain risks. *International Journal of Production Economics* 116, 12 – 27.

Teunter, R., 2004. Lot-sizing for inventory systems with product recovery. *Computers and Industrial Engineering* 46, 431 – 441.

Teunter, R.H., 2001. Economic ordering quantities for recoverable item inventory systems. *Naval Research Logistics* 48, 484 – 495.

Tirpak, T.M., 2000. Design-to-manufacturing information management for electronics assembly. *International Journal of Flexible Manufacturing Systems* 12, 189 – 205.

Ulstein, N.L., Christiansen, M., Grønhaug, R., Magnussen, N., Solomon, M.M., 2006. Elkem uses optimization in redesigning its supply chain. *Interfaces* 36, 314 – 325.

Vidal, C.J., Goetschalckx, M., 2001. A global supply chain model with transfer pricing and transportation cost allocation. *European Journal of Operational Research* 129, 134 – 158.

Vielma, J.P., Ahmed, S., Nemhauser, G.L., 2010. Mixed-integer models for nonseparable piecewise-linear optimization: Unifying framework and extensions. *Operations Research* 58, 303 – 315.

Zeng, Y., Ma, D., Jin, Y., Yan, J., 2004. Hierarchical planning for a surface mounting machine placement. *Journal of Zhejiang Univiversity Science* 5, 1449 – 1455.