Dynamic Multi-Commodity Capacitated Facility Location in Closed-Loop Supply Chain Design

Von der Wirtschaftswissenschaftlichen Fakultät der
Gottfried Wilhelm Leibniz Universität Hannover
zur Erlangung des akademischen Grades

Doktorin der Wirtschaftswissenschaften
-Doctor rerum politicarum-

genehmigte Dissertation

von

M.Eng. Orapadee Joochim

geboren am 17. Juli 1975 in Bangkok, Thailand

2012

Erstgutachter:	Professor Dr. Stefan Helber
Zweitgutachter:	Professor Dr. Cornelia Schön-Peterson
Tag der Promotion:	21. September 2012

Acknowledgement

Several years ago, when I came to Germany, I could hardly imagine that I will ever have a doctoral thesis. As I look back over the course of my doctoral studies, I am deeply grateful to a number of people who helped me to accomplish this goal, and touched my life during my time at Hannover.

This thesis is the result of many years dedicated to my doctoral research. I learned a lot in these years, it is an enrichment and represents an important milestone in my personal life. Even as a teenager, I realized that I would like to be involved in engineering in some particular area. I believed then that the research area would be electrical engineering, but it turned out to be supply chain management. Perhaps this reflects my pragmatic worldview. To achieve this milestone, I would firstly and formostly like to express my deepest appreciation and gratitude to my supervising Professor Dr. Stefan Helber, Head of Production Management Institute, who has contributed tremendously to my knowledge in the subject, motivated me with his enthusiasm, guided me with professional comments and valuable suggestions, and always supported me throughout the whole research process of the thesis. I would also like to sincerely thank him for the nice discussions we had on several topics of this thesis, for his willingness to listen any time to my ideas and for the appropriate amount of freedom he gave me to work on the problems I liked during my doctoral studies. The completion of this thesis would not have been possible without his help and persistent encouragement. I am indebted to him more than these simple words can express.

I wish to express my warm and sincere thanks to Professor Dr. Cornelia Schön-Peterson, Professor of Operations Management/GISMA Business School for accepting to review my thesis. I would also like to thank her for devoting her time to read my thesis and offering her valuable comments and suggestions. I owe my sincere gratitude to Professor Dr. Michael H. Breitner, Head of Information Systems Research Institute, for accepting to be a chairman of my defense and providing constructive comments. My sincere thanks goes to Dr. Erk Peter Piening from the Institute of Human Resource Management for participating in my defense and giving feedback on my thesis.

The members of the Institute of Production Management have contributed immensely to my personal and professional time at Hannover. This institute has been a source of friendship as well as good advice and collaboration. In particular, I would like to give very special thanks to Mrs. Silvia Bertuzies, a secretary of the institute, for helping the institute run smoothly and for assisting me in many different ways. I am very much grateful to Dipl.-Wirtsch.-Ing. Felix Herde for his suggestions, constant support, friendship and help in translating an abstract from English to German. Many warm thanks Junior Professor Dr. Florian Sahling for his valuable advice, kind support and friendly help. I wish to thank in addition Dipl.-Wirtsch.-Ing. Carolin Kellenbrink, Dipl.-Wirtsch.-Ing. Ariane Khoramnia, Dipl.-Kffr. Anja Wolter, Dipl.-Math. Leontina Levenzon, Dipl.-Wirtsch.-Ing. Steffen Kasper and all other members of the institute for their friendship and support.

I would like to express my thanks to the School of Economics and Management, Leibniz University Hannover for providing me a good learning environment to conduct my research. I would like to give a heartfelt, special thanks to Mrs. Judy Arndt, for editing the English of my manuscript.

My time at Hannover was made enjoyable in large part because I have a lot of friends and groups that became a part of my life. I wish to thank my best friends in Germany, Thitinat Mangkang, Dr. Rattiya Suddeephong Lippe, Dr. Chuthaporn Ngokkuen, Thanavut Chaucharoen and Thi Hoa Vu for helping me get through the difficult time, and for all the meaningful emotional support, camaraderie, encouragement, entertainment, and caring they provided. I am fortunate to be a part of Taekwondo

Group of the Universities in Hannover. A great thanks go to my trainer, Phuong Do Duc, for helping me become stronger and teaching me so much more than Taekwondo, and to Rena Struss, Louisa Heimann and Sabrina Glatzer, for their friendship and practical support (like food, training equipment and medical assistance during the training session). I want to present my sincere thanks to Mrs. Chamroen Sievers and Mrs. Vichanee Münkel for helping me a lot during my stay at Hannover. Also special thanks to my Thai friends in the Hannover community who have been supportive during my time in Hannover.

Last but certainly not least, I would like to thank my entire family, my husband, Dr. Chanin Joochim, as well as my older sister, my parents and in-laws. I would not have been where I am now if it were not for their invaluable support, great care and unwavering love. They give me strength to pursue my dreams. Most specially, I want to thank my husband Chanin for understanding me and always believing in me.

Abstract

The reverse part of the supply chain is becoming more important due to the environmental laws, the growing of environmental consciousness of customers, higher volumes of product returns, etc. Therefore, manufacturing firms cannot see the reverse supply chain only as an additional cost being incurred and must be able to think strategically about their supply chain. Strategic supply chain planning involves deciding the network's configuration, i.e., the number, location and capacity of the facilities. However, the design of the supply chain is usually based on an open-loop configuration or the forward flow of products. This means that the recent attention from governments, manufacturers and customers for product take-back and recovery is not considered in the supply chain in spite of their importance.

The aim of this thesis is to make an inquiry about dynamic (i.e., multi-period) facility location problems and related issues in integrated forward and reverse supply chain management. Four integrated forward and reverse network design models also known as closed-loop supply chain network design models are developed. Through the strategic consideration of a multi-period horizon, the design of the supply chain network also entails the specification of when and where facilities should be located and allocated. We first present a generalized modeling framework for strategic closed-loop supply chain network planning. A mixed-integer linear programming (MILP) is used to determine the optimal locations of the production plants, distribution centers, collection centers and remanufacturing facilities along with the integrated forward and reverse flows such that the total cost of facility location, processing, and transportation associated with forward and reverse flows in the network is minimized. The model is tested by its application to an illustrative example dealing with increasing product demands and different levels of product return volumes from customers.

Second, we propose a simple MILP, bidirectional facility location model to deliver final products and collect product returns in a two-tier supply chain. This study quantifies the value of concurrently taking into account forward and returned product flows when designing an integrated closed-loop supply chain network. One application is presented: how to locate and allocate facilities to meet increasing product demands. We then extend the previous bidirectional facility location model by considering capacity relocation and expansion decisions for accommodating forward and reverse logistics activities, and provide numerical results.

Finally, a new MILP model for facility location for the simultaneous design of forward and reverse supply chain networks is developed to comprehensively determine strategic long-term solutions. In order to assess the long-term impact of the problem, this model intends to maximize the net present value (NPV) of cash flows for the whole supply chain. The proposed model encompasses strategic decisions regarding the location, capacity allocation, processing-distribution system, supplier selection and supply chain subcontracting. We examine issues related to relocation and capacity expansion under changes in volume of product demands and returns. Numerical results for the issues presented are given to illustrate the effectiveness and applicability of the proposed model. The results show that the new MILP model can be used to get better insight into the quantitative aspects of strategic long-term planning within the closed-loop supply chain context.

Key words: Strategic Planning, Facility Location, Closed-Loop Supply Chain

Zusammenfassung

Der rückwärtsgewandte Teil einer Lieferkette, d. h. vom Kunden zurück zum Hersteller, erlangt aufgrund anspruchsvollerer gesetzlicher Vorgaben, steigendem Umweltbewusstsein der Kunden, wachsender Rückflussraten von gebrauchten Produkten und weiterer Faktoren eine immer wichtigere Bedeutung für Unternehmen. Es reicht daher für Produktionsunternehmen nicht mehr aus, die sog. Reverse Supply Chain als einen Kostenfaktor aufzufassen, sondern es gilt, diese vielmehr als einen strategischen Wettbewerbsfaktor für sich zu nutzen. Diesem Verständnis folgend bedarf es einer geeignet ausgerichteten strategischen Planung der Lieferkette. Diese umfasst die Entscheidung über die Konfiguration des Lieferantennetzwerks, das durch die Anzahl, die geographische Lage und die jeweils vorzuhaltenden Kapazitäten der Lieferantenstandorte charakterisiert wird. Bisher wird das Design der Lieferkette überwiegend unter der Annahme eines ausschließlich vorwärtsgerichteten Produktflusses zum Kunden hin (offene Lieferkette) erstellt, d.h. ohne die Berücksichtigung eines rückwärtsgerichteten Warenflusses vom Kunden zurück zum Hersteller (geschlossene Lieferkette). Damit lässt sich konstatieren, dass den Herausforderungen und Chancen, die mit der gesteigerten Aufmerksamkeit von Politik, Hersteller und Kunden sowie der zunehmenden Rücknahme und Wiederverwendung von Produkten einhergehen, nicht ausreichend in dem Design der Lieferkette Rechnung getragen werden.

Ziel dieser Dissertation ist die umfassende Untersuchung der dynamischen, d. h. mehr-periodigen, Standortplanung (Facility Location Problem) unter Berücksichtigung der Spezifika sowohl des vorwärts- als auch rückwärtsgerichteten Produktflusses. In

diesem Zusammenhang werden vier integrierte Modelle zum Design eines Liefernetzwerks entwickelt. Diese Modelle werden unter der Bezeichnung Closed-Loop Supply Chain Network Design geführt. Durch die strategische Berücksichtigung eines mehr-periodigen Planungshorizonts erhält das Netzwerkdesign die Erweiterung um die Fragestellungen, wann und wo Standorte errichtet und mit welcher Kapazität sie ausgestattet werden sollten. Dazu werden eingangs die allgemeinen Rahmenbedingungen für die strategische Planung von Closed-Loop Supply Chain-Netzwerken präsentiert. Ein gemischt ganzzahliges lineares Optimierungsmodell (MILP) wird vorgestellt, das einerseits die optimale Lage von Produktions-, Distributions-, Sammel- sowie Aufarbeitungsstandorten bestimmt. Andererseits werden die vorwärts- und rückwärtsgerichteten Produktflüsse festgelegt. Dabei werden die Gesamtkosten im vorwärts- und rückwärtsgerichteten Liefernetzwerk für die Einrichtung der Standorte, die Bearbeitung sowie den Transport von Produkten minimiert. Das Modell wird unter Verwendung eines anschaulichen Beispiels, in dem von einer steigenden Produktnachfrage und unterschiedlichen Niveaus von Rückflussraten von Gebrauchtprodukten vom Kunden zurück zum Hersteller ausgegangen wird, gelöst.

Anschließend wird ein weiteres gemischt ganzzahliges lineares Modell eingeführt. Diesem liegt eine zwei-stufige Lieferkette zugrunde, in der eine bidirektionale Lieferstruktur unterstellt wird, d. h. sowohl der Fluss von Endprodukten als auch der Rückfluss von gebrauchten Produkte zu den jeweiligen Standorten wird simultan berücksichtigt. Anhand einer numerischen Untersuchung wird die Vorteilhaftigkeit der simultanen, integrierten Planung der vorwärts- und rückwärtsgerichteten Produktflüsse in einem geschlossenen Liefernetzwerk demonstriert. In diesem Zusammenhang wird ein Anwendungsbeispiel hervorgehoben, in dem die Frage beantwortet werden soll, wie Standorte anzuordnen und kapazitiv auszustatten sind, sodass eine zunehmende Kundennachfrage bedient werden kann. Vor dem Hintergrund der mit den vorwärts- und rückwärtsgerichteten Produktflüssen verbundenen Aktivitäten , wie z. B. die Entsorgung von zurückkommenden Produkten, findet eine Modellerweiterung um die Möglichkeiten der Kapazitätsverlagerung sowie -erweiterung statt. Die Beschreibung der Erweiterung wird durch numerische Untersuchungen unterstützt.

Abschließend wird ein gemischt ganzzahliges lineares Optimierungsmodell zur integrierten Gestaltung von vorwärts- und rückwärtsgerichteten Supply Chain-Netzwerken aus der langfristigen, strategischen Perspektive vorgestellt. Zur Berücksichtigung des langfristigen Einflusses der Gestaltungsentscheidungen wird der Nettobarwert (Net Present Value (NPV)) der Zahlungsflüsse der gesamten Lieferkette maximiert. Das eingeführte Modell umfasst dabei strategische Entscheidungen bezüglich der geographischen Lage und der Kapazitätsallokation der Lieferantenstandorte, des Produktverarbeitungs- und Distributionssystems, der Wahl der Zulieferer sowie der Auslagerung von Lieferkettenaktivitäten an Subunternehmer. In diesem Zusammenhang werden Kapazitätserweiterungen und -verlagerungen als Folge zeitlich und mengenmäßig variierender Kundennachfrage sowie Rückflussraten von Gebrauchtprodukten untersucht. Numerische Untersuchungen mit unterschiedlichen zugrundeliegenden Szenarien demonstrieren die Effektivität und Anwendbarkeit des entwickelten Modells. Die Ergebnisse zeigen, dass das vorgestellte Modell zum besseren Einblick in die quantitativen Aspekte der strategischen, langfristigen Planung im Zusammenhang mit dem Konzept der geschlossenen Lieferketten verwendet werden kann.

Schlagworte: Strategische Planung, Standortplanung, Closed-Loop Supply Chain

Contents

1
Introduction

1.1 Background and Motivation

Facility location has been one of the most widely studied problems by researchers and investigators according to its many valuable applications. Generally, a solution of a facility location problem is specified to determine the optimal number and/or size of facilities to be established, to identify and to choose the appropriate locations for setting up facilities, and additionally to design the optimal distribution system [57]. These facilities can represent production plants, warehouses, and so forth. In the last few decades, significant research efforts have been devoted to the development of location models for supply chain networks. Facility location plays a crucial role in strategic planning for supply chain management, and has a long-term impact on supply chain performance because it is immensely expensive to open or permanently shut down the facility or move it to another location. In other words, it is generally true of facilities that they are expected to perform as beneficial as possible in a long-term planning horizon. During the planning horizon, many of the parameters of the problem, such as demands and distribution costs, are prone to change. Facility location decisions are therefore particularly costly and time-sensitive. As a consequence, dynamic facility location, which is principally concerned with planning the location and/or size of facilities over a given time planning horizon, has gradually attracted the attention of many researchers since cost and time are two main criteria influencing the related models at most [133].

Due to today's environmental and sustainability concerns, facility location planning for reverse supply chains is becoming an increasingly important problem. Many corporations are attempting to recover the products that have reached the end of their useful life in order to prevent and decrease the negative environmental impact posed by improperly managed waste, and to reduce the natural resource consumption. Product recovery may also be advantageous from an economical point of view. Recovered products that meet the requirements of quality specifications can be used to reduce production costs by replacing raw materials. As such, it is essential to determine the best location and distribution strategies that ensure the ongoing financial viability of a business. However, creating the reverse supply chain separately from the conventional forward supply chain not only increases infrastructure costs, and reduces the profit associated with product recovery activities, but it also overlooks the interdependence between forward and reverse logistics flows according to the influence of the activities of reverse logistics on forward logistics such as the occupancy of the storage spaces and transportation capacity [71, 124]. By integrating the forward and reverse supply chains, a closed-loop supply chain is developed with the aim of closing the loop on material flows to ensure that products can be effectively returned to various facilities in the supply chain, thereby limiting emissions and residual waste, whilst also reducing overhead and enhancing productivity [69].

At the strategic level, closed-loop supply chain management involves long-term decisions regarding the location and capacity allocation of forward/reverse logistics facilities, the assignment of products to facilities, and the distribution of products between facilities and their end users or suppliers. That is, both demand and return handling must be taken into account, and the overall problem becomes more complicated than an isolated, stand-alone forward or reverse supply chain [49]. Clearly, the structure of a closed-loop supply chain network is strongly affected by the concurrent consideration of these aspects and other practical needs. Therefore, the system should be scalable enough for being able to facilitate different kinds of requirements without any potential disruption of supply chain activities. Although, facility location and configuration of closed-loop supply chain networks have been investigated for several years, the literature devoted to dynamic facility location in a multi-commodity, multi-level (or multi-echelon) closed-loop supply chain network is relatively scarce[1].

The motivation of this thesis stems from the need to have a broader context model of facility location in closed loop supply chains to illustrate the effects of factors that can disrupt their supply chains on network configuration decisions. This means that all the above mentioned aspects that play a significant role in determining the optimal structure of the closed-loop supply chain network, are explicitly taken into consideration.

1.2 Objectives and Contributions

Our primary objectives are to investigate and solve the problems combining a dynamic aspect with multi-echelon (or multi-level) facility location in multi-commodity closed-loop supply chains. We specifically address the combination of dynamic and multi-commodity aspects in the problems of relocation and expansion of capacitated facilities for forward and reverse logistics activities from a given set of potential sites.

The problems studied here have two substantial characteristics that distinguish them from the previous work done in this area: they are the capacitated dynamic

[1] See section 5.2 of this thesis for a review of related literature.

facility location problems in closed-loop supply chain networks, which considers the possibility of reconfiguring a location during the planning horizon. As will be shown later in the thesis, our approaches not only deal with the gradual relocation of existing facilities but also permit the capacity expansion by expanding existing facilities and creating new ones. Moreover, the integrated design of forward and reverse logistics networks is investigated. In addition to stand-alone forward and reverse facilities, forward and reverse facilities are jointly located by integrating operations of the forward and reverse channels at the same location.

The contributions of this thesis are to introduce dynamic facility location problems, the models with a number of significant applications, and to present mixed-integer linear programming (MILP) formulations of the problems, which are as follows:

1. We first propose a generic facility location model for closed-loop supply chains. This model deals with the multi-period, multi-commodity, multi- echelon capacitated facility location problem. It is generalized to address several important aspects in configuring supply chains for product recovery. The aspects considered are: the location of many types of facilities, external supply of materials, multiple products with their respective bills of materials, and distribution of products. The objective is to minimize the total cost associated with closed-loop supply chains.

2. We then present a simple hybrid uni/bidirectional facility location model for the integrated design of forward and reverse logistics networks. The forward and reverse networks are integrated by locating bidirectional facilities (besides dedicated unidirectional facilities). The model is made as simple as possible to analyze the impact of integrated demand distribution and return collection between facilities. The objective function simply minimizes overall costs.

3. We extend the previous hybrid uni/bidirectional facility location model by adding constraints restricting the capacity relocation and expansion. The objective function incorporates relocation and expansion costs, in addition to other costs.

4. We further develop a mathematical model to comprehensively determine strategic long-term solutions for the capacitated facility relocation/expansion problem in closed-loop supply chains. The model is proposed for simultaneously capturing many important features of supply chains that incorporate product recovery, while still assuring economic efficiency. We use the net present value (NPV) to maximize the objective function, which considers the time value of money by applying a discount rate to future cash flows over the (long-term) investment time horizon. All key features of the problem, namely multi-site processing facilities, multiple periods, multiple products and several location-allocation options, are included in the model. This problem consists of determining the facility location and relocation, enlargement of facilities, external supply of products, subcontracting of the supply chain function, vendor selection, as well as forward and reverse distribution of items.

This thesis focuses on modeling rather than on algorithmic aspects. We believe our models are generic, simple and scalable enough for further applications in a wide spectrum of real world complex problems with some improvements.

1.3 Outline

The remainder of this thesis is organized as follows. The subsequent chapter, Chapter 2, first introduces the basic concepts and theories that are relevant to this study. This chapter not only describes dynamic problem characteristics of facility location models, but also mentions some different areas of facility location problems having any relation or indeed opposed to dynamic facility location models. Specifically, more attention is paid to discrete network facility location problems. Thereafter, the literature is surveyed to particular insights from related studies of dynamic and discrete network facility location problems.

In Chapter 3, the facility location problem encompassing the context of closed-loop supply chains with product recovery is introduced by means of the general case model. The results illustrating several important aspects are subsequently discussed. In this chapter, we lastly review a set of relevant models in the literature.

Chapter 4 is dedicated to the integrated forward/reverse distribution network design to particularly deal with the problem of capacity relocation and expansion of facilities. The simple formulations of the hybrid uni/bidirectional facility location problem, as well as facility relocation/expansion problem are provided. Afterwards, the results of this chapter are presented. At the end of the chapter, corresponding quantitative models in the literature are reviewed.

Based on the aspects of the problems in Chapter 3 and 4, a model extension for the problem of hybrid uni/bidirectional logistics facilities to obtain relocation and expansion solutions is proposed in Chapter 5, for the purpose of locating facilities in product recovery networks. The proposed model is applied in different case studies in order to demonstrate the effectiveness of the model in creating a strategic facility location plan for closed-loop supply chains. The numerical performance of the model is also evaluated. Furthermore, the chapter provides a review of the existing literature in related research problems, and shows how the proposed model bridges some of the gaps in the literature.

Finally, Chapter 6 consolidates the conclusions derived from this research study, and provides some suggestions, which would be useful for future researches in this field.

2

Dynamic Facility Location

2.1 Dynamic Problems versus Static Problems

Facility location is a crucial strategic decision because it entails a long-term, high commitment to the established facility that cannot easily or inexpensively be changed. Generally, facility location decisions deal with the determination of the number of facilities, geographical locations of facilities, capacity of facilities, and allocation of the demand to facilities such that the demand for a product or service is satisfied. These decisions are usually made by considering the associated costs (or profits) of satisfying the entire market demand and the costs of establishing (or operating) facilities [92, 116].

The majority of traditional facility location models available in the literature are based on the assumption that any of the parameters of the problem (e.g., demands and costs) are known and consistent with the planning time horizon. Such traditional facility location models have ignored time, that is, they are *static*.

Static (also called single-period) facility location models try to optimize system performance deciding all variables simultaneously for one representative period. In other words, these models are able to perform well as long as factors and parameters are fixed and are not changed by time. This is reasonable for many problems because the desired objective is to solve the instant problem, and future data changes are either difficult to forecast or are not important, or all location data changes are approximately the same proportion relative to time, making relative data acceptably and appropriately stable [119].

In practice, in most of the real-world problems and instances, some changes over a period of time could be significant. Facilities such as schools, hospitals, factories, distribution centers, warehouses, and so forth, are often operated for years or decades due to the capital outlays involved. Consequently, there may be some occasions in which the relevant parameters in the location decision are changed or modified with the passage of time. Demands (e.g., quantity and location), costs (e.g., operation and transportation), and required capacity (e.g., availability at any given time) are examples of these parameters. Static facility location models are therefore no longer applicable under above mentioned conditions because a location decision, which is optimum in one period may or may not be optimum in other periods [11].

Dynamic (or multi-period) facility location models have been developed in the literature to overcome the limited application of static facility location models. These models differ from static facility location models in that they incorporate time. They assume that the effective parameters are time varying, and thus can be compatible with the changes and modifications added to the systems. Specifically, dynamic facility location models identify the optimal time and location for establishing facilities when their parameters are likely to be varied between different time periods. In the field of dynamic facility location problems, cost and time are two primary criteria that affect the decision makers in determining the long-term optimal location. High costs associated with establishing a new facility or relocating an existing facility make facility location projects long-term investments. Thus, facilities are planned to remain in place and in operation for an extended time period in order to make sure that such undertakings are profitable. That is, dynamic facility location models aim at ensuring that the minimum cost location of a set of facilities will be satisfied. Furthermore, in the case of time, the models allow determining to open or to close any facility at any location over a specified time horizon [11, 97].

However, dynamic facility location models were defined by Current et al. [25] into two sub-categories: *implicitly* dynamic and *explicitly* dynamic models. Implicitly dynamic models are *static* based on a sense in which all facilities are assumed to be opened in one period, and then remain open throughout the planning horizon. These models are *dynamic* because some of the problem parameters vary over time. The models attempt to account for these changes from the initial set of facility locations. In explicitly dynamic models, facilities will be opened (and possibly closed) over the planning horizon. They extend the *basic, static* models in the sense that a decision for opening and/or closing facilities at pre-specified times and locations is related to changes in parameters over time [11, 35].

As already mentioned above, it can be concluded that static models are deficient for many realistic facility location settings where substantial changes can occur over a long time horizon in strategic business applications. Accordingly, it is necessary to employ several planning periods to address the dynamic considerations of the proper timing for optimal location decisions, especially to increase or decrease capacity of facilities for dealing with varying supply and demand quantities. Dynamic models provide this capability.

2.2 Classification of Dynamic Facility Location Problems

2.2.1 Continuous Facility Location Problems

The continuous facility location problem is the oldest facility location problem dealing with geometrical representations [52]. This problem is the location problem in the plane, which allows facilities to be located anywhere in the planning area (or space under consideration). The set of conceivable locations is the plane or a region of the plane. Since continuous location theory is extremely vast, for the situations in which any place can be a potential facility site in the region, continuous facility location models are therefore suitable. There are two primary factors that establish the framework for continuous facility location models: (1) the solution space is continuous, and feasible to locate facilities on every point in the plane (there is an infinite number of possible locations); and (2) the distance between facilities is measured with a suitable matric. Generally, the Manhattan or right-angle distance metric, the Euclidean or straight-line distance metric, or the l_p-distance metric is applied[1].

Most of the problems within this field are considered in a space at least two dimensions. The *two-dimensional* problem is the most common problem for geographical reasons, i.e. the earth's surface is topologically a sphere, which is two-dimensional. Higher dimensional problems such as within a multiple floor building or underwater for three dimensions also appear [100].

The best known general model to solve the continuous facility location problem using dynamic programming is a model developed by Wesolowsky [133][2]. The author presented a general multi-period formulation of the *Weber problem*[3]. The problem was generalized by using unequal positive weights to the fixed points, and thus the objective becomes the minimization of the sum of weighted Euclidean distances. Later on, several extensions and also other applications of the Weber problem have been improved and analyzed[4].

In the continuous facility location problem, the coordinates $(x, y) \in \mathbb{R}^P \times \mathbb{R}^P$ are calculated for P facilities to minimize the sum of distances between facilities and given destinations.

The Weber problem requires to determine the coordinates $(x, y) \in \mathbb{R} \times \mathbb{R}$ of a facility

[1] See [65] and references therein for more details.

[2] The model was originally proposed by Ballou [16].

[3] The Weber problem was proposed by Weber [132].

[4] A comprehensive literature review within the field of continuous facility location can be found in [100].

such that the weighted sum of distances of a facility x to each destination $k \in \mathscr{K}$ is minimized. The classical, *Weber's continuous model* in the two-dimensional Euclidean plane ($\mathbb{R}^2$) is stated as follows:

$$\textbf{MIN} \sum_{k \in \mathscr{K}} w_k d_k(x, y) \tag{2.1}$$

where:

> w_k: is the positive weight (demand), which transforms distances into costs, associated with destination $k \in \mathscr{K}$.
>
> $d_k(x,y) = \sqrt{(x-a_k)^2 + (y-b_k)^2}$: is the Euclidean distance between a facility to be located at (x, y) and destination $k \in \mathscr{K}$ located at (a_k, b_k).

Figure 2.1 schematically shows an example of deriving x and y components for a facility using the Euclidean distance for each demand point k given in the plane $\mathbb{R}^2$. A simplified version of the model is

$$\textbf{MIN} \sum_{k \in \mathscr{K}} f_k(x, y) \tag{2.2}$$

Using a similar notation, an extended version denoted as the *dynamic (or multi-period) Weber problem*[5] with a planning horizon of $t \in \mathscr{T}$ time periods is given by

$$\begin{aligned} &\textbf{MIN} \sum_{k \in \mathscr{K}_t} \sum_{t \in \mathscr{T}} f_{k,t}(x_t, y_t) + \sum_{t \in \mathscr{T} \setminus \{1\}} CF_t \varphi_t \ , \\ &\varphi_t = \{0, 1\}; \quad \varphi_t = 0 \quad \text{if} \quad d_{t,t-1} = 0 \end{aligned} \tag{2.3}$$

where:

> $f_{k,t}(x_t, y_t)$: is the variable cost of shipping from a facility at (x_t, y_t) in period $t \in \mathscr{T}$ to destination $k \in \mathscr{K}_t$ in period $t \in \mathscr{T}$.

[5] See [133] for a more detailed description of the model.

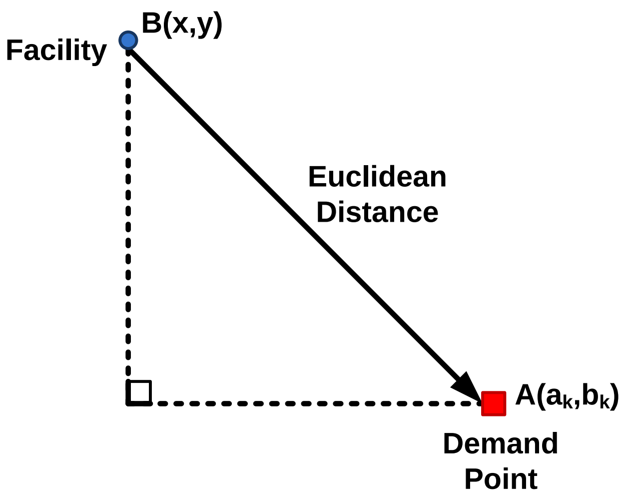


Figure 2.1: Example of the Euclidean distance

CF_t: is the fixed cost of moving a facility at the beginning of period $t \in \mathscr{T}$.

$d_{t,t-1}$: is the distance of moving a facility at the beginning of period $t \in \mathscr{T}$.

2.2.2 Discrete Network Facility Location Problems

In contrast to the continuous facility location problem that facilities can be located anywhere in a space, the discrete facility location problem has a finite feasible set of sites in which to locate a facility. For the most real world applications, the discrete facility location problem is more appropriate because sometimes the optimal location obtained from the continuous model is possibly infeasible, e.g., a manufacturing facility may be located on a sea or lake [54].

The network facility location problem is concerned with a location model in which there are a number of demand points in an underlying network, for example, suppliers, production plants, warehouses, transportation hubs, air and sea ports, retail outlets, customers, etc., some of which are the main facilities of the network. Distances between facilities are computed by the shortest paths through the network. Such points are normally taken to be at the nodes of the network, and are to be served by facilities,

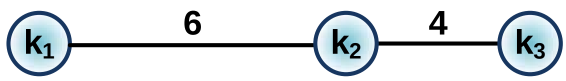


FIGURE 2.2: Example network (modified from [24])

which are to be located at the nodes of the network. If facilities could be located along the arcs of the network, a lower cost facility sitting scheme might be conceivable [24]. It is very useful for instance in locating fire stations or ambulances, where the distance from facilities to their farthest allocated potential client should be minimized [93]. This can be demonstrated by Figure 2.2. For example, if the coverage distance is 5, and facilities can be located only at the nodes, therefore two facilities are required, i.e., one at node k_1 and another one at either node k_2 or k_3. However, if facilities could also be located along the arcs of the network, then only a single facility placed 5 units to the right of node k_1 would cover all three demand nodes[6].

2.2.2.1 The *p*-Median Problem

The classical network facility location problem, called the *p-median problem*, was first introduced by Hakimi [50, 51]. The p-median problem is the problem of locating $p \in \mathscr{P}$ facilities so that the sum of weighted network distances (or the costs of distribution) between each demand point and the nearest of the $p \in \mathscr{P}$ facilities is minimized[7].

In the dynamic (or multi-period) network location problem, $p \in \mathscr{P}$ facilities, where $\mathscr{P} = \{1, ..., P\}$ and thus $|P| = P$, have to be located among $l \in \mathscr{L}$ possible locations to serve $k \in \mathscr{K}$ demand points over a planning horizon of $t \in \mathscr{T}$ periods. This is the p-median problem, when $\mathscr{L}$ is the subset of $\mathscr{K}$, $\mathscr{L} \subseteq \mathscr{K}$, that is, facilities can be only located on the nodes, and the problem is called the *vertex problem*[8]. It is

[6] An overview of the network facility location problem can be found in, e.g., [39] Part II, Chapter 2, and [119] Part II, Chapter 7.

[7] A description of the p-median problem can be found in [101] and references therein.

[8] If facilities can also be located on a branch, i.e., on a path connecting two nodes, then the problem is referred to as the absolute *p-center problem*, see [119] Part II, Chapter 7, for more details.

adequate to limit the set of potential facility locations to the set of the nodes in the case of a concave and non-decreasing function of the distance[9]. Consider the following additional notation.

Parameters:

$w_{k,t}$: positive weight (demand), which transforms distances into costs, associated with node $k \in \mathscr{K}$ in period $t \in \mathscr{T}$

$d_{l,k,t}$: distance between facility location $l \in \mathscr{L}$ and demand node $k \in \mathscr{K}$ in period $t \in \mathscr{T}$

$CF_{l,t}$: fixed cost of removing a facility at location $l \in \mathscr{L}$ in period $t \in \mathscr{T}$

Decision Variables:

$$x_{l,k,t} = \begin{cases} 1 & \text{if demand at node } k \in \mathscr{K} \text{ is served by a facility at location } l \in \mathscr{L} \\ & \text{in period } t \in \mathscr{T}, \\ 0 & \text{otherwise} \end{cases}$$

$$y_{l,t} = \begin{cases} 1 & \text{if a facility is established at location } l \in \mathscr{L} \text{ in period } t \in \mathscr{T}, \\ 0 & \text{otherwise} \end{cases}$$

$$\varphi_{l,t} = \begin{cases} 1 & \text{if a facility is removed from location } l \in \mathscr{L} \text{ in period } t \in \mathscr{T}, \\ 0 & \text{otherwise} \end{cases}$$

The standard, *dynamic (or multi-period) network location model formulation* is as below[10]:

$$\textbf{MIN} \sum_{l \in \mathscr{L}} \sum_{k \in \mathscr{K}} \sum_{t \in \mathscr{T}} w_{k,t} d_{l,k,t} x_{l,k,t} + \sum_{l \in \mathscr{L}} \sum_{t \in \mathscr{T} \setminus \{1\}} CF_{l,t} \varphi_{l,t} \tag{2.4}$$

Subject to constraints (2.5) - (2.8).

[9] See [50, 51, 58] for a detailed explanation.

[10] The model is adapted from the model of Wesolowsky and Truscott [134].

$$\sum_{l \in \mathscr{L}} y_{l,t} = P \ , \quad \forall t \in \mathscr{T} \tag{2.5}$$

$$\sum_{l \in \mathscr{L}} x_{l,k,t} = 1 \ , \quad \forall k \in \mathscr{K}, \ t \in \mathscr{T} \tag{2.6}$$

The objective function (2.4) minimizes the total demand weighted distance between customers and facilities, i.e., the costs of distribution from the facilities to the demand centers. Constraints (2.5) state that there are exactly P facilities located in period $t \in \mathscr{T}$, whereas constraints (2.6) ensure that each demand node $k \in \mathscr{K}$ is assigned to just one facility location $l \in \mathscr{L}$ in each period $t \in \mathscr{T}$.

$$x_{l,k,t} - y_{l,t} \leq 0 \ , \quad \forall l \in \mathscr{L}, \ k \in \mathscr{K}, \ t \in \mathscr{T} \tag{2.7}$$

$$x_{l,k,t}, \ y_{l,t}, \ \varphi_{l,t} \in \{0,1\}, \ \forall l \in \mathscr{L}, \ k \in \mathscr{K}, \ t \in \mathscr{T} \tag{2.8}$$

Constraints (2.7) restrict demand node assignments only to sites at which facilities have been located in period $t \in \mathscr{T}$. Constraints (2.8) are binary requirements for the problem variables.

2.2.2.2 The Uncapacitated Facility Location Problem

The uncapacitated facility location problem is also known as the simple facility location problem, where discrete points represent both of potential facility locations and customer zones on a network [127]. This problem is one of the most extensively studied discrete facility location problems in the literature. Since it is assumed that facilities have no capacity restriction, unlimited quantities of the commodity under consideration can be produced, stored or treated, and then shipped by each facility. Therefore, it is not profitable to assign the whole demand of each customer to more than one supply point. Many firms prefer this single-sourcing solution as it offers a significantly simpler supply chain management [5].

The p-median problem in section 2.2.2.1 may not be suitable for certain locating scenarios. It is assumed that each potential location has the same fixed costs incurred by locating a facility at it. Additionally, it is assumed that one previously knows the number of facilities to be established. The uncapacitated facility location problem relaxes these conditions. In this problem, there are an unspecified number of facilities to be considered for locating to meet the total demand while minimizing the sum of all fixed and variable costs [24, 39]. The problem is, in general, modeled as a *mixed-integer programming (MIP) problem*, which differs only gradually from the p-median problem because both problems can be stated in terms of discrete optimization models. The p-median problem clearly takes the structure of the set of potential facility locations and the distance metric into consideration whilst the MIP problem just simply uses input parameters without addressing where such parameters come from [65].

A number of researchers have focused on relaxing the uncapacitated facility location problem, as well as developing models and solutions for the dynamic problem. The earliest work on this problem is by Warszawski [131]. For the dynamic uncapacitated facility location problem, the objective is to minimize the total discounted cost. The minimized cost represents the cost of meeting the specified demands in different time periods at various customer locations. This amount is the sum of fixed costs for locating facilities at locations $l \in \mathscr{L}$ and operating costs of facilities $l \in \mathscr{L}$ for production and distribution of goods from facilities $l \in \mathscr{L}$ to customers $k \in \mathscr{K}$ over $t \in \mathscr{T}$ time periods, where $\mathscr{T} = \{1, ..., T\}$. $|\mathscr{T}|$ is the number of time periods and $|\mathscr{T}|=T$. The model formulation requires the following additional notation.

Parameters:

$CP_{l,k,t}$: variable cost of producing and shipping the customer's total demand from facility $l \in \mathscr{L}$ to customer $k \in \mathscr{K}$ in period $t \in \mathscr{T}$

$CF_{l,t}$: fixed cost of operating facility $l \in \mathscr{L}$ in period $t \in \mathscr{T}$

Decision Variables:

$x_{l,k,t}$: fraction of demand of customer ($k \in \mathscr{K}$) satisfied from facility $l \in \mathscr{L}$ in period $t \in \mathscr{T}$

$$\varphi_{l,t} = \begin{cases} 1 & \text{if facility } l \in \mathscr{L} \text{ is operating in period } t \in \mathscr{T}, \\ 0 & \text{otherwise} \end{cases}$$

The formulation of the standard, *dynamic (or multi-period) uncapacitated facility location model*[11] is given by the following:

$$\textbf{MIN} \sum_{l\in\mathscr{L}} \sum_{k\in\mathscr{K}} \sum_{t\in\mathscr{T}} CP_{l,k,t} x_{l,k,t} + \sum_{l\in\mathscr{L}} \sum_{t\in\mathscr{T}} CF_{l,t} \varphi_{l,t} \tag{2.9}$$

Subject to constraints (2.10) - (2.13).

$$\sum_{l\in\mathscr{L}} x_{l,k,t} = 1 \ , \quad \forall k \in \mathscr{K}, \ \ t \in \mathscr{T} \tag{2.10}$$

$$\varphi_{l,t} - x_{l,k,t} \geq 0 \ , \quad \forall l \in \mathscr{L}, \ \ k \in \mathscr{K}, \ \ t \in \mathscr{T} \tag{2.11}$$

The objective function (2.9) represents the total fixed and variable costs. Constraints (2.10) guarantee that demand at each customer $k \in \mathscr{K}$ in $t \in \mathscr{T}$ is satisfied, whereas constraints (2.11) ensure that the customer demand can be produced and shipped only from a facility that is operating in period $t \in \mathscr{T}$.

The necessary non-negativity and binary constraints are constraints (2.12) and (2.13), respectively.

$$x_{l,k,t} \geq 0 \ , \quad \forall l \in \mathscr{L}, \ \ k \in \mathscr{K}, \ \ t \in \mathscr{T} \tag{2.12}$$

$$\varphi_{l,t} \in \{0,1\}, \ \forall l \in \mathscr{L}, \ \ k \in \mathscr{K}, \ \ t \in \mathscr{T} \tag{2.13}$$

The most general extension of the dynamic uncapacitated facility location model was proposed by Van Roy and Erlenkitter [105][12]. Their model allows for opening

[11] For more details of the problem see, e.g., [3].

[12] This model was developed from the model of Roodman and Schwarz [103], which was primarily introduced by Scott [114].

new facilities ($l \in \mathscr{N}$) and closing initially existing facilities ($l \in \mathscr{E}$). The following additional constraints are required.

$$\varphi_{l,t} \geq \varphi_{l,t+1} \ , \quad \forall l \in \mathscr{E} \ , \ t \in \mathscr{T} \setminus \{T\} \tag{2.14}$$

$$\varphi_{l,t} \leq \varphi_{l,t+1} \ , \quad \forall l \in \mathscr{N} \ , \ t \in \mathscr{T} \setminus \{T\} \tag{2.15}$$

Constraints (2.14) state that closed facilities ($l \in \mathscr{E}$) cannot be reopened. Constraints (2.15) establish the condition that once a facility ($l \in \mathscr{N}$) is opened, it will remain in operation until the end of planning horizon.

2.2.2.3 The Capacitated Facility Location Problem

A well-known combinatorial optimization problem that is an extension of the uncapacitated facility location problem, in which each facility has a limit capacity constraint, is called the capacitated facility location problem. It is more realistic in many cases to incorporate the facility capacity because the uncapacitated facility location problem is valid in the situation that facilities will usually operate at level so far below their capacity. For these cases, the optimum solution may require that a customer is supplied from more than one source.

To formulate a discrete time model of the capacitated facility location problem, the following notation is needed in addition to that already defined in section 2.2.2.2.

Parameters:

$DP_{k,t}$: demand of customer $k \in \mathscr{K}$ in period $t \in \mathscr{T}$
KL_l^{max}: maximum allowable capacity at facility $l \in \mathscr{L}$
KL_l^{min}: minimum allowable capacity at facility $l \in \mathscr{L}$

Decision Variable[13]*:*

$x_{l,k,t}$: amount of units of customer ($k \in \mathscr{K}$) demand satisfied by facility $l \in \mathscr{L}$ in

[13]This variable is different from the variable in section 2.2.2.2.

period $t \in \mathscr{T}$

In addition to constraints (2.9) and (2.12)-(2.15) in the formulation of the uncapacitated problem, the standard, *dynamic (or multi-period) capacitated facility location model*[14] can be obtained by adding the following constraints.

$$\sum_{l \in \mathscr{L}} x_{l,k,t} = DP_{k,t} \ , \quad \forall k \in \mathscr{K}, \ t \in \mathscr{T} \tag{2.16}$$

Constraints (2.16) guarantee that the demand of each customer $k \in \mathscr{K}$ in each time period $t \in \mathscr{T}$ must be fully satisfied.

$$\sum_{k \in \mathscr{K}} x_{l,k,t} \leq KL_l^{max} \varphi_{l,t} \ , \quad \forall l \in \mathscr{L}, \ t \in \mathscr{T} \tag{2.17}$$

$$\sum_{k \in \mathscr{K}} x_{l,k,t} \geq KL_l^{min} \varphi_{l,t} \ , \quad \forall l \in \mathscr{L}, \ t \in \mathscr{T} \tag{2.18}$$

Constraints (2.17) and (2.18) ensure that each facility $l \in \mathscr{L}$ cannot supply more than and less than its maximum, respectively minimum amount of capacity.

2.2.2.4 The Multi-Echelon Multi-Commodity Capacitated Facility Location Problem

In the previous described models, facilities only distribute one type of commodities to satisfy the customer demands. However, in reality, there is such a large variety of industrial applications concerning capacity planning that different commodities are produced in production centers (or plants) and delivered direct to customers, or via distribution centers (or warehouses). A majority of the problem seeks to minimize the costs of both inbound and outbound distribution for various types of commodity

[14] A description of the dynamic (multi-period) capacitated facility location problem can be found, e.g., in [60].

orders, i.e., from production centers to facilities and from facilities to demand points, plus the operating costs of facilities [20]. This problem is known as the *multi-echelon multi-commodity capacitated facility location problem.*

A Multi-echelon (or multi-level) system consists of different level facilities such as suppliers, plants, distribution centers and customers (see Figure 2.3). The arrows indicate the commodity flow direction. Because these echelons are mostly organized as separate business entities, the goal of this problem is to integrate the multi-echelon decisions simultaneously, which result in increased levels of an optimized profit distribution (i.e. the allocation of profits between members in echelons), as well as customer service and safety stock.

A dynamic or multi-period version of the problem requires to locate facilities and to allocate demand of products to the chosen facilities in each period. An example problem of a two echelon distribution system can be stated simply as follows. The list of index sets, parameters and decision variables are introduced for problem formulation.

2.2.2.4.1 Notation

2.2.2.4.1.1 Index Sets

$\mathscr{L}$	:	set of facilities, indexed by $l \in \mathscr{L}$
$\mathscr{O} \subset \mathscr{L}$	:	set of selectable facilities, indexed by $o \in \mathscr{O}$
$\mathscr{E} \subset \mathscr{O}$	:	set of existing facilities, indexed by $e \in \mathscr{E}$
$\mathscr{N} \subset \mathscr{O}$	:	set of potential sites for establishing new facilities, indexed by $n \in \mathscr{N}$
$\mathscr{J} \subset \mathscr{O}$	:	set of plants, indexed by $j \in \mathscr{J}$
$\mathscr{I} \subset \mathscr{O}$	:	set of distribution centers, indexed by $i \in \mathscr{I}$
$\mathscr{K} \subset \mathscr{L}$	:	set of customer locations, indexed by $k \in \mathscr{K}$
$\mathscr{P}$	:	set of product types, indexed by $p \in \mathscr{P}$
$\mathscr{T}$	:	set of periods in the planning horizon, indexed by $t \in \mathscr{T}$

Set $\mathscr{L}$ contains all types of facilities. These are classified as selectable and non-selectable facilities. Selectable facilities $\mathscr{O}$ are a subset of $\mathscr{L}$, and include existing

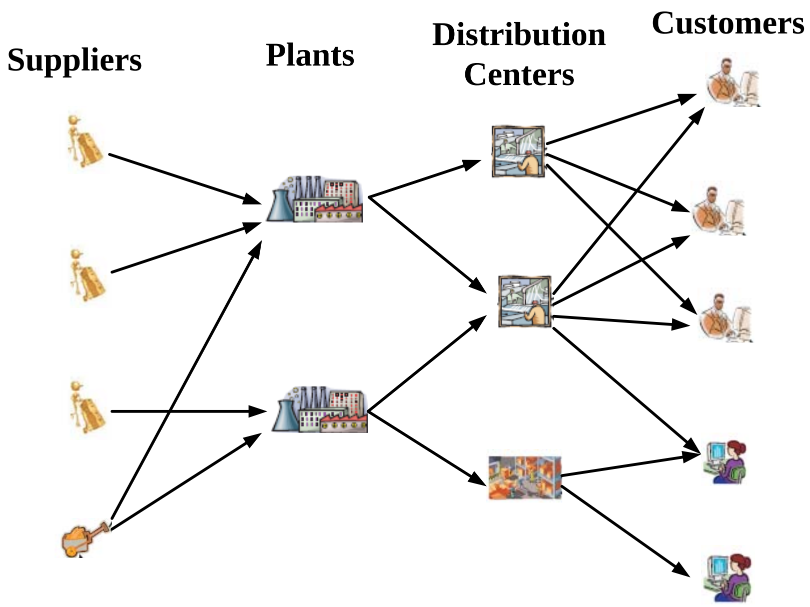


FIGURE 2.3: Example of the multi-echelon network

facilities $\mathscr{E}$ and potential sites for establishing new facilities $\mathscr{N}$. At the beginning of the planning horizon, all existing facilities in the set $\mathscr{E}$ are operating. Afterwards, these facilities can be closed, and new facilities located at the sites in $\mathscr{N}$ can be established. Selectable facilities $\mathscr{O}$ also include plants (the set $\mathscr{J}$) and distribution centers (the set $\mathscr{I}$). Note that $\mathscr{E} \cap \mathscr{N} = \emptyset$, $\mathscr{J} \cap \mathscr{I} = \emptyset$, $\mathscr{J} \cup \mathscr{I} = \mathscr{E} \cup \mathscr{N}$ and $\mathscr{O} = (\mathscr{E} \cup \mathscr{N}) \cap (\mathscr{J} \cup \mathscr{I})$.

The second category of facilities, the so-called non-selectable facilities form the set $\mathscr{L} \backslash \mathscr{O}$, which includes all facilities that exist at the beginning of the planning project, and continue in operation until the end of the planning horizon. Non-selectable facilities correspond to the locations of customers (the set $\mathscr{K}$).

The set of all product types is represented by $\mathscr{P}$. The planning horizon is partitioned into a set $\mathscr{T} = \{1, ..., T\}$ of consecutive and integer time periods. There are totally $|\mathscr{T}|$ planning periods, i.e., $|\mathscr{T}|$=T.

2.2.2.4.1.2 Parameters

$CP_{j,p,t}$: variable cost of producing one unit of product $p \in \mathscr{P}$ by plant $j \in \mathscr{J}$ in period $t \in \mathscr{T}$

$CT_{l,l',p,t}$: variable cost of shipping one unit of product $p \in \mathscr{P}$ from facility $l \in \mathscr{L}$ to facility $l' \in \mathscr{L}$ $(l \neq l')$ in period $t \in \mathscr{T}$

$CF_{o,t}$: fixed cost of operating selectable facility $o \in \mathscr{O}$ in period $t \in \mathscr{T}$

$DP_{k,p,t}$: external demand of product $p \in \mathscr{P}$ at customer $k \in \mathscr{K}$ in period $t \in \mathscr{T}$

$KO^{max}_{o,p}$: maximum allowable capacity of product $p \in \mathscr{P}$ at selectable facility $o \in \mathscr{O}$

$KO^{min}_{o,p}$: minimum allowable capacity of product $p \in \mathscr{P}$ at selectable facility $o \in \mathscr{O}$

2.2.2.4.1.3 Decision Variables

$x_{j,p,t}$: amount of product $p \in \mathscr{P}$ produced by plant $j \in \mathscr{J}$ in period $t \in \mathscr{T}$

$y_{l,l',p,t}$: amount of product $p \in \mathscr{P}$ shipped from facility $l \in \mathscr{L}$ to facility $l' \in \mathscr{L}$ $(l \neq l')$ in period $t \in \mathscr{T}$

$$\varphi_{o,t} = \begin{cases} 1 & \text{if selectable facility } o \in \mathscr{O} \text{ is operating in period } t \in \mathscr{T}, \\ 0 & \text{otherwise} \end{cases}$$

2.2.2.4.2 Formulation of the Dynamic Problem

The formulation of the standard, *dynamic (or multi-period) two echelon (or two level) multi-commodity capacitated facility location model*[15] can then be stated as:

2.2.2.4.2.1 Objective Function

The objective function (2.19) is to minimize the total cost over all time periods $t \in \mathscr{T}$. The total cost includes the cost of production, the cost of transportation between facilities and the fixed operating cost at facilities.

[15] The model is adapted by combining the models developed by Canel et al. [20] and Melo et al. [84].

$$\text{MIN} \sum_{j\in\mathscr{J}} \sum_{p\in\mathscr{P}} \sum_{t\in\mathscr{T}} CP_{j,p,t}x_{j,p,t} + \sum_{l\in\mathscr{L}} \sum_{l'\in\mathscr{L}\setminus\{l\}} \sum_{p\in\mathscr{P}} \sum_{t\in\mathscr{T}} CT_{l,l',p,t}y_{l,l',p,t} + \sum_{o\in\mathscr{O}} \sum_{t\in\mathscr{T}} CF_{o,t}\varphi_{o,t} \tag{2.19}$$

Subject to constraints 2.20 - 2.30.

2.2.2.4.2.2 Constraints

The constraints are classified into: flow constraints, capacity constraints, logical constraints, and non-negativity and integrity constraints.

Flow Constraints

Constraints 2.20 are the flow constraints balancing the amount of manufactured products $p \in \mathscr{P}$ in each period $t \in \mathscr{T}$.

$$x_{j,p,t} = \sum_{i\in\mathscr{I}} y_{j,i,p,t}\ , \quad \forall j \in \mathscr{J},\ ,p \in \mathscr{P},\ t \in \mathscr{T} \tag{2.20}$$

These constraints require that the quantity of manufactured products $p \in \mathscr{P}$ at any plant $j \in \mathscr{J}$ $\left(x_{j,p,t}\right)$ is equal to the quantity delivered to one or more distribution centers $i \in \mathscr{I}$ $\left(\sum_{i\in\mathscr{I}} y_{j,i,p,t}\right)$.

Constraints 2.21 are the flow conservation conditions that must hold for each product type $p \in \mathscr{P}$ at each distribution center $i \in \mathscr{I}$ in each period $t \in \mathscr{T}$.

$$\sum_{j\in\mathscr{J}} y_{j,i,p,t} = \sum_{k\in\mathscr{K}} y_{i,k,p,t}\ , \quad \forall i \in \mathscr{I},\ ,p \in \mathscr{P},\ t \in \mathscr{T} \tag{2.21}$$

The distribution center $i \in \mathscr{I}$ must receive enough products from one or more plants $j \in \mathscr{J}$ to further meet all demands from customers $k \in \mathscr{K}$.

Constraints 2.22 are the demand constraints for each customer $k \in \mathscr{K}$ in each period $t \in \mathscr{T}$, all customer demands must be met.

$$\sum_{i\in\mathscr{I}} y_{i,k,p,t} = DP_{k,p,t}\ , \quad \forall k \in \mathscr{K},\ p \in \mathscr{P},\ t \in \mathscr{T} \tag{2.22}$$

Capacity Constraints

Plants and distribution centers have the specified maximum and minimum capacity.

The two constraints (2.23) and (2.24) are the constraints ensuring that the manufacturing amount of each product type $p \in \mathscr{P}$ at any plant $j \in \mathscr{J}$ cannot respectively exceed, and go below the maximum and minimum allowable capacity of that plant.

$$x_{j,p,t} \leq KO^{max}_{j,p}\,\varphi_{j,t}\ , \quad \forall j \in \mathscr{J},\ p \in \mathscr{P},\ t \in \mathscr{T} \tag{2.23}$$

$$x_{j,p,t} \geq KO^{min}_{j,p}\,\varphi_{j,t}\ , \quad \forall j \in \mathscr{J},\ p \in \mathscr{P},\ t \in \mathscr{T} \tag{2.24}$$

Constraints (2.25) and (2.26) are similar to constraints (2.23) and (2.24) but applied to the distribution centers.

$$\sum_{j \in \mathscr{J}} y_{j,i,p,t} \leq KO^{max}_{i,p}\,\varphi_{i,t}\ , \quad \forall i \in \mathscr{I},\ p \in \mathscr{P},\ t \in \mathscr{T} \tag{2.25}$$

$$\sum_{j \in \mathscr{J}} y_{j,i,p,t} \geq KO^{min}_{i,p}\,\varphi_{i,t}\ , \quad \forall i \in \mathscr{I},\ p \in \mathscr{P},\ t \in \mathscr{T} \tag{2.26}$$

Constraints (2.25) restrict the maximum capacity of each product type $p \in \mathscr{P}$ at any distribution center $i \in \mathscr{I}$. Constraints (2.26) establish the minimum capacity limit for each product type $p \in \mathscr{P}$ at any distribution center $i \in \mathscr{I}$.

Logical Constraints

Constraints (2.27) and (2.28) prevent each selectable facility to change its status (opened or closed) more than once. Closed existing facilities $e \in \mathscr{E}$ cannot be reopened, and established new facilities $n \in \mathscr{N}$ will remain in operation until the end of the planning horizon.

$$\varphi_{e,t} \geq \varphi_{e,t+1}\ , \quad \forall e \in \mathscr{E}\ ,\ t \in \mathscr{T} \setminus \{T\} \tag{2.27}$$

$$\varphi_{n,t} \leq \varphi_{n,t+1}\ , \quad \forall n \in \mathscr{N}\ ,\ t \in \mathscr{T} \setminus \{T\} \tag{2.28}$$

Non-Negativity and Integrity Constraints

Finally, constraints (2.29) and (2.30) respectively represent non-negativity and integrality constraints.

$$x_{j,p,t},\ y_{l,l',p,t} \geq 0\ ,\quad \forall l \in \mathscr{L},\ l' \in \mathscr{L} \setminus \{l\}\ ,\ j \in \mathscr{J},\ p \in \mathscr{P},\ t \in \mathscr{T} \tag{2.29}$$

$$\varphi_{o,t} \in \{0,1\},\ \forall o \in \mathscr{O},\ t \in \mathscr{T} \tag{2.30}$$

2.2.3 Stochastic Facility Location Problems

The dynamic (or multi-period) facility location models described in the previous sections assume that the changes over time are known with certainty. In certainty situations, all parameters are deterministic and known. However, in many facility location problems, some of the data may be subject to significant uncertainty. Stochastic facility location models have been developed to deal with uncertainty in some of the model parameters, for example, travel times, demand locations, demand quantities and costs. The objective is to provide optimal decisions, which hedge against such uncertainty [63, 97]. In order to define these models, we should first decide which parameters are stochastic (i.e., uncertain), how they are distributed, whether they are correlated, and what decision criteria will be used for different applications [26].

Researches on dynamic (or multi-period) stochastic facility location problems can be classified into two primary approaches: (1) the probabilistic approach; and (2) the scenario approach. The first, the probabilistic approach allows to account for the stochastic aspects of the problems through the explicit consideration of the probability distributions associated with the modeled random variables in each period. The second approach utilizes scenario planning for exploring different futures. Scenarios reflect a set of possible values for parameters that may vary over the planning horizon[16].

In order to avoid the potentially high computational complexity of optimization with uncertain data, the models proposed in this thesis do not include stochastic aspects.

[16]For more details on stochastic facility location problems see, e.g., [97, 115], and references therein.

2.3 Review of Dynamic and Discrete Network Facility Location Models and Approaches

In this section, researches and publications dedicated to dynamic (multi-period) and discrete network facility location problems are discussed[17]. The voluminous publications exposed to each of the problems are classified, so that the reader can be first familiar with these research areas. Subsequently, in the section below, more details of the publications for which the optimization and formulation approaches, as well as the related performance measures (i.e., objective functions) are going to be clarified. The classification of the problems is listed in Table 2.1. We concentrate our review on papers published in the last two decades.

Figure 2.4 illustrates the classification of the relevant papers reviewed in this section. It can be easily seen that the majority of papers has been subjected to dynamic and discrete network models applied for deterministic facility location problems. Because of the difficulty in solving stochastic problems, research on facility location problems under uncertainty has received much less attention, although uncertainty is one of the most challenging, and also important problems [106]. Additionally, most of the literature deals with capacitated facility location problems. Only a small number of papers relate to p-median or uncapacitated facility location problems. Furthermore, a large number of facility location problems have been studied for multiple echelons when compared with single echelon. Another important conclusion is that many of the existing models focus on multiple commodities, rather than single commodity.

Finally, it should be noted that half of the previous papers concerned with capacitated facility location problems refer to the joint consideration of multi-echelon and multi-commodity aspects. As already mentioned in section 2.2.2.4, this is because these problems are useful for modeling real-world applications.

[17] See [85] for a review of facility location and supply chain management, and see [11, 12] for a review of classifications and applications of dynamic facility location models.

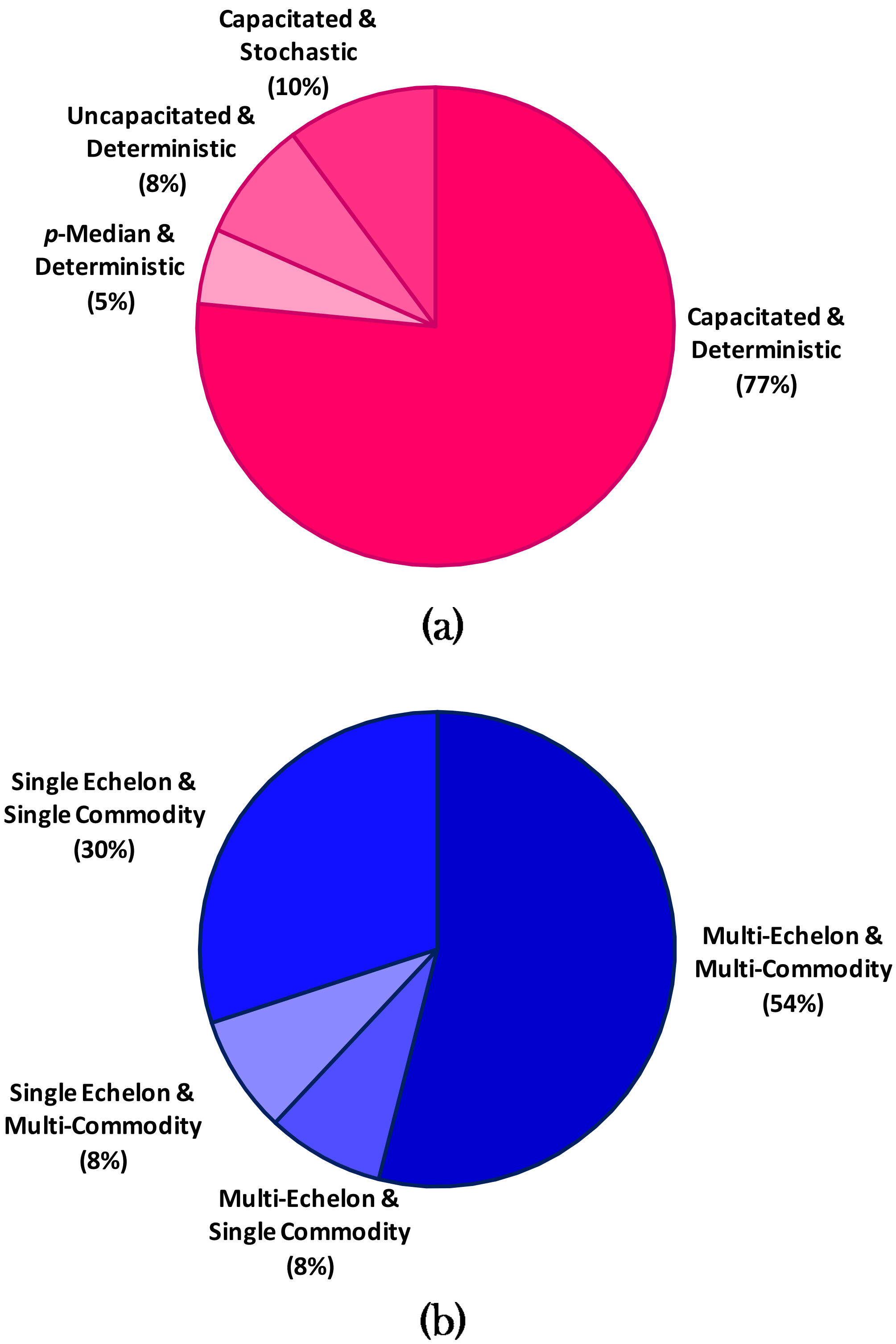


FIGURE 2.4: Proportion of existing models and their interrelated areas

Article	Echelon[a]	Commodity[a]	*p*-Median	Uncap.[b]	Cap.[c]	Deterministic	Stochastic
[1] Aghezzaf, 2005	M	S			✓		✓
[4] Albareda-Sambola et al., 2009	S	S	✓			✓	
[6] Alumur et al., 2012	M	M			✓	✓	
[7] Ambrosino and Scutellà, 2005	M	S			✓	✓	
[9] Antunes and Peeters, 2000	S	S			✓	✓	
[10] Antunes and Peeters, 2001	S	S			✓		✓
[14] Assavapokee and Wongthatsanekorn, 2012	M	M			✓	✓	
[19] Canel and Khumawala, 1997	S	S		✓		✓	
[20] Canel et al., 2001	M	M			✓	✓	
[21] Canel and Khumawala, 2001	S	S		✓		✓	
[31] Dias et al., 2006	S	S			✓	✓	
[32] Dias et al., 2007	S	S			✓	✓	
[33] Dias et al., 2008	S	S			✓	✓	
[34] Drezner et al., 1995	S	S	✓			✓	
[43] Fleischmann et al., 2006	S	M			✓	✓	
[48] Gue et al., 2003	M	M			✓	✓	
[53] Hammami et al., 2009	M	M			✓	✓	
[55] Hinojosa et al., 2008	M	M			✓	✓	
[56] Hinojosa et al., 2000	M	M			✓	✓	
[59] Hugo and Pistikopoulos, 2005	S	M			✓	✓	
[66] Ko and Evan, 2007	M	M			✓	✓	
[71] Lee and Dong, 2009	M	M			✓		✓
[78] Mansour and Zarei, 2008	M	M			✓	✓	
[79] Manzini and Gebennini, 2008	M	M			✓	✓	
[82] Melachrinousdis and Min, 2000	S	S			✓	✓	

Table 2.1: Classification of existing models according to modeling features

Article	Echelon[a]	Commodity[a]	p-Median	Uncap.[b]	Cap.[c]	Deterministic	Stochastic
[84] Melo et al., 2006	M	M			✓	✓	
[86] Melo et al., 2011	M	M			✓	✓	
[87] Melo et al., 2012	M	M			✓	✓	
[88] Min et al., 2006	S	S		✓		✓	
[90] Min and Ko, 2008	M	M			✓	✓	
[95] Naraharisetti et al., 2008	M	M			✓	✓	
[96] Naraharisetti and Karimi, 2010	M	M			✓	✓	
[109] Salema et al., 2009	M	M			✓	✓	
[110] Salema et al., 2010	M	M			✓		✓
[118] Srivastava, 2008	M	M			✓	✓	
[120] Thanh et al., 2008	M	M			✓	✓	
[121] Torres-Soto and Üster, 2011	S	S			✓	✓	
[122] Troncoso and Garrido, 2005	M	S			✓	✓	
[123] Ulstein et al., 2006	S	M			✓	✓	

[a] S: Single, M: Multiple.
[b] Uncap. = Uncapacitated
[c] Cap. = Capacitated

Table 2.1: Classification of existing models according to modeling features (continued)

2.3.1 Dynamic and Discrete Network Facility Location Optimization

An overview of the types of objective functions, which measure the performance of the problems is provided in this subsection. Moreover, an insight of the types of methodologies, which have been used for solving the problems is also provided.

Table 2.2 categories the literature according to the types of objective functions (performance measures). The vast proportion of papers exploits a cost minimization objective. This objective is generally expressed as a single objective through the sum of different cost components, which depend on the decision set modeled. Even though, most business activities are profit-oriented economic activities, the profit maximization has received relatively less attention in the literature. There are two different categories of the profit maximization: (1) the maximization of revenues minus costs, and (2) the maximization of after-tax profit. In addition, under a profit maximization goal, it may not always be attractive for companies to meet all demands of customers due to the prohibitively high costs of servicing and maintaining customers. Much less attention than the cost minimization problem and relatively less attention than the profit maximization problem has been paid to the multi-objective (or multi-criteria) optimization problem. Nevertheless, this optimization is beneficial for the problems that involve several objectives. Conventionally, the resource utilization and customer responsiveness are also investigated in addition to economic aspects.

The remaining two types of objective functions have been documented in the literature, but have attracted less attention than the types of objective functions previously stated. The first is a single objective minimization, which is not the cost minimization, e.g., the facility distance minimization (Drezner et al. [34]) and the total inventory minimization (Gue et al. [48]).

Secondly, if the investment aspect is taken into consideration of particular interest to the problems for the long-range planning, the maximization of the net present value (NPV) then seems to be the more appropriate objective. As observed from the existing literature, however, the amount of papers devoted to the models using the net present value (NPV) as the objective function is still scarce. Only Naraharisetti et al. [95] and Naraharisetti and Karimi [96] introduced this type of objective function to their models. Hence, the objective of the proposed model in Chapter 5 is to maximize the net present value (NPV) of cash flows to analyze the profitability obtained over a long-term planning horizon.

Objective function	**Article**		
Cost minimization	[1] Aghezzaf, 2005	[4] Albareda-Sambola et al., 2009	[7] Ambrosino and Scutellà, 2005
	[9] Antunes and Peeters, 2000	[10] Antunes and Peeters, 2001	[20] Canel et al., 2001
	[31] Dias et al., 2006	[32] Dias et al., 2007	[43] Fleischmann et al., 2006
	[55] Hinojosa et al., 2008	[56] Hinojosa et al., 2000	[66] Ko and Evan, 2007
	[71] Lee and Dong, 2009	[78] Mansour and Zarei, 2008	[79] Manzini and Gebennini, 2008
	[84] Melo et al., 2006	[86] Melo et al., 2011	[87] Melo et al., 2011
	[88] Min et al., 2006	[90] Min and Ko, 2008	[110] Salema et al., 2010
	[118] Srivastava, 2008	[120] Thanh et al., 2008	[121] Torres-Soto and Üster, 2011
	[122] Troncoso and Garrido, 2005		
Other minimization	[34] Drezner et al., 1995	[48] Gue et al., 2003	
Profit maximization	[6] Alumur et al., 2012	[14] Assavapokee and Wongthatsanekorn, 2012	[19] Canel and Khumawala, 1997
	[21] Canel and Khumawala, 2001	[53] Hammami et al., 2009	[109] Salema et al., 2009
	[123] Ulstein et al., 2006		
NPV maximization	[95] Naraharisetti et al., 2008	[96] Naraharisetti and Karimi, 2010	
Multi-objective	[33] Dias et al., 2008	[59] Hugo and Pistikopoulos, 2005	[82] Melachrinousdis and min, 2000

TABLE 2.2: Classification of existing models according to their performance measures

Table 2.3 classifies the literature by the types of solution methodologies that have been applied for solving dynamic (multi-period) and discrete network facility location problems. In case of solution methodologies, two general classes are distinguished: (1) general-purpose approaches (either commercial software or not), and (2) specially configured approaches. Within each of which, two further cases are considered. For instance, a mathematical programming approach to solve a problem with the optimal or near-optimal solutions is classified as *General solver*, *exact approach*. Differently, if the error margin is likely greater than 1%, it is sufficient to run the mathematical solver until a solution approach within 1% of the optimal solution. As a result, large computation times can be reduced. Otherwise, an off-the-shelf solver can be run until a specific limit of time is reached. This procedure is termed as *General solver*, *heuristic approach*.

Methodology	**Article**		
General solver			
Exact approach	[6] Alumur et al., 2012	[7] Ambrosino and Scutellà, 2005	[14] Assavapokee and Wongthatsanekorn, 2012
	[43] Fleischmann et al., 2006	[48] Gue et al., 2003	[59] Hugo and Pistikopoulos, 2005
	[79] Manzini and Gebennini, 2008	[82] Melachrinousdis and Min, 2000	[84] Melo et al., 2006
	[95] Naraharisetti et al., 2008	[96] Naraharisetti and Karimi, 2010	[109] Salema et al., 2009
	[110] Salema et al., 2010	[118] Srivastava, 2008	[122] Troncoso and Garrido, 2005
	[123] Ulstein et al., 2006		
Heuristic approach	[34] Drezner et al., 1995		
Specific algorithm			
Exact approach	[1] Aghezzaf, 2005	[19] Canel and Khumawala, 1997	[20] Canel et al., 2001
	[120] Thanh et al., 2008		
Heuristic approach	[4] Albareda-Sambola et al., 2009	[9] Antunes and Peeters, 2000	[10] Antunes and Peeters, 2001
	[21] Canel and Khumawala, 2001	[31] Dias et al., 2006	[32] Dias et al., 2007
	[33] Dias et al., 2008	[53] Hammami et al., 2009	[55] Hinojosa et al., 2008
	[56] Hinojosa et al., 2000	[66] Ko and Evan, 2007	[71] Lee and Dong, 2009
	[78] Mansour and Zarei, 2008	[86] Melo et al., 2011	[87] Melo et al., 2012
	[88] Min et al., 2006	[90] Min and Ko, 2008	[121] Torres-Soto and Üster, 2011

Table 2.3: Classification of existing models according to their methodologies

It is the same for the second general class, specially configured approach, for which two categories are identified: *Specific algorithm*, *exact approach* and *Specific algorithm*, *heuristic approach*. For the first category, the most popular used algorithms go as follows, branch-and-bound, branch-and-cut, column generation, and decomposition methods. Where branch-and-bound algorithms sometimes are combined with Lagrangian relaxation or heuristic procedures in order to obtain the required bounds. However, if the number of decision variables is large, and the models are comparatively more complex, therefore it is difficult to acquire an optimal solution by using exact algorithms. In this case, the heuristic method is applied. Lagrangian relaxation, linear programming based heuristics and metaheuristics are among the most widely used techniques.

Some conclusions can be drawn from this table. The classes *General solver*, *exact approach* and *Specific algorithm*, *heuristic approach* have received a lot of attention in the literature since they are easy to implement, as well as have an effort to solve complex and real-world problems. Whereas, only a few papers concern the problems solved with *Specific algorithm*, *exact approach* and *General solver*, *heuristic approach* because they have less beneficial use when compared with *General solver*, *exact approach* and *Specific algorithm*, *heuristic approach*.

2.3.2 Applications and Case Studies

The literature related to the applications of dynamic (multi-period) discrete network facility location problems is addressed in this section through Table 2.4. The papers listed in this table are sorted by two types of measures: (1) the type of context, and (2) the type of industry. The latter has two sub-classes: *Case study* refers to real life applications in industries, even though implementing them in practice is not, and the sub-class *Industrial context* stands for the studies applying randomly generated data sets for industries.

Area	Context	Article	
Automotive	Case study	[43] Fleischmann et al., 2006	[53] Hammami et al., 2009
Chemistry	Case study	[19] Canel and Khumawala, 1997 [59] Hugo and Pistikopoulos, 2005 [96] Naraharisetti and Karimi, 2010	[21] Canel and Khumawala, 2001 [95] Naraharisetti et al., 2008
Education	Industrial context	[9] Antunes and Peeters, 2000	[10] Antunes and Peeters, 2001
Electronics	Case study	[6] Alumur et al., 2012 [79] Manzini and Gebennini, 2008	[14] Assavapokee and Wongthatsanekorn, 2012
Forestry	Case study	[122] Troncoso and Garrido, 2005	
Material	Case study	[123] Ulstein et al., 2006	
Military	Case study	[48] Gue et al., 2003	
Reverse logistics	Case study	[66] Ko and Evan, 2007 [90] Min and Ko, 2008 [110] Salema et al., 2010	[88] Min et al., 2006 [109] Salema et al., 2009 [118] Srivastava, 2008
	Industrial context	[71] Lee and Dong, 2009	[78] Mansour and Zarei, 2008
Service	Industrial context	[4] Albareda-Sambola et al., 2009	
Non-specific	Case study	[1] Aghezzaf, 2005 [82] Melachrinousdis and Min, 2000	[20] Canel et al., 2001
	Industrial context	[7] Ambrosino and Scutellà, 2005 [32] Dias et al., 2007 [34] Drezner et al., 1995 [56] Hinojosa et al., 2000 [86] Melo et al., 2011 [120] Thanh et al., 2008	[31] Dias et al., 2006 [33] Dias et al., 2007 [55] Hinojosa et al., 2008 [84] Melo et al., 2006 [87] Melo et al., 2012 [121] Torressoto and Üster, 2011

Table 2.4: Applications of dynamic and discrete network facility location models

It can be seen from this table that almost 60% of papers present the results from case studies, whereas the remainder apply randomly generated data for specific or non-specific industrial applications. The reason for an aforementioned large amount of contrast is that when enough task knowledge and data are acquired, it is more beneficial to conduct a case study. In the former case, the types of industries for which the applications come from are investigated. It can be noticed from Table 2.4 that the non-specific area of interest is dealt with by the most literature followed by reverse logistics, chemistry, electronics, automotive and education. The smallest category of areas of attention belongs to forestry, material, military and service.

In spite of the papers presented in several tables throughout the review, there is no generic and comprehensive model that captures all important activities to cope with strategic long-range requirements in asset investment planning. All of existing models dealing with such strategic planning are not general and scalable enough. This highlights an important area for the development of further new models.

3

Facility Location in Closed-Loop Supply Chain Design

3.1 Closed-Loop Supply Chains

Recently, the concept of closed-loop supply chains has begun to receive growing attention from both practitioners and researchers owing to the potential benefits from integration of the conventional activities of forward supply chain and reverse supply chain activities. Many industries, such as auto parts manufacturing, computers, consumer electronics, telecommunications and publishing, have adopted closed-loop supply chain practices. There are two major reasons for this trend: first, the legislative environmental regulation for companies, especially in Europe, and secondly, the economic

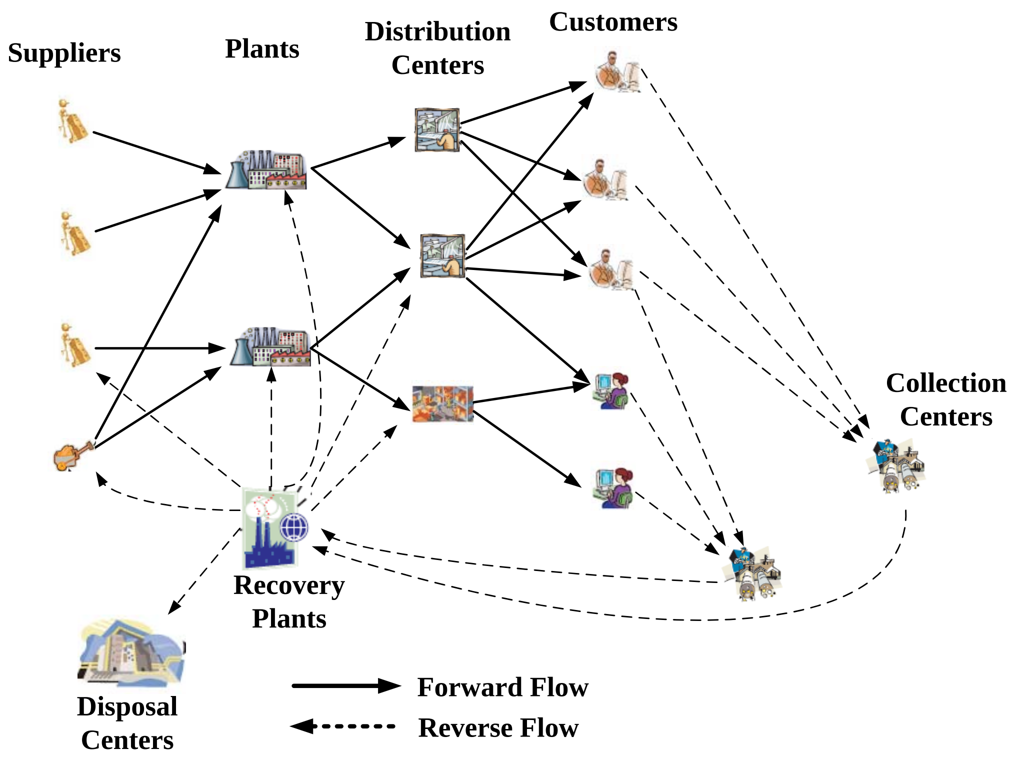


Figure 3.1: A generic closed-loop supply chain network

factors influencing intensity of competition fight among the existing firms [129].

Based on the following description, a general view and diagram of the closed-loop supply chain network is illustrated in Figure 3.1 and 3.2, respectively. In a typical supply chain process, plant manufacturers obtain raw materials/parts from suppliers to create the final products. Most customers buy the products through distributors, rather than directly from manufacturers. With returns policies at present, end users may send products back to the supply chain for recovery (see Figure 3.1). Product recovery, which may be direct or may involve a form of re-processing (see Figure 3.2), encompasses a broad range of activities for the entire reverse supply chain process. The five major activities of a reverse supply chain are as below[1].

- *Collection (or acquisition).* Collection refers to receiving the used products from the final customers to a point of recovery.

- *Inspection/selection/sorting process.* The products are graded at this point, and

[1] See [29, 42] for more details.

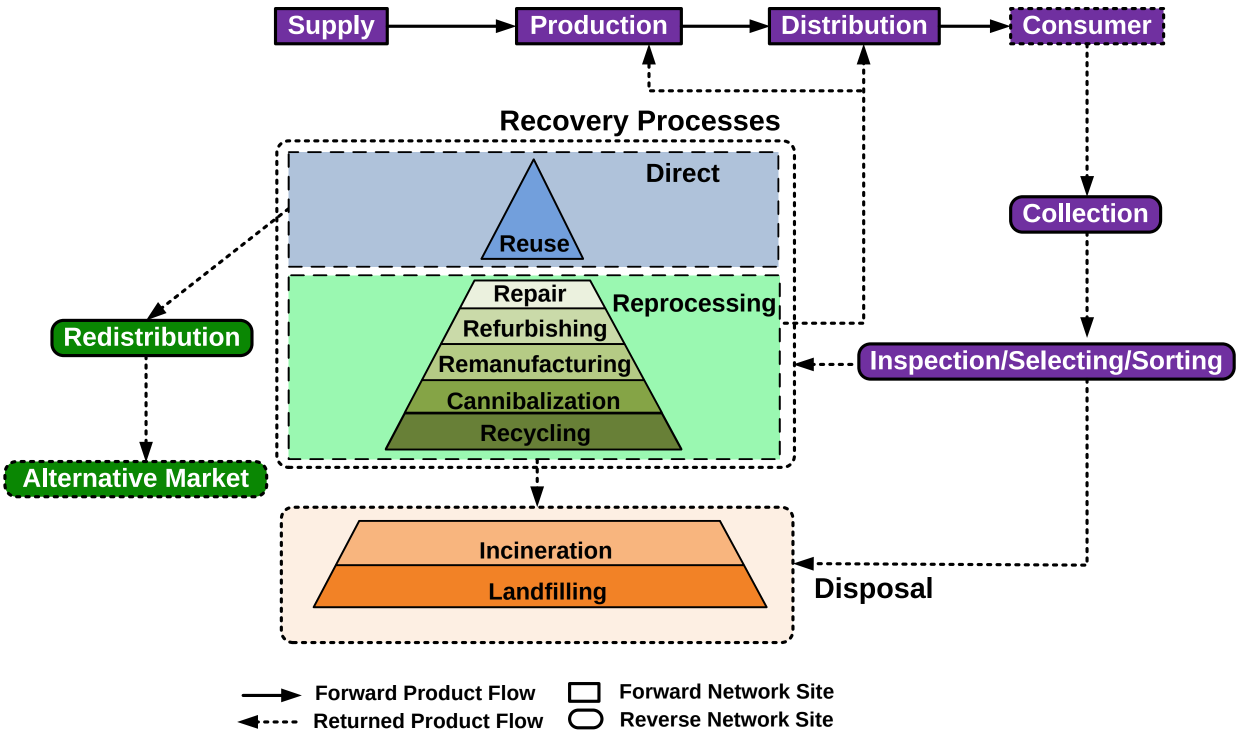


FIGURE 3.2: A diagram of closed-loop supply chain system (modified from [42, 129])

then are split according to distinct recovery options.

- *Re-distribution.* In case of direct recovery, the returned items are almost as-good-as new (reusable), and can be re-distributed to the potential markets rapidly.

- *Re-processing.* If the quality is inadequate, products may be shipped for re-processing. A form of re-processing is also recognized as process recovery, denoting the transformation of used products for future use. This stage embraces repair, refurbishing, remanufacturing/retrievals, cannibalization and recycling. Additionally, activities, e.g. cleaning, replacement and re-assembly, may be included.

- *Disposal.* The non-reusable items are disposed of either through incineration or by using a landfill.

As shown in Figure 3.2, the top point of the pyramid indicates the highest recovery value, while recovery activities close to the bottom of the pyramid recover less value from the returned items [70]. This reinforces the view that firms should allocate returns to recovery options or disposal appropriately.

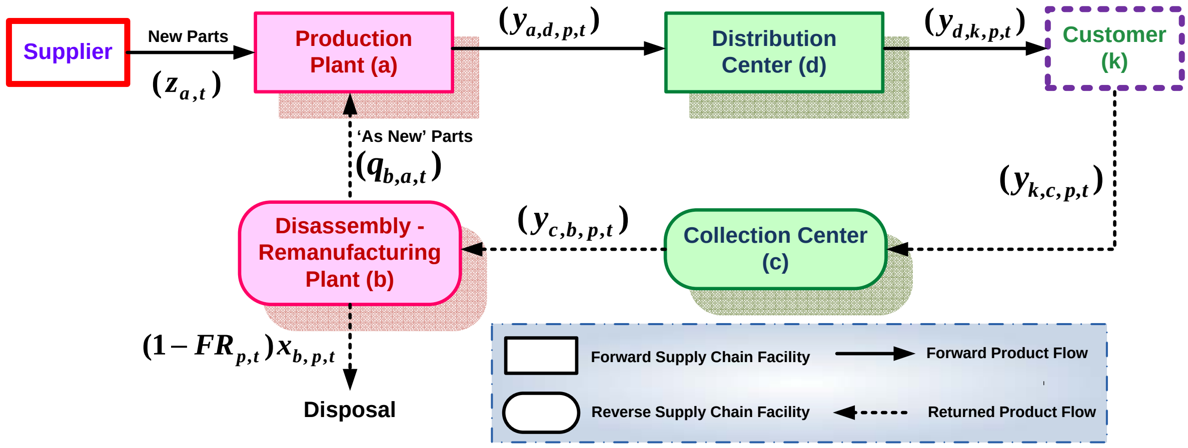


Figure 3.3: Structure of the closed-loop supply chain model

More importantly, inefficient locations of production, recovery, distribution, collection and disposal facilities will result in considerable excess costs that are incurred throughout the lifetime of facilities. Decisions need to be taken very carefully. For instance, facilities should be close to where demands for manufactured and recovered products exist, in case transportation is a large portion of the total cost, whereas facilities with high fixed costs may require centralized operations [22]. Hence, the solutions should be properly extensible, and align the organization with long-term strategic targets. To this end, a generalized model summarizing the essential characteristics discussed above is formulated.

3.2 A Generic Facility Location Model for Closed-Loop Supply Chains

In a dynamic or multi-period version of the problem, forward and reverse flows and their mutual interaction are concurrently considered to provide the optimal values of production and transportation quantities of manufactured and remanufactured products, as well as to solve the location problem of forward and reverse facilities in each period. A closed or open option for every facility is available over a given planning horizon. To this end, we first formulate a generic model summarizing the essential characteristics of a closed-loop supply chain network design problem simultaneously. Consider the following dynamic (or multi-period) problem.

Figure 3.3 represents the underlying network structure, which illustrates the facility location sets along with forward and reverse material flows, assignments and facility location variables in the entire closed-loop supply chain under consideration. In a general closed-loop supply chain network, products are initially shipped to distribution centers and to customers from there as a forward flow. Reverse flow begins with the return of used products from customers to collection centers. The used products are then transported from collection centers to disassembly-remanufacturing plants for remanufacturing and disposal processes. Returned products that are considered good enough quality for remanufacturing will be disassembled, and processed until they become as good as new parts and/or components. Reusable parts/components are subsequently transported to production plants, and used for manufacturing products. The notation to be used in the model formulation is described below.

3.2.1 Notation

3.2.1.1 Index Sets

$\mathscr{L}$: set of facilities, indexed by $l \in \mathscr{L}$

$\mathscr{O} \subset \mathscr{L}$: set of selectable facilities, indexed by $o \in \mathscr{O}$

$\mathscr{E} \subset \mathscr{O}$: set of existing facilities, indexed by $e \in \mathscr{E}$

$\mathscr{N} \subset \mathscr{O}$: set of potential sites for establishing new facilities, indexed by $n \in \mathscr{N}$

$\mathscr{J} \subset \mathscr{O}$: set of plants, indexed by $j \in \mathscr{J}$

$\mathscr{A} \subset \mathscr{J}$: set of production plants, indexed by $a \in \mathscr{A}$

$\mathscr{B} \subset \mathscr{J}$: set of disassembly-remanufacturing plants, indexed by $b \in \mathscr{B}$

$\mathscr{I} \subset \mathscr{O}$: set of intermediate centers, indexed by $i \in \mathscr{I}$

$\mathscr{D} \subset \mathscr{I}$: set of distribution centers, indexed by $d \in \mathscr{D}$

$\mathscr{C} \subset \mathscr{I}$: set of collection centers, indexed by $c \in \mathscr{C}$

$\mathscr{K} \subset \mathscr{L}$: set of customer locations, indexed by $k \in \mathscr{K}$

$\mathscr{P}$: set of product types, indexed by $p \in \mathscr{P}$

$\mathscr{T}$: set of periods in the planning horizon, indexed by $t \in \mathscr{T}$

Set $\mathscr{L}$ contains all types of facilities, which are classified in so-called selectable and non-selectable facilities. Selectable facilities $\mathscr{O}$ are a subset of $\mathscr{L}$. These facilities consist of existing facilities $\mathscr{E}$ and potential sites for establishing new facilities $\mathscr{N}$. At the beginning of the planning horizon, all existing facilities in the set $\mathscr{E}$ are operating. Later on, these facilities can be closed, and new facilities located at the sites in $\mathscr{N}$ can be opened. Selectable facilities $\mathscr{O}$ also consist of production plants (the set $\mathscr{J}$) and distribution centers (the set $\mathscr{I}$). Note that $\mathscr{E} \cap \mathscr{N} = \emptyset$, $\mathscr{J} \cap \mathscr{I} = \emptyset$, $\mathscr{J} \cup \mathscr{I} = \mathscr{E} \cup \mathscr{N}$ and $\mathscr{O} = (\mathscr{E} \cup \mathscr{N}) \cap (\mathscr{J} \cup \mathscr{I})$.

The set of plants $\mathscr{J}$ includes production plants (the set $\mathscr{A}$) and disassembly-remanufacturing plants (the set $\mathscr{B}$). In the set of intermediate centers $\mathscr{I}$, distribution centers (the set $\mathscr{D}$) and collection centers (the set $\mathscr{C}$) are included. Observe that $\mathscr{A} \cap \mathscr{B} = \emptyset$, $\mathscr{A} \cup \mathscr{B} = \mathscr{J}$, $\mathscr{D} \cap \mathscr{C} = \emptyset$ and $\mathscr{D} \cup \mathscr{C} = \mathscr{I}$.

The second category of facilities, the so-called non-selectable facilities form the set $\mathscr{L} \setminus \mathscr{O}$, which includes all facilities that exist at the beginning of the planning project, and continue in operation until the end of the planning horizon. Non-selectable facilities correspond to the locations of customers (the set $\mathscr{K}$).

Set $\mathscr{P}$ is the set of all types of products. The planning horizon is partitioned into a set $\mathscr{T} = \{1, ..., T\}$ of consecutive and integer time periods. In total, there are $|\mathscr{T}|$ planning periods, i.e., $|\mathscr{T}|=T$.

3.2.1.2 Parameters

3.2.1.2.1 Costs

CB_t : variable cost of purchasing one unit of part/component in period $t \in \mathscr{T}$

$CP_{j,p,t}$: variable cost of processing one unit of product $p \in \mathscr{P}$ by plant $j \in \mathscr{J}$ in period $t \in \mathscr{T}$

$CT_{l,l',p,t}$: variable cost of shipping one unit of product $p \in \mathscr{P}$ from facility $l \in \mathscr{L}$ to facility $l' \in \mathscr{L}$ $(l \neq l')$ in period $t \in \mathscr{T}$

CR_t : variable cost of shipping one unit of part/component from a disassembling and remanufacturing plant in period $t \in \mathscr{T}$

$CF_{o,t}$: fixed cost of operating selectable facility $o \in \mathscr{O}$ in period $t \in \mathscr{T}$

$CC_{e,t}$: fixed cost of closing existing facility $e \in \mathscr{E}$ in period $t \in \mathscr{T}$

$CO_{n,t}$: fixed cost of establishing new facility $n \in \mathscr{N}$ in period $t \in \mathscr{T}$

$CD_{b,p,t}$: variable disposal cost per unit of product $p \in \mathscr{P}$ discarded from disassembly-remanufacturing plant $b \in \mathscr{B}$ in period $t \in \mathscr{T}$

3.2.1.2.2 Other Parameters

$DP_{k,p,t}$: external demand of product $p \in \mathscr{P}$ at customer $k \in \mathscr{K}$ in period $t \in \mathscr{T}$

KO_o^{max} : maximum processing capacity at selectable facility $o \in \mathscr{O}$

KO_o^{min} : minimum processing capacity at selectable facility $o \in \mathscr{O}$

$UJ_{j,p}$: unit capacity consumption factor of product $p \in \mathscr{P}$ processed at plant $j \in \mathscr{J}$

$UI_{l,i,p}$: unit capacity consumption factor of product $p \in \mathscr{P}$ shipped from facility $l \in \mathscr{L}$ to intermediate center $i \in \mathscr{I}$

AM_p : amount of part/component for assembling one unit of product $p \in \mathscr{P}$

RM_p : amount of part/component obtained from disassembling and remanufacturing one unit of returned product $p \in \mathscr{P}$

$RC_{k,p,t}$: fraction of product $p \in \mathscr{P}$ returned from customer $k \in \mathscr{K}$ in period $t \in \mathscr{T}$

$FR_{p,t}$: fraction of returned product $p \in \mathscr{P}$ satisfying the quality specifications in period $t \in \mathscr{T}$

3.2.1.3 Decision Variables

$x_{j,p,t}$: amount of product $p \in \mathscr{P}$ processed by plant $j \in \mathscr{J}$ in period $t \in \mathscr{T}$

$y_{l,l',p,t}$: amount of product $p \in \mathscr{P}$ shipped from facility $l \in \mathscr{L}$ to facility $l' \in \mathscr{L}$ $(l \neq l')$ in period $t \in \mathscr{T}$

$z_{a,t}$: amount of part/component purchased from an external supplier to production plant $a \in \mathscr{A}$ in period $t \in \mathscr{T}$

$q_{b,a,t}$: amount of part/component shipped from disassembly-remanufacturing plant $b \in \mathscr{B}$ to production plant $a \in \mathscr{A}$ in period $t \in \mathscr{T}$

$$\varphi_{o,t} = \begin{cases} 1 & \text{if selectable facility } o \in \mathscr{O} \text{ is operated in period } t \in \mathscr{T}, \\ 0 & \text{otherwise} \end{cases}$$

3.2.2 Formulation of the Dynamic Problem

The full mathematical formulation of the general, *dynamic (or multi-period) multi-echelon (or multi-level) multi-commodity capacitated facility location model for closed-loop supply chains*[2] can be written as in the sections below.

3.2.2.1 Objective Function

The objective function (3.1) minimizes the total cost, i.e., the sum of all costs (TOC^{total}), of the closed-loop supply chain system.

$$\textbf{MIN } TOC^{total} = TOC^1 + TOC^2 + TOC^3 \tag{3.1}$$

The total cost consists of the following costs.

3.2.2.1.1 Variable Purchasing, Processing and Transportation Costs (TOC^1)

In equation (3.2), the first component is the costs of purchasing all parts/components from external suppliers for the manufacturing process at production plants $a \in \mathscr{A}$ in periods $t \in \mathscr{T}$.

$$\begin{aligned} TOC^1 = & \sum_{a\in\mathscr{A}} \sum_{t\in\mathscr{T}} CB_t z_{a,t} + \sum_{j\in\mathscr{J}} \sum_{p\in\mathscr{P}} \sum_{t\in\mathscr{T}} CP_{j,p,t} x_{j,p,t} \\ & + \sum_{l\in\mathscr{L}} \sum_{l'\in\mathscr{L}\setminus\{l\}} \sum_{p\in\mathscr{P}} \sum_{t\in\mathscr{T}} CT_{l,l',p,t} y_{l,l',p,t} + \sum_{b\in\mathscr{B}} \sum_{a\in\mathscr{A}} \sum_{t\in\mathscr{T}} CR_t q_{b,a,t} \end{aligned} \tag{3.2}$$

[2] Our model is modified and extended by integrating the single-period closed-loop supply chain model of Demirel and Gökçen [30] and the dynamic (or multi-period) facility location model developed by Melo et al. [84].

The second component is the costs of processing all products $p \in \mathscr{P}$ by plants $j \in \mathscr{J}$ in periods $t \in \mathscr{T}$. The third component is the costs paid for transporting all products $p \in \mathscr{P}$ from facilities $l \in \mathscr{L}$ to facilities $l' \in \mathscr{L}$ in periods $t \in \mathscr{T}$. The last component is the costs of transporting all parts/components from disassembly-remanufacturing plants $b \in \mathscr{B}$ to production plants $a \in \mathscr{A}$ in periods $t \in \mathscr{T}$.

3.2.2.1.2 Fixed Costs of Operating, Closing and Establishing Facilities (TOC^2)

The first component in equation 3.3 is the costs of operating one or more selectable facilities $o \in \mathscr{O}$ in periods $t \in \mathscr{T}$.

$$\begin{aligned} TOC^2 = & \sum_{o \in \mathscr{O}} \sum_{t \in \mathscr{T}} CF_{o,t}\varphi_{o,t} + \sum_{e \in \mathscr{E}} CC_{e,1}\left(1 - \varphi_{e,1}\right) \\ & + \sum_{e \in \mathscr{E}} \sum_{t \in \mathscr{T} \setminus \{1\}} CC_{e,t}\left(\varphi_{e,t-1} - \varphi_{e,t}\right) + \sum_{n \in \mathscr{N}} \sum_{t \in \mathscr{T}} CO_{n,t}\left(\varphi_{n,t} - \varphi_{n,t-1}\right) \end{aligned} \tag{3.3}$$

The second and third components are respectively the costs of closing one or more existing facilities $e \in \mathscr{E}$ in the first period and all subsequent periods. The costs of opening one or more new facilities $n \in \mathscr{N}$ in periods $t \in \mathscr{T}$ are the fourth component.

3.2.2.1.3 Variable Disposal Costs (TOC^3)

These are the costs incurred in disposing all discarded products $p \in \mathscr{P}$ in periods $t \in \mathscr{T}$ 3.4. It is computed based on a fraction $\left(1 - FR_{p,t}\right)$ of returned products from disassembly-remanufacturing plants $b \in \mathscr{B}$ sent for disposal.

$$TOC^3 = \sum_{b \in \mathscr{B}} \sum_{p \in \mathscr{P}} \sum_{t \in \mathscr{T}} CD_{b,p,t}\left(1 - FR_{p,t}\right) x_{b,p,t} \tag{3.4}$$

Subject to constraints 3.5 to 3.20.

3.2.2.2 Constraints

The constraints are separated into five groups: forward flow constraints, reverse flow constraints, capacity constraints, logical constraints, and non-negativity and integrity constraints.

3.2.2.2.1 Forward Flow Constraints

The constraints below ensure that each production plant $a \in \mathscr{A}$ receives enough parts/components in order to manufacture the required quantity of products $p \in \mathscr{P}$.

$$z_{a,t} + \sum_{b \in \mathscr{B}} q_{b,a,t} = \sum_{p \in \mathscr{P}} AM_p x_{a,p,t} \ , \quad \forall a \in \mathscr{A}, \ t \in \mathscr{T} \tag{3.5}$$

Constraints (3.5) assure that the total number of units to be produced of products $p \in \mathscr{P}$ at production plant $a \in \mathscr{A}$ in period $t \in \mathscr{T}$ $\left(\sum_{p \in \mathscr{P}} x_{a,p,t}\right)$ times the number of parts/components needed to produce one unit of product $p \in \mathscr{P}$ (AM_p), must be equal to the total amount of parts/components delivered from external suppliers in period $t \in \mathscr{T}$ $(z_{a,t})$ and disassembly-remanufacturing plants in period $t \in \mathscr{T}$ $\left(\sum_{b \in \mathscr{B}} q_{b,a,t}\right)$.

The following constraints require that total outgoing flows from each production plant $a \in \mathscr{A}$ should be as big as the amount of manufactured products.

$$x_{a,p,t} = \sum_{d \in \mathscr{D}} y_{a,d,p,t} \ , \quad \forall a \in \mathscr{A}, \ p \in \mathscr{P}, \ t \in \mathscr{T} \tag{3.6}$$

Constraints (3.6) are the constraints ensuring that the quantity of manufactured products $p \in \mathscr{P}$ in period $t \in \mathscr{T}$ $(x_{a,p,t})$ is equal to the quantity distributed to one or more distribution centers $d \in \mathscr{D}$ in period $t \in \mathscr{T}$ $\left(\sum_{d \in \mathscr{D}} y_{a,d,p,t}\right)$.

Constraints (3.7) guarantee that each distribution center $d \in \mathscr{D}$ must receive enough products to meet the demands.

$$\sum_{a \in \mathscr{A}} y_{a,d,p,t} = \sum_{k \in \mathscr{K}} y_{d,k,p,t} \ , \quad \forall d \in \mathscr{D}, \ p \in \mathscr{P}, \ t \in \mathscr{T} \tag{3.7}$$

The amount that enters each distribution center $d \in \mathscr{D}$ for selling in period $t \in \mathscr{T}$ $\left(\sum_{a \in \mathscr{A}} y_{a,d,p,t}\right)$ must be equal to the total product purchased from that distribution center, and sent to one or more customers $k \in \mathscr{K}$ in period $t \in \mathscr{T}$ $\left(\sum_{k \in \mathscr{K}} y_{d,k,p,t}\right)$.

Constraints (3.8) are the demand fulfillment constraints. These constraints ensure that the total sales quantity for each product $p \in \mathscr{P}$ must be equal to the demand quantity $(DP_{k,p,t})$.

$$\sum_{d \in \mathscr{D}} y_{d,k,p,t} = DP_{k,p,t} \ , \quad \forall k \in \mathscr{K}, \ p \in \mathscr{P}, \ t \in \mathscr{T} \tag{3.8}$$

3.2.2.2.2 Reverse Flow Constraints

The flow constraints balancing the amount of returned products are constraints (3.9).

$$\sum_{d \in \mathscr{D}} y_{d,k,p,t} RC_{k,p,t} = \sum_{c \in \mathscr{C}} y_{k,c,p,t} \ , \quad \forall k \in \mathscr{K}, \ p \in \mathscr{P}, \ t \in \mathscr{T} \tag{3.9}$$

These constraints require that the predefined rate of return for each product $p \in \mathscr{P}$ in period $t \in \mathscr{T}$ is determined as the return quantity $\left(\sum_{c \in \mathscr{C}} y_{k,c,p,t}\right)$ from each customer $k \in \mathscr{K}$ in period $t \in \mathscr{T}$.

Constraints (3.10) represent the conservation (mass balance) at each collection center $c \in \mathscr{C}$.

$$\sum_{k \in \mathscr{K}} y_{k,c,p,t} = \sum_{b \in \mathscr{B}} y_{c,b,p,t} \ , \quad \forall c \in \mathscr{C}, \ p \in \mathscr{P}, \ t \in \mathscr{T} \tag{3.10}$$

Constraints (3.10) are defined to assure that the quantity returned from one or more customers $k \in \mathscr{K}$ to each collection center $c \in \mathscr{C}$ in period $t \in \mathscr{T}$ $\left(\sum_{k \in \mathscr{K}} y_{k,c,p,t}\right)$ must be equal to the quantity distributed from that collection center to one or more disassembly-remanufacturing plants $b \in \mathscr{B}$ in period $t \in \mathscr{T}$ $\left(\sum_{b \in \mathscr{B}} y_{c,b,p,t}\right)$.

Constraints (3.11) bound the units of each product $p \in \mathscr{P}$ shipped for disassembly-remanufacturing process.

$$\sum_{c \in \mathscr{C}} y_{c,b,p,t} = x_{b,p,t} \ , \quad \forall b \in \mathscr{B}, \ p \in \mathscr{P}, \ t \in \mathscr{T} \tag{3.11}$$

The outflow quantity from one or more collection centers $c \in \mathscr{C}$ to each disassembly-remanufacturing plant $b \in \mathscr{B}$ in period $t \in \mathscr{T}$ $\left(\sum_{c \in \mathscr{C}} y_{c,b,p,t}\right)$ equal the amount of disassembled and remanufactured units in period $t \in \mathscr{T}$ $\left(x_{b,p,t}\right)$.

The requirement for the outbound flow of parts/components from each disassembly-remanufacturing plant $b \in \mathscr{B}$ is assured by constraints (3.12).

$$FR_{p,t} \left(\sum_{p \in \mathscr{P}} x_{b,p,t} RM_p \right) = \sum_{a \in \mathscr{A}} q_{b,a,t} \ , \quad \forall b \in \mathscr{B}, \ t \in \mathscr{T} \tag{3.12}$$

The reusable parts/components that transfer from each disassembly-remanufacturing plant $b \in \mathscr{B}$ for manufacturing at one or more production plants $a \in \mathscr{A}$ in period $t \in \mathscr{T}$ $\left(\sum_{a\in\mathscr{A}} q_{b,a,t}\right)$ must be equal to the amount of parts/components obtained from disassembling the returned products $p \in \mathscr{P}$ at that disassembly-remanufacturing plant in period $t \in \mathscr{T}$ $\left(\sum_{p\in\mathscr{P}} x_{b,p,t} RM_p\right)$ multiplied by a fraction of part/component satisfying the quality specifications in period $t \in \mathscr{T}$ $\left(FR_{p,t}\right)$.

3.2.2.2.3 Capacity Constraints

3.2.2.2.3.1 Capacity Constraints of Plants

Constraints (3.13) and (3.14) limit the maximum and minimum processing capacity allowable for all products $p \in \mathscr{P}$ at any plant $j \in \mathscr{J}$.

$$\sum_{p\in\mathscr{P}} UJ_{j,p} x_{j,p,t} \leq KO_j^{max} \varphi_{j,t}\ , \quad \forall j \in \mathscr{J},\ t \in \mathscr{T} \tag{3.13}$$

$$\sum_{p\in\mathscr{P}} UJ_{j,p} x_{j,p,t} \geq KO_j^{min} \varphi_{j,t}\ , \quad \forall j \in \mathscr{J},\ t \in \mathscr{T} \tag{3.14}$$

The amount of all products $p \in \mathscr{P}$ processed at any plant $j \in \mathscr{J}$ in each period $t \in \mathscr{T}$ cannot exceed the maximum allowable capacity KO_j^{max}, and must exceed the lower limit on allowable capacity KO_j^{min} of that plant.

3.2.2.2.3.2 Capacity Constraints of Intermediate centers

The maximum and minimum capacity of all product types $p \in \mathscr{P}$ delivered to any intermediate site $i \in \mathscr{I}$ is specified by (3.15) and (3.16).

$$\sum_{l\in\mathscr{L}} \sum_{p\in\mathscr{P}} UI_{l,i,p} y_{l,i,p,t} \leq KO_i^{max} \varphi_{i,t}\ , \quad \forall i \in \mathscr{I},\ t \in \mathscr{T} \tag{3.15}$$

$$\sum_{l\in\mathscr{L}} \sum_{p\in\mathscr{P}} UI_{l,i,p} y_{l,i,p,t} \geq KO_i^{min} \varphi_{i,t}\ , \quad \forall i \in \mathscr{I},\ t \in \mathscr{T} \tag{3.16}$$

The inbound flow of all products $p \in \mathscr{P}$ from one or more location sites $l \in \mathscr{L}$ to any intermediate site $i \in \mathscr{I}$ in each period $t \in \mathscr{T}$ must not be above the maximum allowable capacity KO_i^{max}, and must be more than the minimum allowable capacity KO_i^{min} of that intermediate site.

3.2.2.2.4 Logical Constraints

The facility configuration constraints (3.17) and (3.18) prevent each facility changing its status (opened or closed) more than once.

Constraints (3.17) state that if the existing facility $e \in \mathscr{E}$ is closed ($\varphi_{e,t}$ is 0), it cannot be later reopened ($\varphi_{e,t+1}$ must be 0).

$$\varphi_{e,t} \geq \varphi_{e,t+1} \ , \quad \forall e \in \mathscr{E} \ , \ t \in \mathscr{T} \setminus \{T\} \tag{3.17}$$

Constraints (3.18) ensure that once the new facility $n \in \mathscr{N}$ is opened, it will remain in operation for the remainder of the planning horizon. Clearly, if $\varphi_{n,t}$ is 1, $\varphi_{n,t+1}$ must be 1.

$$\varphi_{n,t} \leq \varphi_{n,t+1} \ , \quad \forall n \in \mathscr{N} \ , \ t \in \mathscr{T} \setminus \{T\} \tag{3.18}$$

3.2.2.2.5 Non-Negativity and Integrity Constraints

These sets of constraints specify the domain of variables. Constraints (3.19) assure the non-negativity of decision variables. Constraints (3.20) require that this variable is binary.

$$\begin{aligned} & x_{j,p,t},\ y_{l,l',p,t},\ z_{a,t},\ q_{b,a,t} \geq 0 \ , \\ & \forall l \in \mathscr{L},\ l' \in \mathscr{L} \setminus \{l\},\ j \in \mathscr{J},\ a \in \mathscr{A},\ b \in \mathscr{B},\ p \in \mathscr{P},\ t \in \mathscr{T} \end{aligned} \tag{3.19}$$

$$\varphi_{o,t} \in \{0,1\},\ \forall o \in \mathscr{O},\ t \in \mathscr{T} \tag{3.20}$$

3.3 An Example Problem with Increasing Product Returns

3.3.1 Description of the Example Problem

In this section, the model is demonstrated through an example. A small set of input parameters reflecting a fictitious test case is selected for the example. The main scope of this study is to specify the plan for facility locations and for allocations of product demands that have to face increasing product returns. The network presented includes two existing production plants (pl1 and pl2), one potential new production plant (pl3), one existing disassembly-remanufacturing plant (dl1), one potential new disassembly-remanufacturing plant (dl2), one existing distribution center (in1), one potential new distribution center (in2), one existing collection center (cl1), one potential new collection center (cl2) and customers (cu1, cu2 and cu3). The model is implemented in GAMS software version 23.2.1 and solved with CPLEX solver version 12.1.0 for the parameters given in Tables 3.1 and 3.2. All tests are performed on a Pentium IV 2.66 GHz personal computer with 1 GB RAM[3].

Customers	**Products**	**Demands in each period (year)**				
		1st yr.	**2nd yr.**	**3rd yr.**	**4th yr.**	**5th yr.**
cu1	p1	11000	12000	13000	14000	15000
	p2	10000	12000	12500	13000	14500
cu2	p1	10000	11000	12000	13000	14000
	p2	10000	12000	13000	13500	15000
cu3	p1	12000	13500	14000	14800	16000
	p2	11000	12000	12500	13500	15000

Table 3.1: Product demands of customers ($DP_{k,p,t}$)

Table 3.1 provides the data on customer demands over a five year planning period. In order to simplify the model, demands are assumed to be deterministic and known in advance. It can be noticed that demands of all customers (cu1, cu2 and cu3) for both types of products (p1 and p2) gradually increase every year.

[3] For the detailed GAMS code, see Appendix A.2 of this thesis.

Customers	Products	Return rates in each period (year)				
		1st yr.	2nd yr.	3rd yr.	4th yr.	5th yr.
cu1	p1	0.2	0.1	0.3	0.2	0.3
	p2	0.1	0.2	0.2	0.3	0.1
cu2	p1	0.2	0.2	0.1	0.2	0.3
	p2	0.2	0.1	0.2	0.2	0.2
cu3	p1	0.1	0.2	0.2	0.3	0.1
	p2	0.2	0.1	0.1	0.2	0.3

(a) Low rates of returns (scenario L)

Customers	Products	Return rates in each period (year)				
		1st yr.	2nd yr.	3rd yr.	4th yr.	5th yr.
cu1	p1	0.5	0.4	0.4	0.5	0.6
	p2	0.4	0.4	0.5	0.6	0.5
cu2	p1	0.5	0.5	0.4	0.4	0.6
	p2	0.5	0.4	0.4	0.6	0.5
cu3	p1	0.4	0.5	0.5	0.6	0.4
	p2	0.4	0.6	0.4	0.5	0.5

(b) Medium rates of returns (scenario M)

Customers	Products	Return rates in each period (year)				
		1st yr.	2nd yr.	3rd yr.	4th yr.	5th yr.
cu1	p1	0.8	0.8	0.9	0.8	0.7
	p2	0.7	0.7	0.8	0.7	0.8
cu2	p1	0.8	0.7	0.7	0.9	0.8
	p2	0.8	0.9	0.7	0.9	0.7
cu3	p1	0.9	0.7	0.8	0.8	0.9
	p2	0.7	0.8	0.7	0.8	0.8

(c) High rates of returns (scenario H)

TABLE 3.2: Return rates of products from customers ($RC_{k,p,t}$)

In Table 3.2, the values of several return rates (0.1-0.9) are presented in order to study the sensitivity of the model. Three different scenarios are considered including low rates of returns (scenario L), medium rates of returns (scenario M) and high rates of returns (scenario H). Since the problem is with strategic planning, it is supposed that the amount of returned products is dependent on demands and also known before.

Therefore, these scenarios are defined in terms of the percentage of products returned from customers over a period of five years. In scenario L, low rates of returns are considered. Product demands of 10%- 30% are assumed to return to the supply chain. The scenario M considers medium rates of returns. Products returns from customers of 40%- 60% are assumed. For scenario H, high rates of returns are assumed to be 70%- 90%[4].

3.3.2 Numerical Results and Discussion

The optimal example networks in the first period (t=1) and the last period (t=5) for high rates of product returns (scenario H) are shown in Figures 3.4 and 3.5, respectively. The product flows between the different levels in the network for high rates of product returns are also illustrated. As will be discussed in greater detail later in this section, the model results revealed that the existing distribution center in1 and the existing collection center cl1 are closed, while the new production plant pl3, the new distribution center in2 and the new collection center cl2 are opened in the first period (see Figure 3.4). This is because production costs of plant pl3 (for product p2), and shipping costs to and from distribution and collection centers in2 and cl2 are much cheaper. It can be also easily seen that, due to higher recovery costs, the model decided not to open the potential new disassembly-remanufacturing plant dl2.

The optimal network structure in the first period thus includes two production plants pl1 and pl2 for product p1 and production plant pl3 for product p2, one disassembly-remanufacturing plant dl1 for both products p1 and p2, one distribution center (in2) and one collection center cl2. All of these facilities serve three customers

[4] For the remaining data associated with the problem see Appendix A.1.

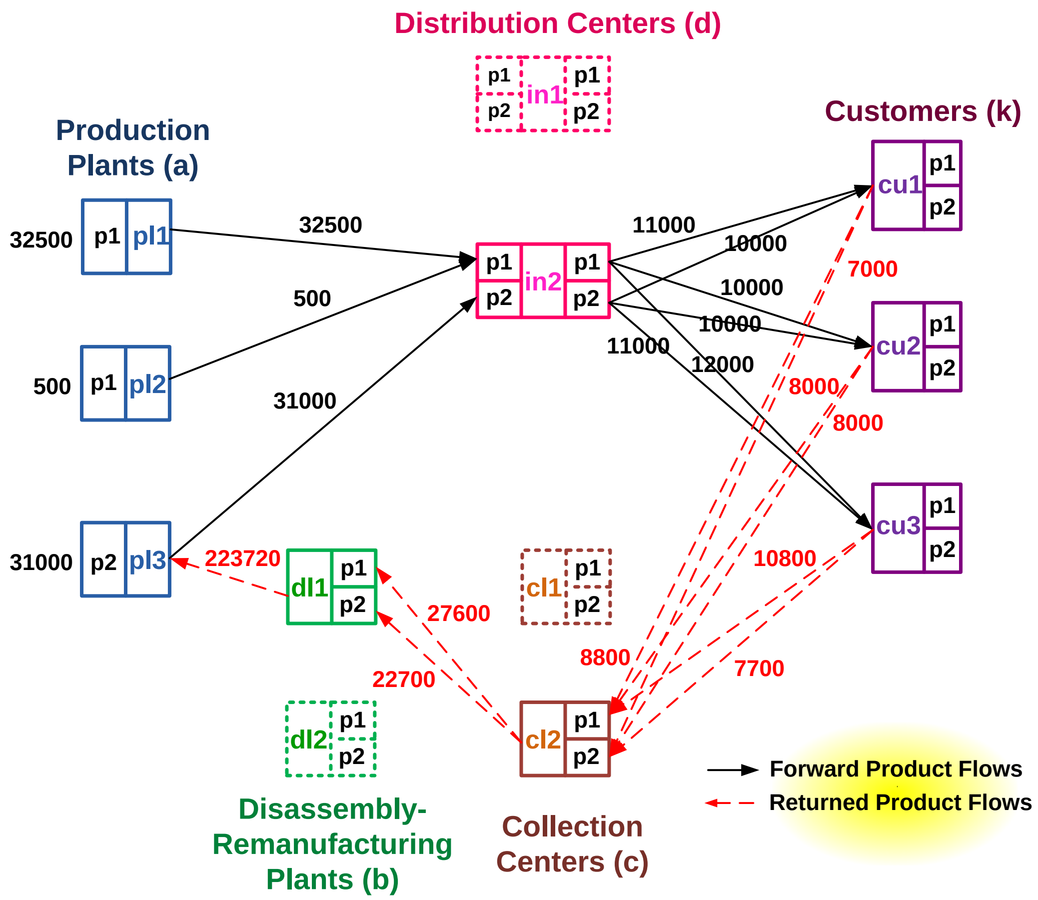


FIGURE 3.4: Illustrative example of the optimal network in the first period (scenario H)

(cu1, cu2 and cu3). Since demands gradually increase over the time horizon, the network structure is the same as in Figure 3.4 for all other periods and return rate scenarios except the optimal network in the last period of scenario H. It can be noticed from Figure 3.5 that the model selected to open the new disassembly-remanufacturing plant dl2 for product p1 to meet the highest volumes of product returns from customers.

Figure 3.6(a) shows the variation in fixed costs for all return rate scenarios (except scenario H). The total fixed costs are comprised of the costs of operating, closing and opening facilities. As seen from the Figure, the total fixed costs in the first period (t=1) are the highest value of the planning horizon because all closing and opening of facilities occurred in this period of time. In scenario H, there are also the costs of

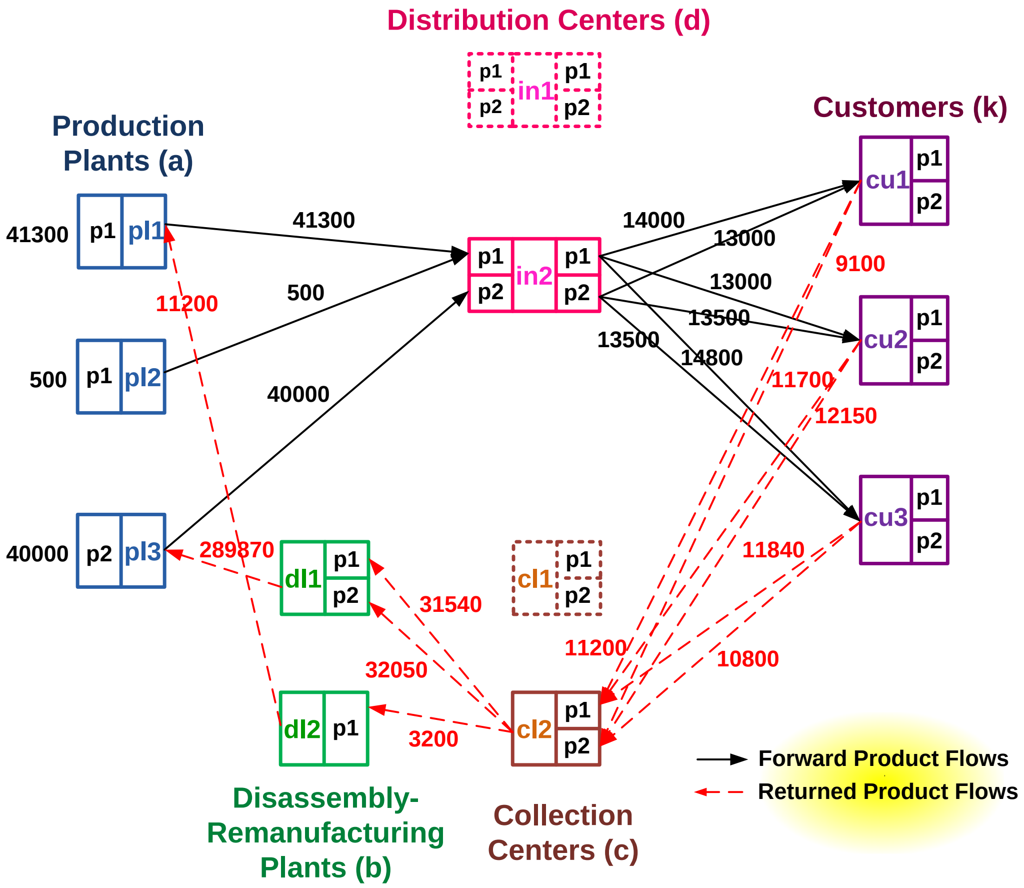


Figure 3.5: Illustrative example of the optimal network in the last period (scenario H)

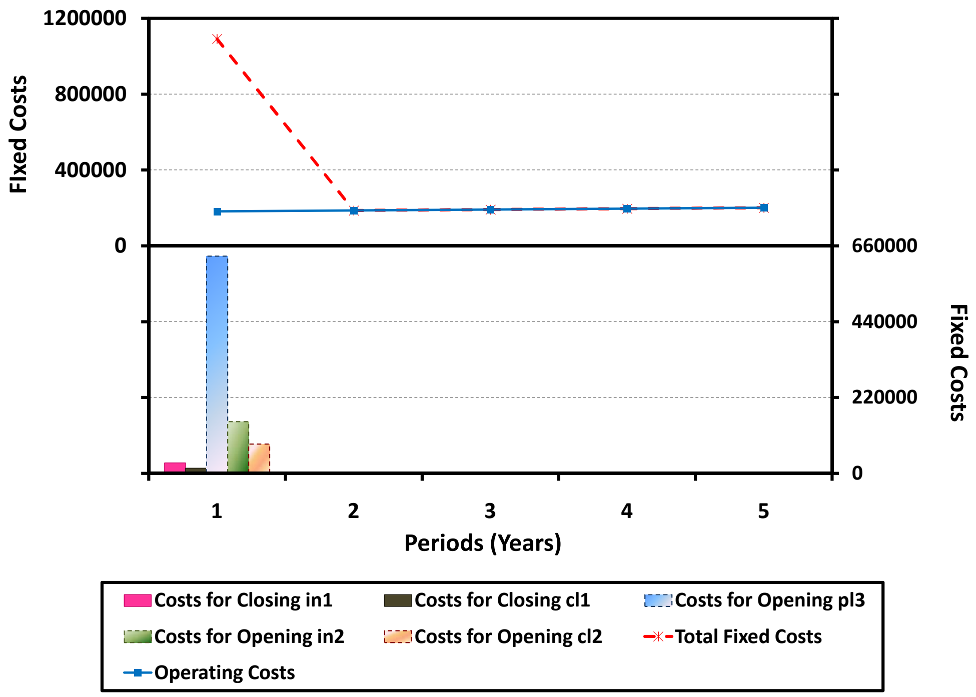
opening the new disassembly-remanufacturing plant dl2 in the last period (t=5), see Figure 3.6(b).

The amount of parts/components to be used in production is presented in Figure 3.7. It should be noted that the quantity of new parts/components shipped from an external supplier and reusable parts/components having the same characteristics with the new ones transported from disassembly-remanufacturing plants to production plants are dependent on the amount of product returns from customers. We assume that the cost of purchasing one unit of new part/component is more expensive than the cost of recovering one unit part/component. In case of low rates of returns, the amount of parts/components for producing final products are mostly from the supplier (see Figure 3.7(a)). As shown in Figures 3.7(b) and 3.7(c), if the values of return rates increase, the greater the number of reusable parts/components and the fewer new parts/components are used for the production.

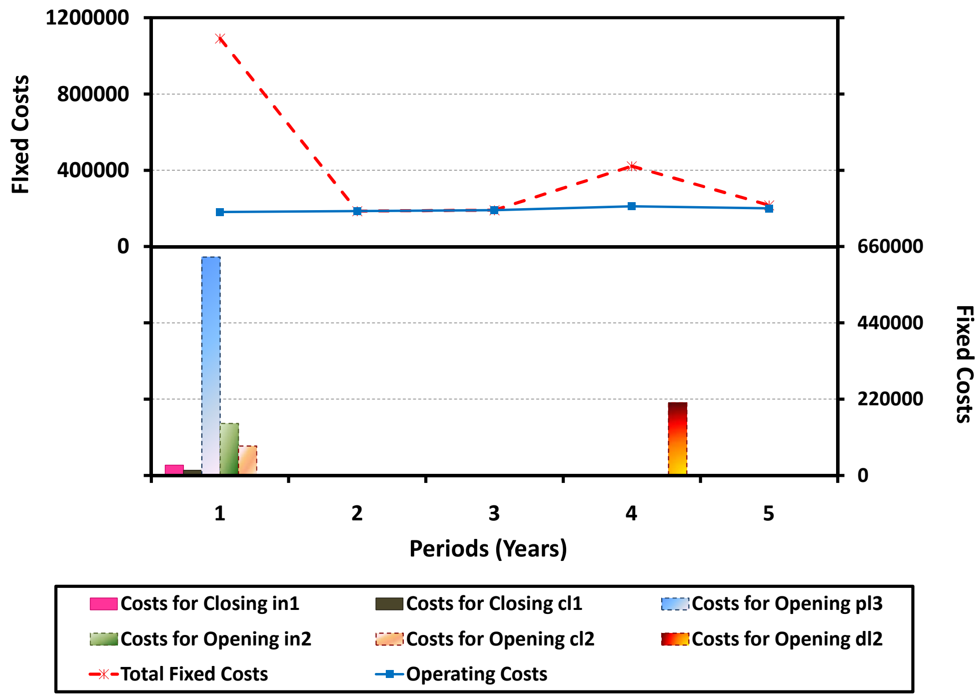
Figure 3.8 displays the impact of changing the values of return rates on the optimal processing levels during the planning horizon. According to the high unit production costs in the production plant pl2, the major amount of the production is carried out in the production plant pl1 for product p1 and in production plant pl3 for product pl2 For scenarios L and M, all remanufactured and disposed quantities are carried out at the disassembly-remanufacturing plant dl1 due to the high unit remanufacturing costs in the disassembly-remanufacturing plant dl2. Because the returned products increase in scenario H, remanufactured and disposed quantities of product p1 are also remanufactured and disposed at the disassembly-remanufacturing plant dl2 in the last period (t=5).

Figure 3.9 shows the relationship between the overall processing costs, production costs, purchasing part/component costs, disassembly-remanufacturing costs and disposal costs over a given planning horizon. It can be observed from Figure 3.9 that production costs are the most expensive level followed by purchasing part/component costs, disassembly-remanufacturing costs and disposal costs, respectively. Figure 3.8(a) together with Figure 3.9(a) demonstrate that when a fewer number of products are returned for recovery, disassembly-remanufacturing and disposal costs are significantly less expensive. With a greater return of products, the number of recovered products increases and therefore the costs of disassembly-remanufacturing and disposal increase (see Figures 3.8(b), 3.8(c), 3.9(b) and 3.9(c)).

The distribution plan between all production plants and the distribution center in2 is shown in Figure 3.10. Figure 3.10 shows that all the manufactured products are delivered to the distribution center in2 because only this distribution center is in operation. Since only collection center cl2 is operating during the planning horizon, all of the returned products from customers are initially distributed to this collection

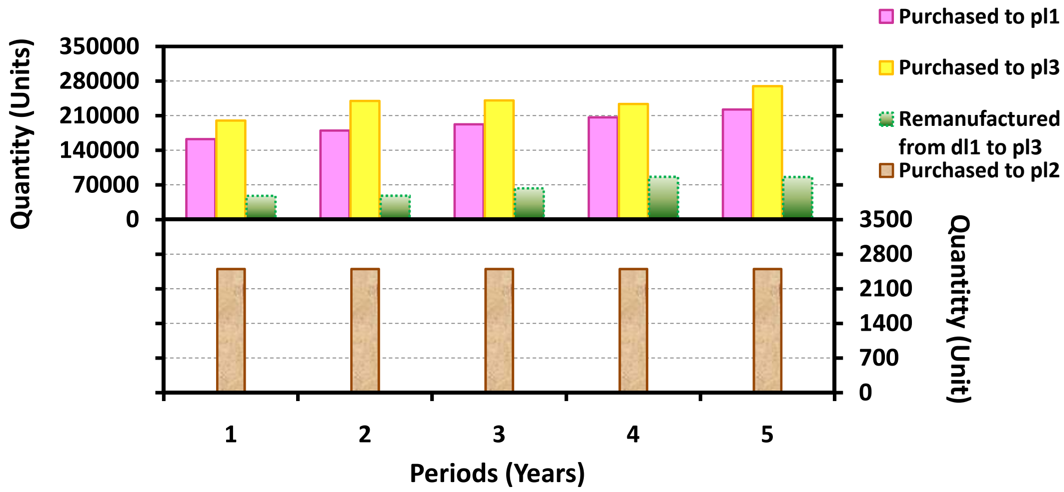


(a) for all return rate scenarios (except scenario H)

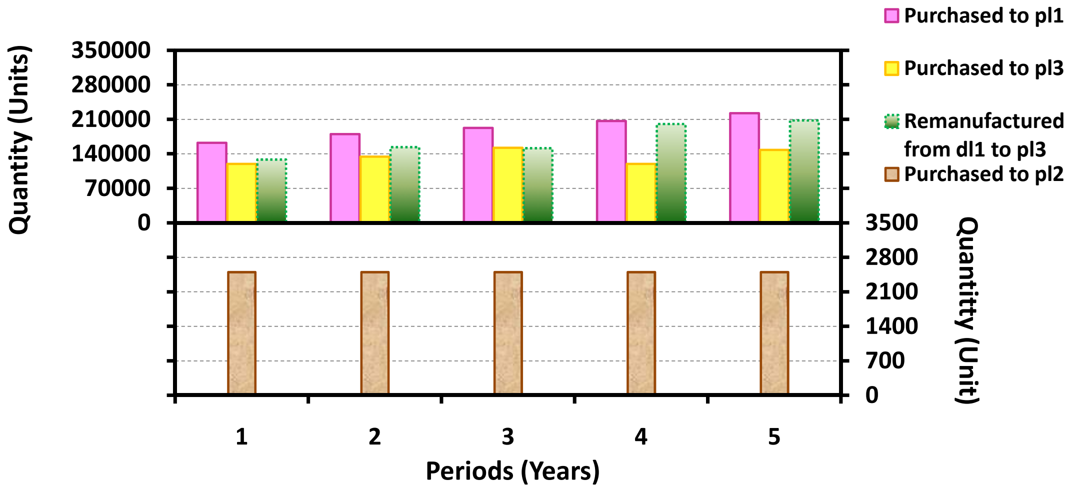


(b) for high rates of returns (scenario H)

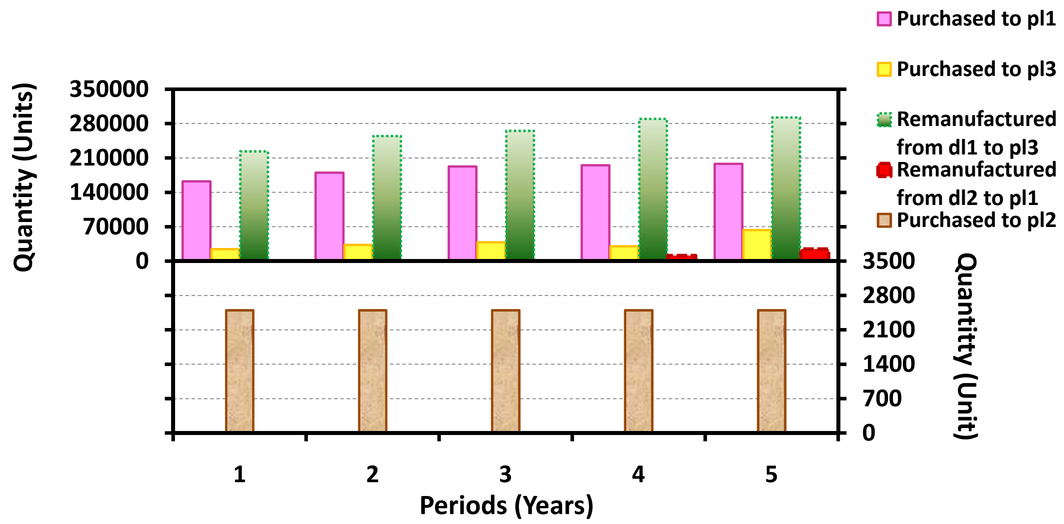
Figure 3.6: Fixed cost variation (for all return rate scenarios)



(a) for low rates of returns (scenario L)

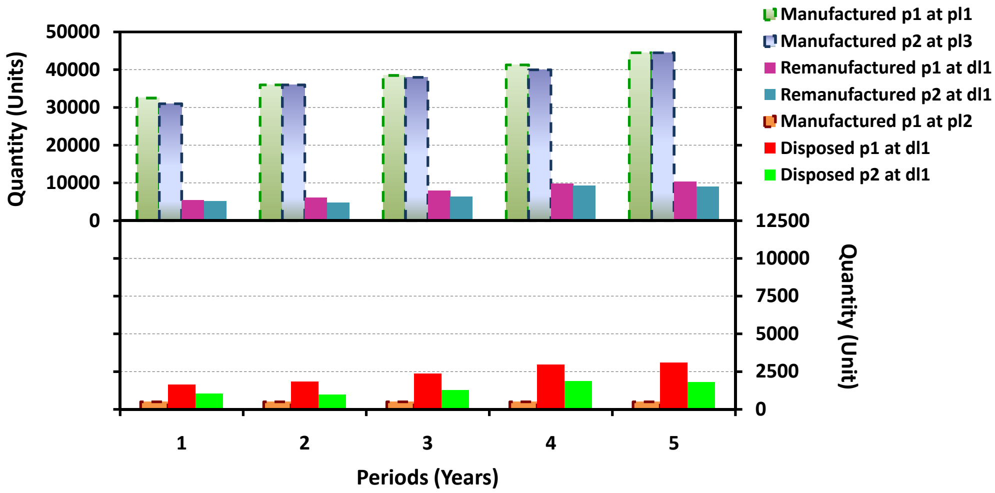


(b) for mediums rates of returns (scenario M)

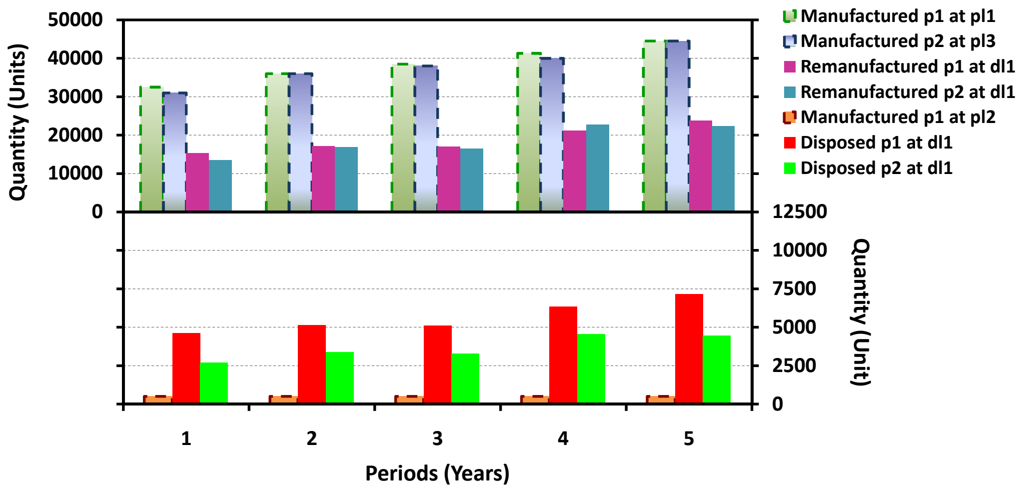


(c) for high rates of returns (scenario H)

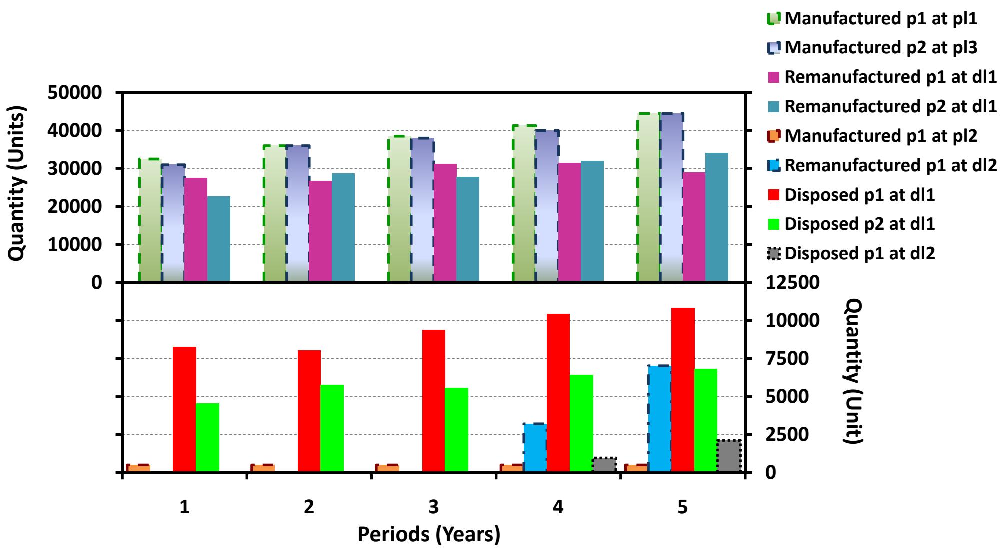
FIGURE 3.7: Flows of parts/components to production plants



(a) for low rates of returns (scenario L)

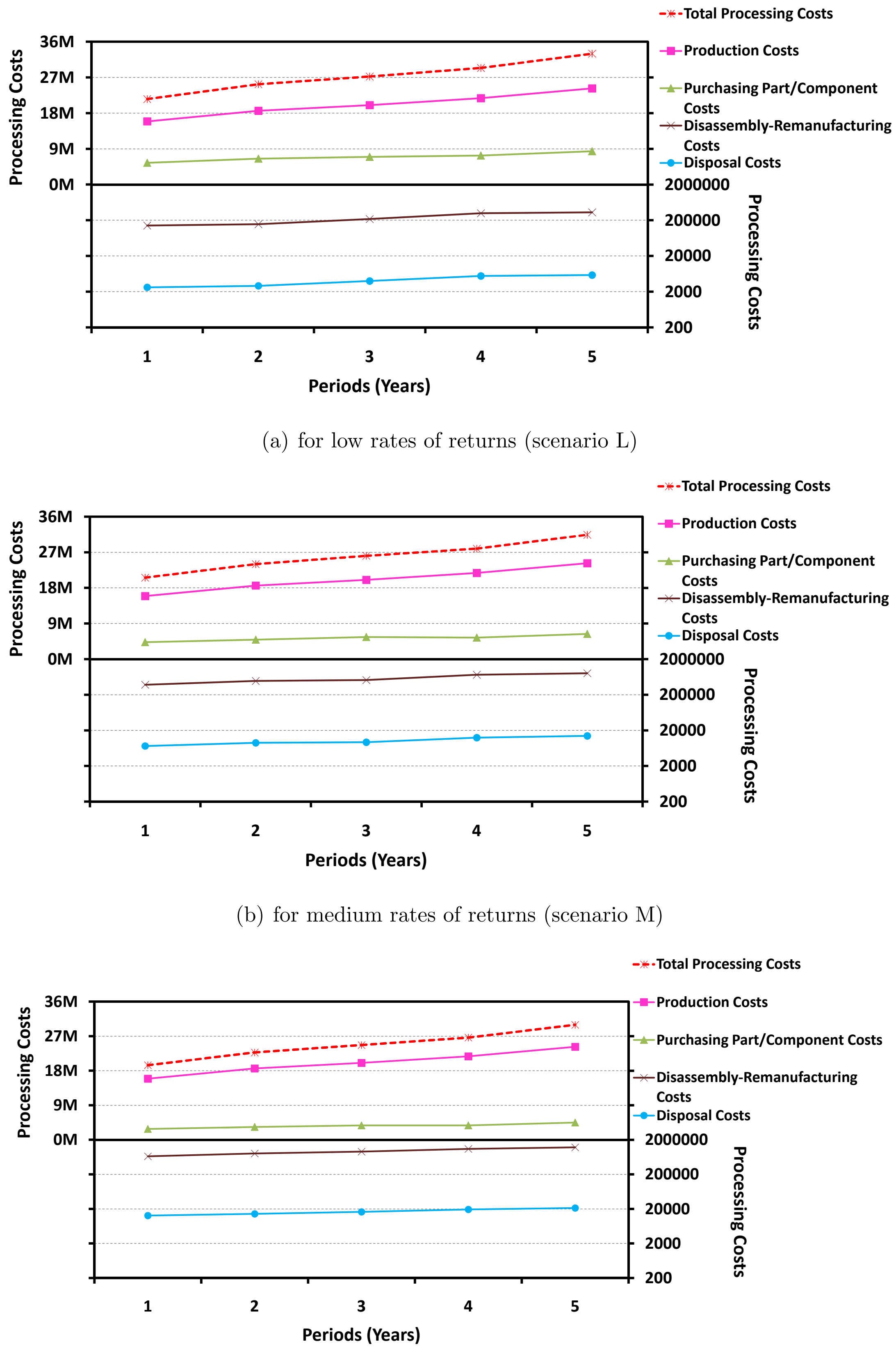


(b) for medium rates of returns (scenario M)



(c) for high rates of returns (scenario H)

Figure 3.8: Processing quantity



(a) for low rates of returns (scenario L)

(b) for medium rates of returns (scenario M)

(c) for high rates of returns (scenario H)

Figure 3.9: Processing cost variation

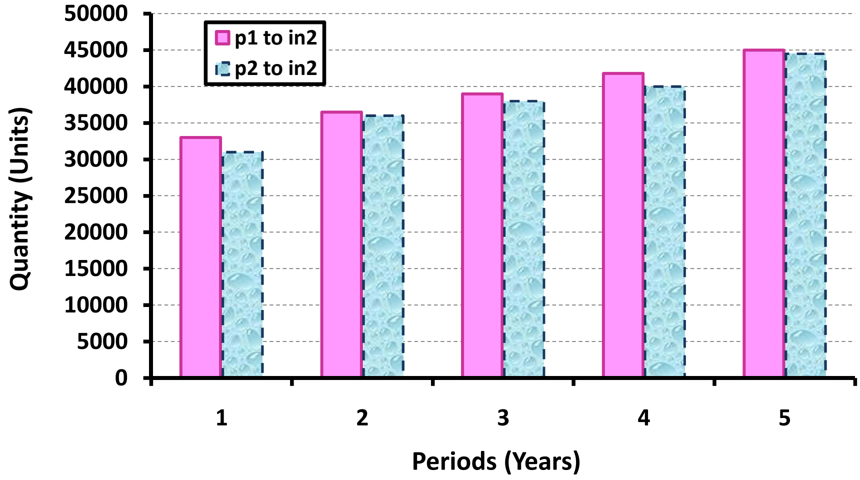
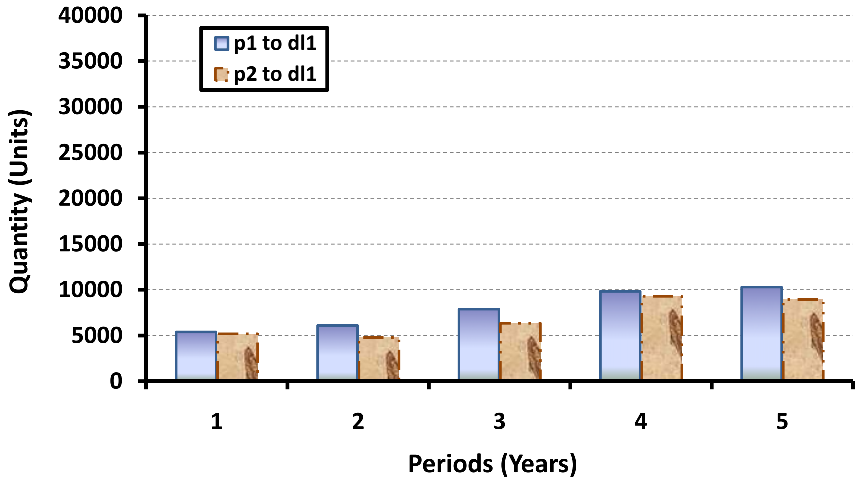


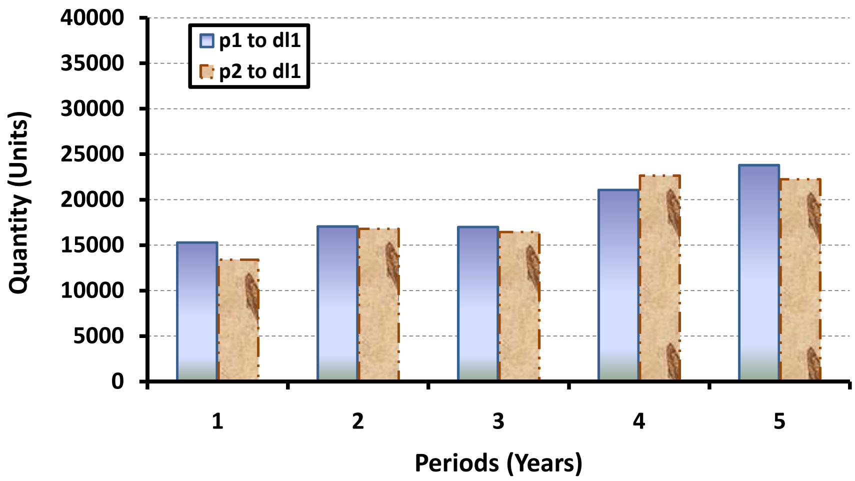
Figure 3.10: Flows of products to the distribution center (for all return rate scenarios)

center.

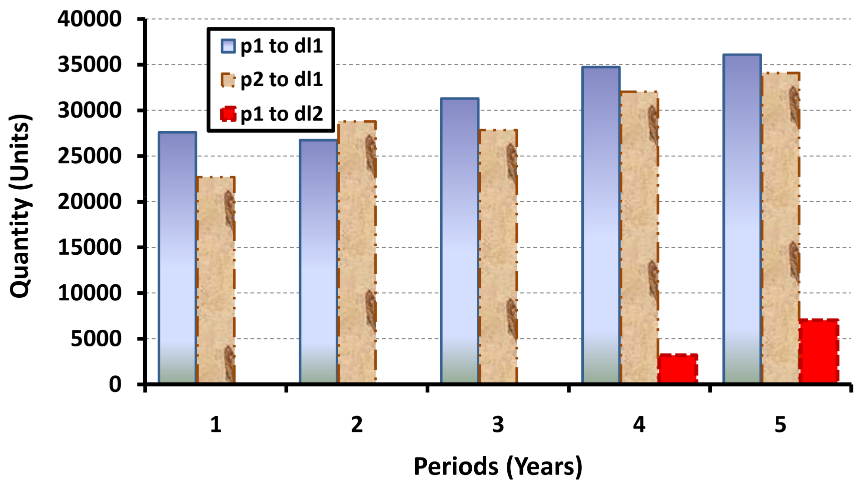
If the products are no longer beneficial for their users, some of these used products are incorporated into the supply chain in order to satisfy the government regulations or customer expectations and/or to get more revenue. In Figure 3.11, product returns from the collection process are shown. The quantities of products p1 and p2 are returned from the collection center to the disassembly-remanufacturing plant dl1 because only this disassembly-remanufacturing plant is active (scenarios L and M). This figure illustrates that the number of recovered products increases as the values of return rates rise. For scenario H, the small quantity of product p1 is therefore returned from the collection center to the disassembly-remanufacturing plant dl2 in addition to being returned to the disassembly-remanufacturing plant dl1. As a result, in case of higher values of return rates, the costs for transporting returned items also increase, and hence the total transportation costs are higher compared to the costs incurred with lower values of return rates (see Figure 3.12).



(a) Return flows to the disassembly-remanufacturing plants (scenario L)

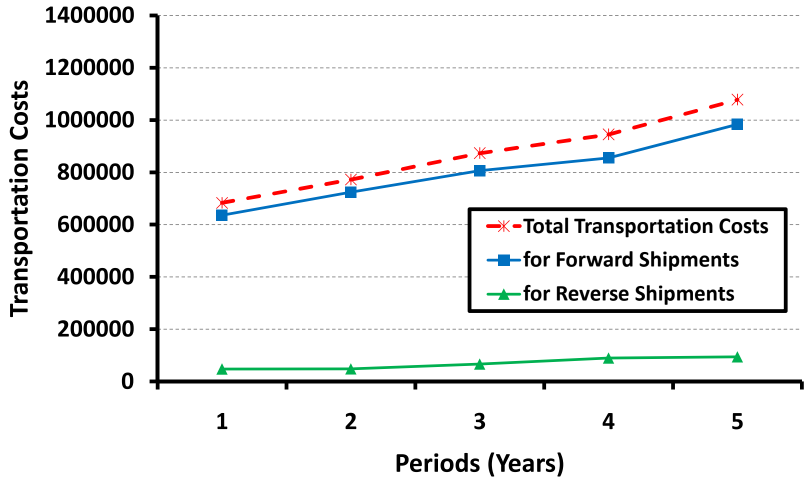


(b) Return Flows to the disassembly-remanufacturing plants (scenario M)

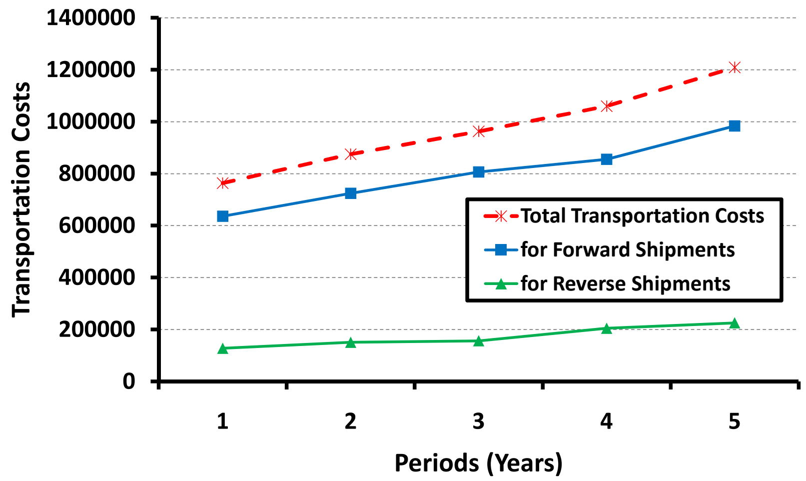


(c) Return flows to the disassembly-remanufacturing plants (scenario H)

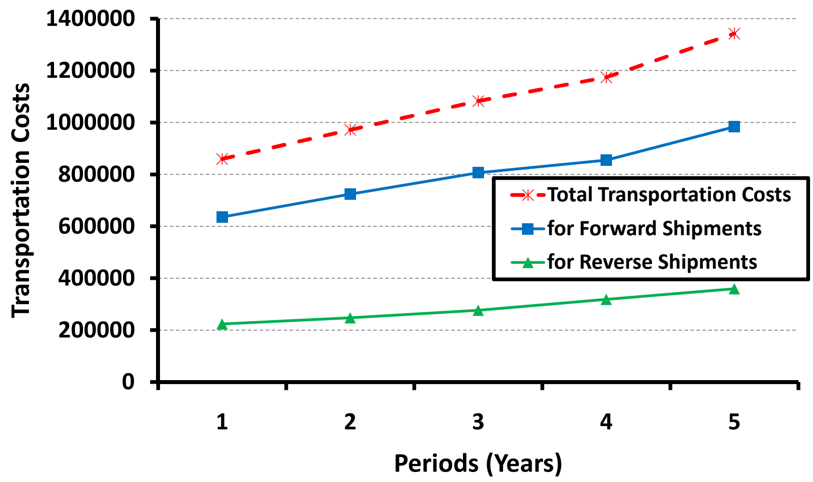
FIGURE 3.11: Return flows to the disassembly-remanufacturing plants



(a) for low rates of returns (scenario L)

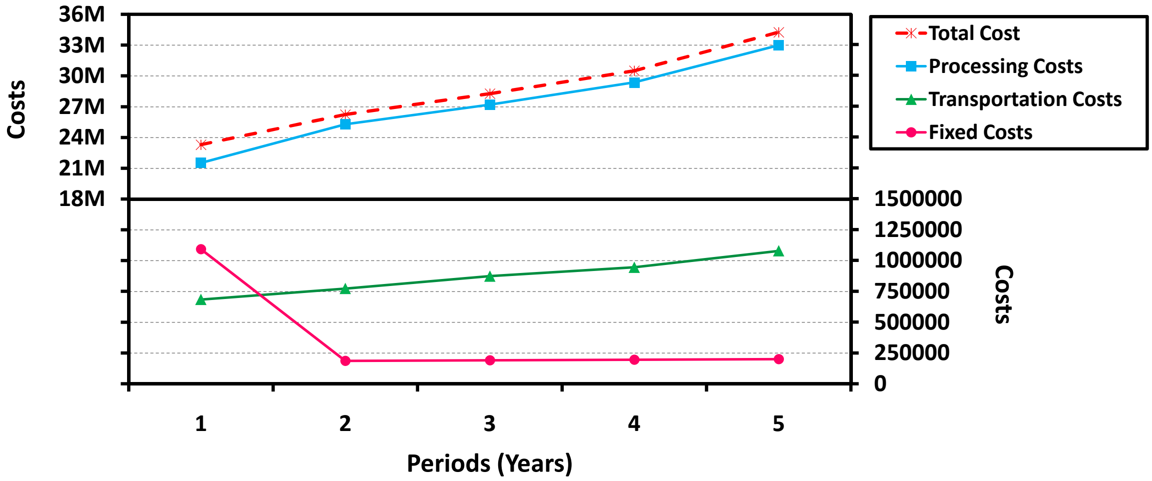


(b) for medium rates of returns (scenario M)

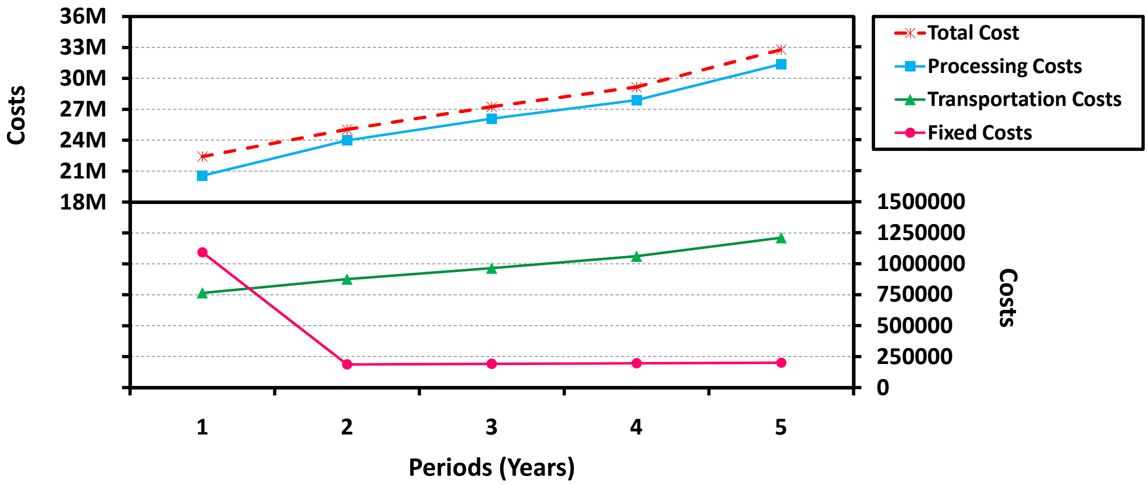


(c) for high rates of returns (scenario H)

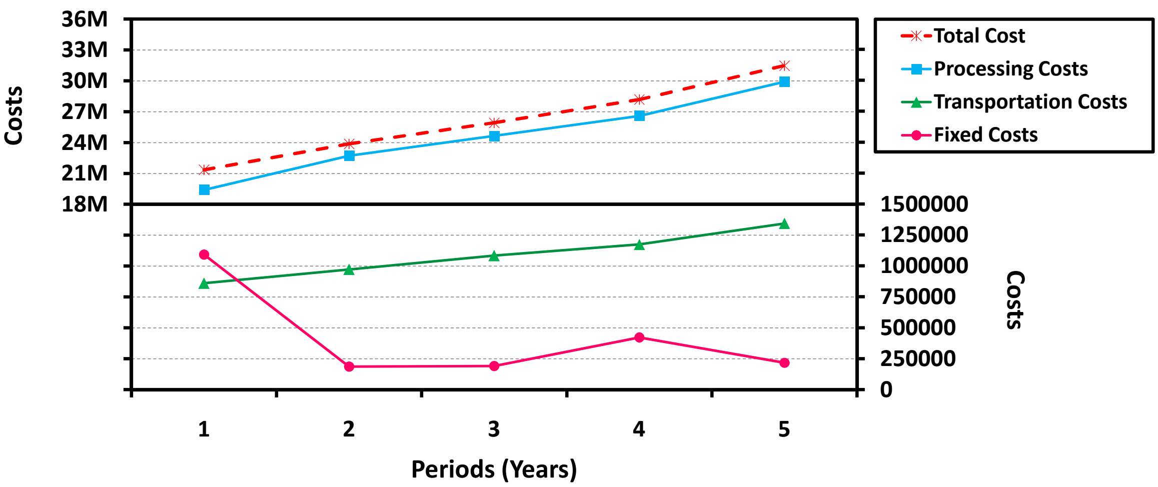
Figure 3.12: Transportation cost variation



(a) for low rate of returns (scenario L)



(b) for medium rate of returns (scenario M)



(c) for high rate of returns (scenario H)

FIGURE 3.13: Total cost versus other costs

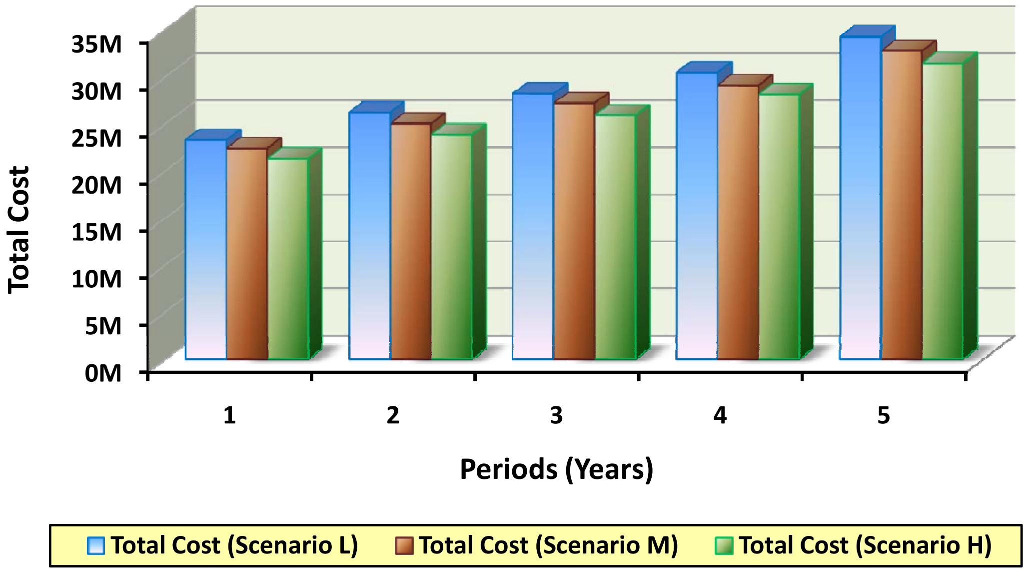


Figure 3.14: Total cost for different rates of returns

In term of costs, Figure 3.13 demonstrates the total cost in comparison with other costs, including those for the scenarios considered in this study. The results show that the total cost of the supply chain system decreases when return rates increase due to the reduction in processing costs. Although, transportation costs increase when return rates increase, processing costs are, however, much more expensive than transportation costs. Figure 3.14 graphically represents the total cost for different return rate scenarios. The most cost savings can be seen in case of high rates of returns.

3.4 Literature on Facility Location Models within Reverse and Closed-Loop Supply Chain Contexts

The literature related to facility location problems for reverse logistics can be categorized into strategic planning problems where the reverse supply chain network is combined with the forward supply chain network and those that completely concentrate on reverse logistics activities. The former refers to as a *closed-loop supply chain* *network* and the latter as a *reverse supply chain network*.

Network Structure	Location-Allocation	Article	
Reverse	Collection	[13] Aras et al., 2006	[23] Cruz-Rivera and Ertel, 2009
		[89] Min et al., 2006	[102] Ren and Ye, 2011
	Recovery	[83] Melachrinousdis et al., 1995	[117] Spengler et al., 1997
	Collection, Recovery	[2] Ahluwalia and Nema, 2006	[6] Alumur et al., 2012
		[14] Assavapokee and Wongthatsanekorn, 2012	[17] Barros et al., 1998
		[18] Beamon and Fernandes, 2004	[28] Dat et al., 2012
		[36] Du and Evans, 2008	[46] Fonseca and García-Sánchez, 2010
		[62] Jayaraman et al., 2003	[64] Kara and Onut, 2010
		[73] Lieckens and Vandaele, 2007	[75] Listeş and Dekker, 2005
		[78] Mansour and Zarei, 2008	[91] Min et al., 2006
		[94] Mutha and Pokharel, 2009	[98] Pati et al., 2008
		[111] Sasikumar et al., 2010	[118] Srivastava, 2008
Closed-loop	Collection	[61] Jayaraman et al., 1999	[80] Marín and Pelegrín, 1998
		[99] Pishvaee et al., 2011	[107] Sahyouni et al., 2007
		[112] Savaskan et al., 2004	[126] Vahdani et al., 2012
		[135] Zarandi et al., 2011	[136] Zhou et al., 2005
	Collection, Recovery	[8] Amin and Zhang, 2012	[27] Das and Chowdhury, 2012
		[30] Demirel and Gökçen, 2008	[37] Easwaran and Üster, 2009
		[38] Easwaran and Üster, 2010	[40] El-Sayed et al., 2010
		[41] Fleischmann et al., 2001	[66] Ko and Evans et al., 2007
		[67] Krikke, 2010	[68]Krikke et al., 2003
		[71] Lee and Dong, 2009	[74] Listeş, 2007
		[76] Lu and Bostel et al., 2007	[90] Min and Ko et al., 2008
		[108] Salema et al., 2007	[109] Salema et al., 2009
		[110] Salema et al., 2010	[113] Schultmann et al., 2003
		[125] Üster et al., 2007	[130] Wang and Hsu, 2010

Table 3.3: Classification of the literature on facility location models for reverse logistics

The closed-loop supply chain network is usually more complex than the stand-alone reverse supply chain network. For example, the number of echelons is increased by the echelons associated with forward logistics activities. Table 3.3 classifies the surveyed literature regarding the network structure (reverse or closed-loop) and the types of facilities for which location decisions are made. We will examine some papers dedicated to these aspects.

Min et al. [89] dealt with the problem of determining the number and location of initial collection points to hold the products returned from customers in addition to a centralized returned center. Melachrinousdis et al. [83] developed realistic decision-aid tools to locate landfills for disposing garbage. The model of Pati et al. [98] assisted in determining the location, routes and flows of different varieties of recyclable wastepaper. Savaskan et al. [112] modeled different reverse channel structures for collecting used products as decentralized decision-making systems. In the model developed by Lee and Dong [71], returned products are treated in the same facilities, which support direct recovery activities.

It can be seen from Table 3.3 that various papers introduce comprehensive models dealing with the selection of both collection and recovery facilities and the allocation of returned items to and from these facilities. More than half of the previous papers proposed closed-loop supply chain network models. This is because an integrated forward and reverse supply chain network can capture the complexity of supply chain network design problems in comparison with a separate reverse supply chain network.

4

Problem of Capacity Planning for Hybrid Uni/Bidirectional Facilities

4.1 Hybrid Uni/Bidirectional Flows of Facilities

4.1.1 The Impact of a Product's Life Cycle on Integrated Forward and Reverse Supply Chain Strategy

Although there are particular industries, which can be characterized as either forward or reverse dominant networks, various industries experience significant changes in forward and reverse supply chain processes throughout a product's life cycle. In this situation, network design decisions may change over time. During an introductory

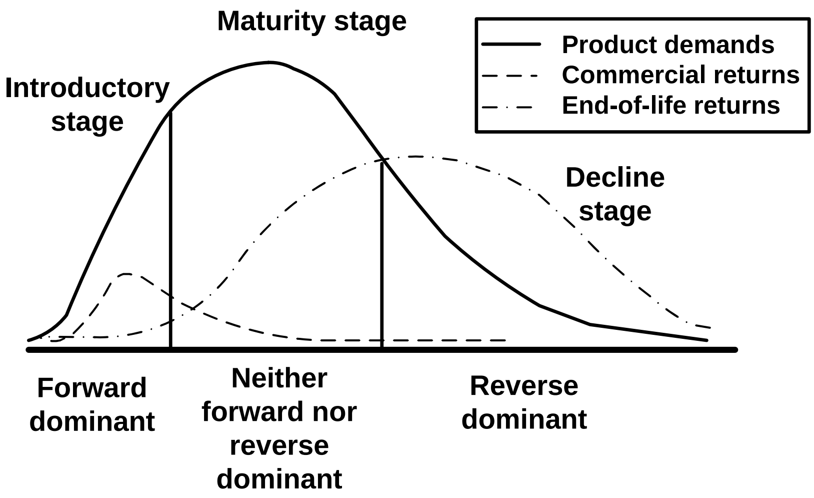


Figure 4.1: Product flows throughout the life cycle (from [107])

phase of the product's life cycle, there are a small number of product units in the market, leading to even lower product returns. At this time, a company will focus on forward product distribution, and there is generally little need for collecting returned products. The product is new, and there are many costs involved in order to introduce the product into the market, for instance new product development costs, expenses involved in promotional activities, high operational costs, etc. The company may concentrate on the design of forward supply chain network. Online retailers in the textile industries with centralized returns handling and decentralized product distribution are an example of *forward dominant* reverse logistics network.

As the introductory stage of the product's life cycle ends, the product has spent a considerably moderate amount of time in the market where customers get familiar with the product, and begin to buy the product. This now brings the product to its maturity stage, forward and reverse flows of logistics are usually stable. *Neither forward nor reverse dominant* can be distinguished. For example, the Dell asset recovery services program collects both end of life and commercial product returns.

During the end of the product's life cycle, the product demands decrease and the product returns increase. Sales continue to deteriorate through decline. Remanufacturing and recycling networks are examples of *reverse dominant* network structures, where there are many collection and/or disassembly-remanufacturing sites and some centralized manufacturing and/or distribution facilities. Figure 4.1 depicts typical demand and return patterns for products throughout the introductory, maturity and decline phases of the product's life cycle[1].

4.1.2 A Simple Facility Location Model for Hybrid Uni/Bidirectional Flows

Practically, the joint design of forward and reverse supply chain network is not often considered. This is because of the evolution of the product and market demands or restricted management attention or resources. Thus, it is important to know how much value is missed by not combining forward and reverse logistics decision making and the conditions under which the combination is essential [107]. In this section, instead of only determining locations for separate forward and reverse processing facilities, a new type of integrated forward and reverse facilities, namely hybrid uni/bidirectional facilities, are taken into account. An extension to the uncapacitated facility location model for bidirectional flows of Sahyouni et. al. [107] is developed. Since it is more realistic not to assume unlimited capacity for facilities, we present a relatively simple capacitated version of the problem. The objective is to identify the location of stand-alone forward and reverse facilities (unidirectional facilities), and integrated forward and reverse facilities (bidirectional facilities), as well as the assignment of demands and returns to those facilities.

Figure 4.2 demonstrates a situation where forward and reverse activities are carried out at different locations or at the same site. A bidirectional facility is capable of performing both forward and reverse logistics processes, in which the items flow both out from and into this facility, while a unidirectional facility conveys items in one direction for a forward or reverse process only. In a dynamic or multi-period version of the problem, for every facility (i.e., either unidirectional or bidirectional types of

[1] For more details about the impact of product's life cycle on reverse and forward supply chains see, e.g., [47] and [107].

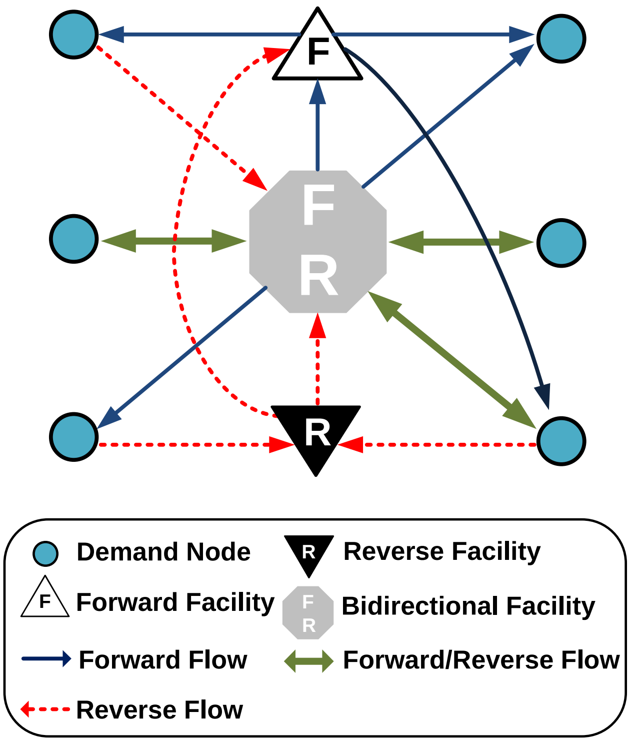


Figure 4.2: Sample network configuration of uni/bidirectional flows of facilities

facilities), the closed and open options are available in each period. To formulate this problem, we define the following notation.

4.1.2.1 Notation

4.1.2.1.1 Index Sets

$\mathscr{L}$: set of location sites, indexed by $l \in \mathscr{L}$

$\mathscr{O} \subset \mathscr{L}$: set of selectable location sites, indexed by $o \in \mathscr{O}$

$\mathscr{E} \subset \mathscr{O}$: set of existing location sites, indexed by $e \in \mathscr{E}$

$\mathscr{N} \subset \mathscr{O}$: set of potential new location sites, indexed by $n \in \mathscr{N}$

$\mathscr{K} \subset \mathscr{L}$: set of demand nodes, indexed by $k \in \mathscr{K}$

$\mathscr{C}$: set of center types for supply chain processes, indexed by $c \in \mathscr{C}$

$\mathscr{F} \subset \mathscr{C}$: set of the type of forward supply chain centers, indexed by $f \in \mathscr{F}$

$\mathscr{R} \subset \mathscr{C}$: set of the type of reverse supply chain centers, indexed by $r \in \mathscr{R}$

$\mathscr{T}$: set of periods in the planning horizon, indexed by $t \in \mathscr{T}$

Set $\mathscr{L}$ contains all types of location sites, which are categorized as selectable and non-selectable location sites. Selectable location sites form the set $\mathscr{O}$, which is a subset of $\mathscr{L}$, and includes existing location sites $\mathscr{E}$ and potential new location sites $\mathscr{N}$. At the beginning of the planning horizon, all existing location sites in the set $\mathscr{E}$ are in operation. Thereafter, these location sites can be closed, and new location sites in the set $\mathscr{N}$ can be opened. Note that $\mathscr{E} \cap \mathscr{N} = \emptyset$, $\mathscr{E} \cup \mathscr{N} = \mathscr{O}$.

The second classification group of facilities, the so-called non-selectable group, forms the set $\mathscr{L} \backslash \mathscr{O}$, and includes all location sites that exist at the beginning of the planning project, and will remain in operation until the end of the planning horizon. Non-selectable location sites correspond to demand nodes (the set $\mathscr{K}$).

Set $\mathscr{C}$ includes all types of centers for supply chain processes. These are classified into two groups: (1) the type of forward supply chain centers and (2) the type of reverse supply chain centers. The center type for the forward supply chain process forms the set $\mathscr{F}$, a subset of $\mathscr{C}$. The center type for the reverse supply chain process forms the set $\mathscr{R}$, which is also a subset of $\mathscr{C}$. Note that $\mathscr{F} \cap \mathscr{R} = \emptyset$ and $\mathscr{F} \cup \mathscr{R} = \mathscr{C}$.

The planning horizon is partitioned into a set $\mathscr{T} = \{1, ..., T\}$ of consecutive and integer time periods. There are totally $|\mathscr{T}|$ planning periods, i.e., $|\mathscr{T}|=T$.

4.1.2.1.2 Parameters

4.1.2.1.2.1 Costs

$CP_{l,l',t}$: unit variable cost of processing and shipping demand or return from location site $l \in \mathscr{L}$ to location site $l' \in \mathscr{L}$ $(l \neq l')$ in period $t \in \mathscr{T}$

$CF_{o,c,t}$: fixed cost of operating center $c \in \mathscr{C}$ at selectable location site $o \in \mathscr{O}$ in period $t \in \mathscr{T}$

$CC_{e,c,t}$: fixed cost of closing center $c \in \mathscr{C}$ at existing location site $e \in \mathscr{E}$ in period $t \in \mathscr{T}$

$CO_{n,c,t}$: fixed cost of establishing center $c \in \mathscr{C}$ at new location site $n \in \mathscr{N}$ in period $t \in \mathscr{T}$

4.1.2.1.2.2 Other Parameters

$DP_{k,t}$: demand amount at node $k \in \mathscr{K}$ in period $t \in \mathscr{T}$

$RC_{k,t}$: return amount from node $k \in \mathscr{K}$ in period $t \in \mathscr{T}$

$KC_{o,c}^{max}$: maximum allowable capacity of center $c \in \mathscr{C}$ at selectable location site $o \in \mathscr{O}$

$KC_{o,c}^{min}$: minimum allowable capacity of center $c \in \mathscr{C}$ at selectable location site $o \in \mathscr{O}$

4.1.2.1.3 Decision Variables

$x_{l,l',c,t}$: amount of demand or return shipped from center $c \in \mathscr{C}$ of location site $l \in \mathscr{L}$ $(l \neq l')$ to location site $l' \in \mathscr{L}$ in period $t \in \mathscr{T}$

$$\delta_{o,c,t} = \begin{cases} 1 & \text{if center } c \in \mathscr{C} \text{ at selectable location site } o \in \mathscr{O} \text{ is operated in period } t \in \mathscr{T} \\ 0 & \text{otherwise} \end{cases}$$

4.1.2.2 Formulation of the Dynamic Problem

The simple, *dynamic (or multi-period) capacitated facility location model for hybrid uni/bidirectional flows*[2] can be formulated as in the following sections.

4.1.2.2.1 Objective Function

The objective is to minimize the total cost, i.e, the sum of all costs $\left(TOC^{total}\right)$, which includes the processing and transportation costs, as well as fixed costs.

$$\textbf{MIN } TOC^{total} = TOC^{1} + TOC^{2} \tag{4.1}$$

The total cost is the sum of the costs below.

[2] The model is developed by combining the ideas from the previous models that are formulated by Melo et al. [84] and Sahyouni et al. [107].

4.1.2.2.1.1 Variable Processing and Transportation Costs (TOC^1)

The costs of processing and transporting the total demand and return from centers $c \in \mathscr{C}$ at location sites $l \in \mathscr{L}$ to location sites $l' \in \mathscr{L}$ in periods $t \in \mathscr{T}$ are represented in equation (4.2).

$$TOC^1 = \sum_{l \in \mathscr{L}} \sum_{l' \in \mathscr{L} \setminus \{l\}} \sum_{c \in \mathscr{C}} \sum_{t \in \mathscr{T}} CT_{l,l',t} x_{l,l',c,t} \tag{4.2}$$

4.1.2.2.1.2 Fixed Costs of Operating, Closing and Establishing Facilities (TOC^2)

In equation (4.3), the costs of operating one or more centers $c \in \mathscr{C}$ at selectable location sites $o \in \mathscr{O}$ in periods $t \in \mathscr{T}$ is the first component.

$$\begin{aligned} TOC^2 = & \sum_{o \in \mathscr{O}} \sum_{c \in \mathscr{C}} \sum_{t \in \mathscr{T}} CF_{o,c,t} \delta_{o,c,t} + \sum_{e \in \mathscr{E}} \sum_{c \in \mathscr{C}} CC_{e,c,1} \left(1 - \delta_{e,c,1}\right) \\ & + \sum_{e \in \mathscr{E}} \sum_{c \in \mathscr{C}} \sum_{t \in \mathscr{T} \setminus \{1\}} CC_{e,c,t} \left(\delta_{e,c,t-1} - \delta_{e,c,t}\right) \\ & + \sum_{n \in \mathscr{N}} \sum_{c \in \mathscr{C}} \sum_{t \in \mathscr{T}} CO_{n,c,t} \left(\delta_{n,c,t} - \delta_{n,c,t-1}\right) \end{aligned} \tag{4.3}$$

The second and third components are respectively the costs of closing one or more centers $c \in \mathscr{C}$ at the existing location sites $e \in \mathscr{E}$ in the first period and all later periods. The costs of opening one or more centers $c \in \mathscr{C}$ at the new location sites $n \in \mathscr{N}$ in periods $t \in \mathscr{T}$ are the last component.

Subject to constraints (4.4) - (4.13).

4.1.2.2.2 Constraints

4.1.2.2.2.1 Flow Constraints

The demand ($DP_{k,t}$) of any demand node $k \in \mathscr{K}$ in period $t \in \mathscr{T}$ is satisfied by constraints (4.4).

$$\sum_{o \in \mathscr{O}} x_{o,k,f,t} \geq DP_{k,t} \ , \quad \forall k \in \mathscr{K}, \ f \in \mathscr{F}, \ t \in \mathscr{T} \tag{4.4}$$

This demand must be greater than or equal to the processed quantity at the forward supply chain centers $f \in \mathscr{F}$ of one or more selectable location sites $o \in \mathscr{O}$, which is shipped to that demand node in period $t \in \mathscr{T}$.

Constraints (4.5) guarantee that the return ($RC_{k,t}$) from any demand node $k \in \mathscr{K}$ in period $t \in \mathscr{T}$ for further reverse supply chain process is met.

$$RC_{k,t} \leq \sum_{o \in \mathscr{O}} x_{k,o,r,t} \ , \quad \forall k \in \mathscr{K}, \ r \in \mathscr{R}, \ t \in \mathscr{T} \tag{4.5}$$

This amount must be less than or equal to the quantity processed at the reverse supply chain centers $r \in \mathscr{R}$ of one or more selectable location sites $o \in \mathscr{O}$, which is sent from that demand node in period $t \in \mathscr{T}$.

4.1.2.2.2.2 Capacity Constraints

Capacity Constraints of Forward Supply Chain Centers

Constraints (4.6) and (4.7) set the limits on maximum and minimum capacity units of each forward supply chain center $f \in \mathscr{F}$ at any selectable location site $o \in \mathscr{O}$.

$$\sum_{k \in \mathscr{K}} x_{o,k,f,t} \leq KC^{max}_{o,f} \delta_{o,f,t} \ , \quad \forall o \in \mathscr{O}, \ f \in \mathscr{F}, \ t \in \mathscr{T} \tag{4.6}$$

$$\sum_{k \in \mathscr{K}} x_{o,k,f,t} \geq KC^{min}_{o,f} \delta_{o,f,t} \ , \quad \forall o \in \mathscr{O}, \ f \in \mathscr{F}, \ t \in \mathscr{T} \tag{4.7}$$

Constraints (4.6) and (4.7) are the constraints ensuring that the demand quantity satisfied from each forward supply chain center $f \in \mathscr{F}$ at any selectable location site $o \in \mathscr{O}$ does not exceed and is below its maximum and minimum allowable capacity, respectively.

Capacity Constraints of Reverse Supply Chain Centers

Constraints (4.8) and (4.9) establish maximum and minimum capacity limits of each reverse supply chain center $r \in \mathscr{R}$ at any selectable location site $o \in \mathscr{O}$.

$$\sum_{k \in \mathscr{K}} x_{k,o,r,t} \leq KC^{max}_{o,r} \delta_{o,r,t} \ , \quad \forall o \in \mathscr{O}, \ r \in \mathscr{R}, \ t \in \mathscr{T} \tag{4.8}$$

$$\sum_{k\in\mathscr{K}} x_{k,o,r,t} \geq KC^{min}_{o,r}\delta_{o,r,t}\ , \quad \forall o \in \mathscr{O},\ \ r \in \mathscr{R},\ \ t \in \mathscr{T} \tag{4.9}$$

Constraints (4.8) and (4.9) ensure that the quantity returned from one or more demand nodes $k \in \mathscr{K}$ for processing at each reverse supply chain center $r \in \mathscr{R}$ of any selectable location site $o \in \mathscr{O}$ respectively does not go above and under its maximum and minimum allowable capacity.

4.1.2.2.2.3 Logical Constraints

Constraints (4.10) and (4.11) allow each center $c \in \mathscr{C}$ at any selectable location site $o \in \mathscr{O}$ to change its status at most once.

Closed center $c \in \mathscr{C}$at any existing location site $e \in \mathscr{E}$ cannot be reopened (constraints (4.10)). If $\delta_{e,c,t}$ is 0, then $\delta_{e,c,t+1}$ must be 0.

$$\delta_{e,c,t} \geq \delta_{e,c,t+1}\ , \quad \forall e \in \mathscr{E}\ ,\ \ c \in \mathscr{C},\ \ t \in \mathscr{T} \setminus \{T\} \tag{4.10}$$

Established center $c \in \mathscr{C}$at any new location site $n \in \mathscr{N}$ will remain in operation until the end of the planning horizon (constraints (4.11)). For $\delta_{n,c,t}$=1, $\delta_{n,c,t+1}$ must be equal to 1.

$$\delta_{n,c,t} \leq \delta_{n,c,t+1}\ , \quad \forall n \in \mathscr{N}\ ,\ \ c \in \mathscr{C},\ \ t \in \mathscr{T} \setminus \{T\} \tag{4.11}$$

4.1.2.2.2.4 Non-Negativity and Integrity Constraints

Lastly, constraints (4.12) and (4.13) represent non-negativity and integrality constraints, respectively.

$$x_{l,l',c,t} \geq 0\ , \quad \forall l \in \mathscr{L},\ \ l' \in \mathscr{L},\ \ c \in \mathscr{C},\ \ t \in \mathscr{T} \tag{4.12}$$

$$\delta_{o,c,t} \in \{0,1\},\ \forall o \in \mathscr{O},\ \ c \in \mathscr{C}\ \ t \in \mathscr{T} \tag{4.13}$$

4.1.3 An Example Problem to Identify the Locations of Forward, Reverse and Bidirectional Facilities

4.1.3.1 Description of the Example Problem

In order to illustrate the properties of the problem and the model, the model is applied to a small example size of the problem such that the results would be easy to comprehend. The example contains two existing location sites (pl1 and pl2), one potential new location site (pl3) and three customers (cu1, cu2 and cu3). It is assumed that any location site has one forward supply chain center (a1) and/or one reverse supply chain center (a2). The model is solved in the same way as the previous model in Chapter 3 by using CPLEX 12.1.0 in GAMS 23.2.1 on a Pentium IV personal computer with 2.66 GHz and 1 GB RAM[3].

Demand nodes	**Demand amount in each period (year)**				
	1st yr.	**2nd yr.**	**3rd yr.**	**4th yr.**	**5th yr.**
cu1	41000	42000	42500	52000	62000
cu2	40000	41000	42000	52000	62000
cu3	43000	43500	42000	53300	62000

Table 4.1: Demand amount at demand nodes ($DP_{k,t}$)

Demand nodes	**Return amount in each period (year)**				
	1st yr.	**2nd yr.**	**3rd yr.**	**4th yr.**	**5th yr.**
cu1	20500	16800	17000	26000	37200
cu2	20000	20500	16800	20800	37200
cu3	17200	21750	21000	31980	24800

Table 4.2: Return amount from demand nodes ($RC_{k,t}$)

[3] For the detailed GAMS code, see Appendix B.2.

Shipping routes	**Processing/shipping costs in each period (year)**					**Shipping routes**	**Processing/shipping costs in each period (year)**				
	1st yr.	**2nd yr.**	**3rd yr.**	**4th yr.**	**5th yr.**		**1st yr.**	**2nd yr.**	**3rd yr.**	**4th yr.**	**5th yr.**
pl1 to cu1	200	205	205	210	210	cu1 to pl1	11	12	13	14	15
pl1 to cu2	250	255	260	265	270	cu1 to pl2	21	22	23	24	25
pl1 to cu3	250	255	260	265	270	cu1 to pl3	8	8	10	10	11
pl2 to cu1	250	255	260	265	270	cu2 to pl1	11	12	13	14	15
pl2 to cu2	220	225	230	230	230	cu2 to pl2	15	16	17	18	19
pl2 to cu3	250	255	260	265	270	cu2 to pl3	8	8	10	10	11
pl3 to cu1	230	235	240	240	240	cu3 to pl1	11	12	13	14	15
pl3 to cu2	200	205	205	210	210	cu3 to pl2	15	16	17	18	19
pl3 to cu3	200	205	205	210	210	cu3 to pl3	8	8	10	10	11

(a) Forward dominant network (scenario F)

Shipping routes	**Processing/shipping costs in each period (year)**					**Shipping routes**	**Processing/shipping costs in each period (year)**				
	1st yr.	**2nd yr.**	**3rd yr.**	**4th yr.**	**5th yr.**		**1st yr.**	**2nd yr.**	**3rd yr.**	**4th yr.**	**5th yr.**
pl1 to cu1	200	205	205	210	210	cu1 to pl1	8	8	10	10	11
pl1 to cu2	200	205	205	210	210	cu1 to pl2	11	12	13	14	15
pl1 to cu3	200	205	205	210	210	cu1 to pl3	11	12	13	14	15
pl2 to cu1	230	235	240	240	240	cu2 to pl1	11	12	13	14	15
pl2 to cu2	230	235	240	240	240	cu2 to pl2	8	8	10	10	12
pl2 to cu3	230	235	240	240	240	cu2 to pl3	11	12	13	14	15
pl3 to cu1	200	205	205	210	210	cu3 to pl1	11	12	13	14	15
pl3 to cu2	230	235	240	240	240	cu3 to pl2	11	12	13	14	15
pl3 to cu3	230	235	240	240	240	cu3 to pl3	8	8	10	10	11

(b) Reverse dominant network (scenario R)

TABLE 4.3: Costs of processing and shipping demand and return amount between location sites $\left(CP_{l,l',t}\right)$

Shipping routes	Processing/shipping costs in each period (year)					Shipping routes	Processing/shipping costs in each period (year)				
	1st yr.	2nd yr.	3rd yr.	4th yr.	5th yr.		1st yr.	2nd yr.	3rd yr.	4th yr.	5th yr.
pl1 to cu1	200	205	205	210	210	cu1 to pl1	8	8	10	10	11
pl1 to cu2	230	235	240	240	240	cu1 to pl2	21	22	23	24	25
pl1 to cu3	230	235	240	240	240	cu1 to pl3	11	12	13	14	15
pl2 to cu1	230	235	240	240	240	cu2 to pl1	11	12	13	14	15
pl2 to cu2	200	205	205	210	210	cu2 to pl2	15	16	17	18	19
pl2 to cu3	230	235	240	240	240	cu2 to pl3	8	8	10	10	11
pl3 to cu1	230	235	240	240	240	cu3 to pl1	11	12	13	14	15
pl3 to cu2	230	235	240	240	240	cu3 to pl2	15	16	17	18	19
pl3 to cu3	230	235	240	240	240	cu3 to pl3	8	8	10	10	11

(c) Neither forward nor reverse dominant network (scenario N)

Table 4.3: Costs of processing and shipping demand and return amount between location sites $\left(CP_{l,l',t}\right)$ (continued)

Demand and Return amount of all customer nodes are assumed to be deterministic parameters with known distribution for the five year plan periods as shown in Tables 4.1 and 4.2, respectively. In order to evaluate the model, the model considered is the one in which the demand gradually increases, and approximately 40% to 60% of demand returns to the chain.

The aspect analyzed is the impact of increasing demand on the supply chain configuration under different integrated forward and reverse network scenarios: (1) a forward dominant network (scenario F), (2) a reverse dominant network (scenario R), and (3) neither a forward nor a reverse dominant network (scenario N). The forward dominant network contains only bidirectional and stand-alone forward facilities. The reverse dominant network only consists of bidirectional and stand-alone reverse facilities, and neither the forward nor the reverse dominant network comprises the bidirectional facility in addition to forward and reverse facilities. As stated in section 4.1.1, these three different network scenarios are influenced by distribution flow changes during a product's life cycle.

Centers at location sites	Operation costs in each period (year)				
	1st yr.	2nd yr.	3rd yr.	4th yr.	5th yr.
a1 at pl1	50000	51250	52531	53844	55190
a1 at pl2	50000	51250	52531	53844	55190
a1 at pl3	50000	51250	52531	53844	55190
a2 at pl2	15000	15375	15759	16153	16557
a2 at pl3	15000	15375	15759	16153	16557
a2 at pl3	15000	15375	15759	16153	16557

(a) Forward and neither forward nor reverse dominant networks (scenarios F and N)

Centers at location sites	Operation costs in each period (year)				
	1st yr.	2nd yr.	3rd yr.	4th yr.	5th yr.
a1 at pl1	70000	71250	72531	73844	75190
a1 at pl2	70000	71250	72531	73844	75190
a1 at pl3	50000	51250	52531	53844	55190
a2 at pl2	15000	15375	15759	16153	16557
a2 at pl3	15000	15375	15759	16153	16557
a2 at pl3	15000	15375	15759	16153	16557

(b) Reverse dominant network (scenario R)

TABLE 4.4: Costs of operating centers at selectable location sites ($CF_{o,c,t}$)

The parameters under the network scenarios are shown in Tables 4.3 and 4.4. In practice, processing, transportation and facility operating costs are the major parts of the total cost and the primary factors influencing distribution decisions of the firms [22]. To depict the effects of such issues related to each scenario, we therefore define the processing and transportation costs in Table 4.3, and the costs of operating supply chain process centers in Table 4.4[4].

[4] For the remaining data associated with the problem see Appendix B.1.

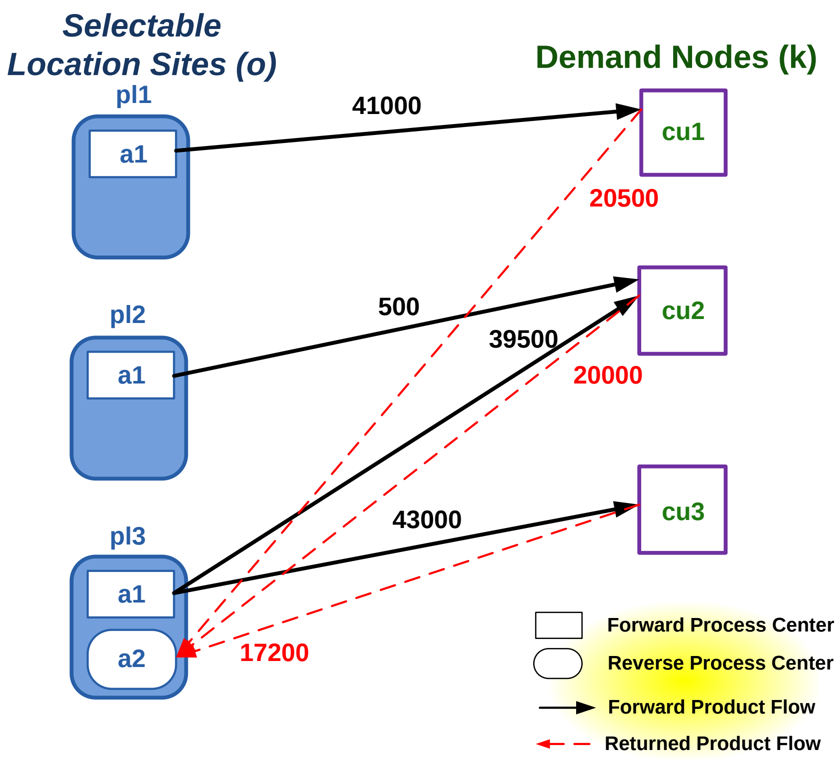
4.1.3.2 Numerical Results and Discussion

This section contains an illustrative example of numerical results and also provides a discussion of the results. The optimal supply chain configurations under three different network scenarios during the first period (t=1) and the last period (t=5) are depicted in Figures 4.3-4.5. The resulting networks with allocated transportation routes and subsequent demand and return allocations to facilities are also illustrated.

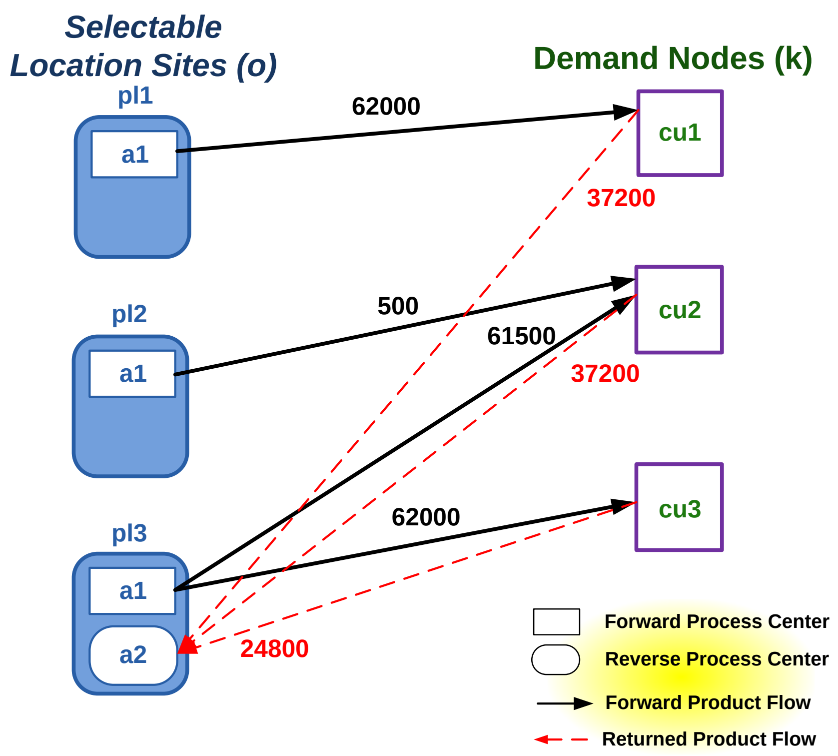
Figure 4.3 demonstrates the optimal solution of forward dominant network (scenario F). As can be observed, the solution shows that both forward and reverse supply chain centers a1 and a2 are opened at the new location site pl3, whilst the reverse supply chain centers a2 located at both existing location sites pl1 and pl2 are closed. This is because the costs of processing and shipping the amount from and to the new location site pl3 are lower than processing and shipping costs from and to both existing location sites pl1 and pl2. The network therefore consists of two stand-alone forward facilities (existing location sites pl1 and pl2) and one bidirectional facility (new location site pl3).

The optimal reverse dominant network (scenario R) is exhibited in Figure 4.4. It can be seen from Figure 4.4 that the forward supply chain center a1 located at the existing location site pl2 is closed due to the high costs associated with processing and shipping the demand amount from demand nodes, as well as operating facility. Whereas, the reverse supply chain center a2 at the new location site pl3 is opened for processing and shipping the amount returned from the demand node cu3 to this location site because its processing and shipping costs are cheaper than the costs of processing and shipping the returned amount to other location sites. Hence, the network contains two stand-alone reverse facilities (existing and new location sites pl2 and pl3, respectively) and one bidirectional facility (existing location site pl1).

In Figure 4.5, the optimal network, which is neither forward nor reverse dominant is illustrated. The Figure shows that the reverse supply chain center a2 located at the existing location site pl2 is closed resulting from the high processing and shipping costs

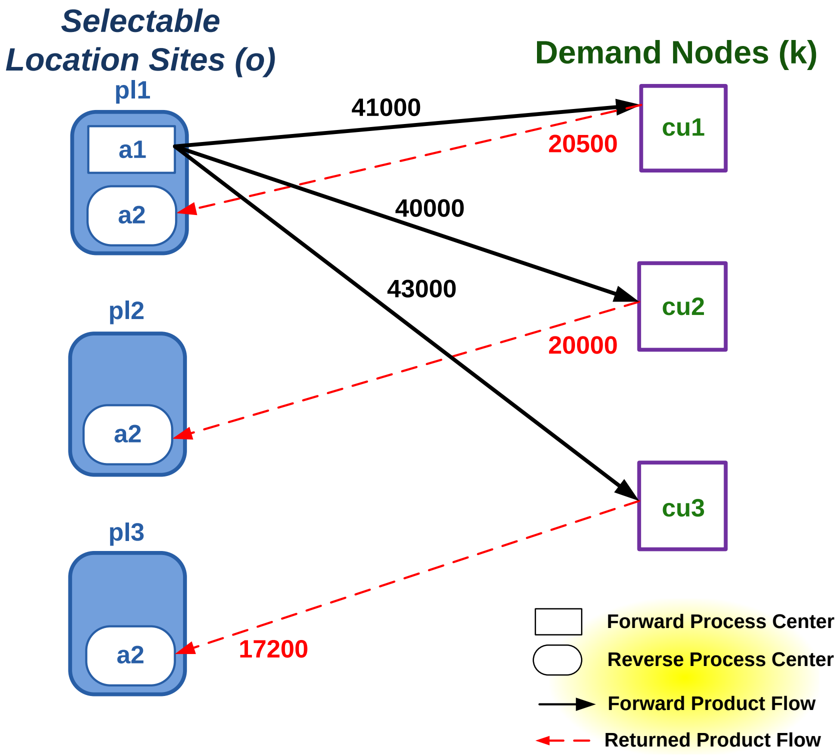


(a) in the first period (t=1)

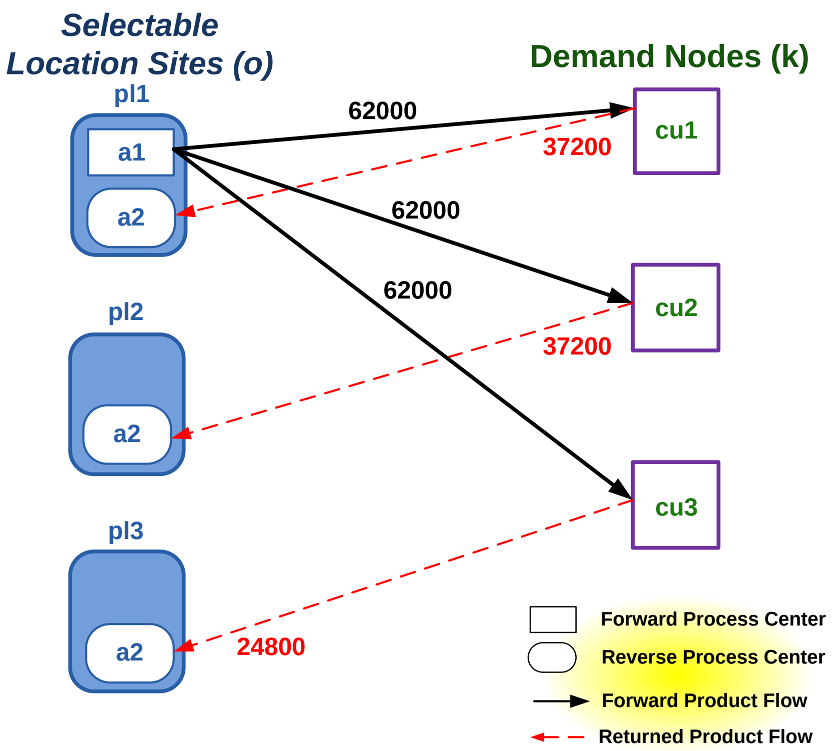


(b) in the last period (t=5)

FIGURE 4.3: Illustrative example of the optimal forward dominant network (scenario F)

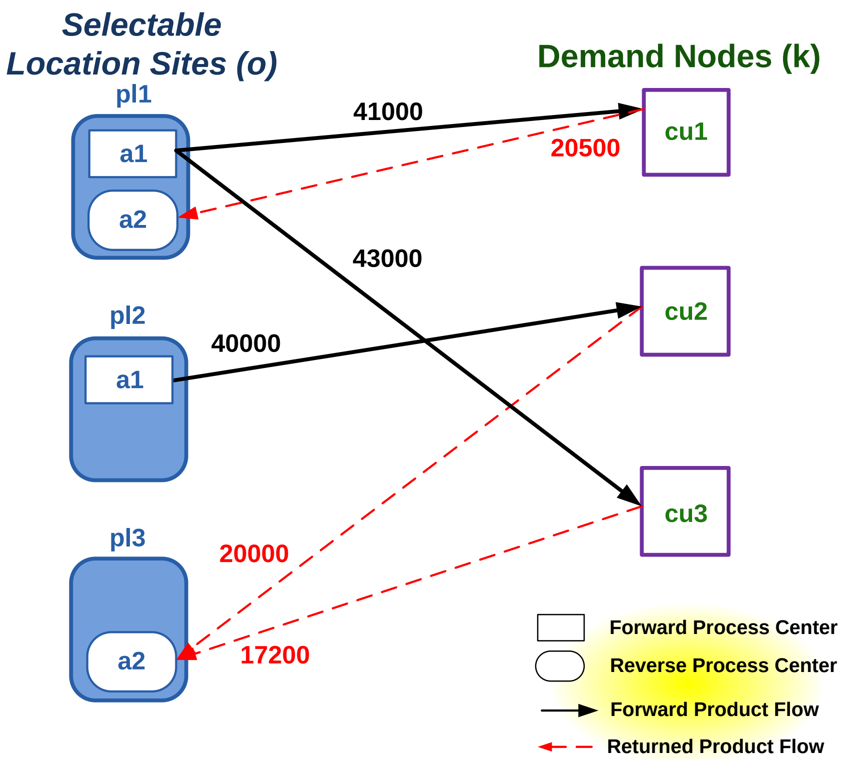


(a) in the first period (t=1)

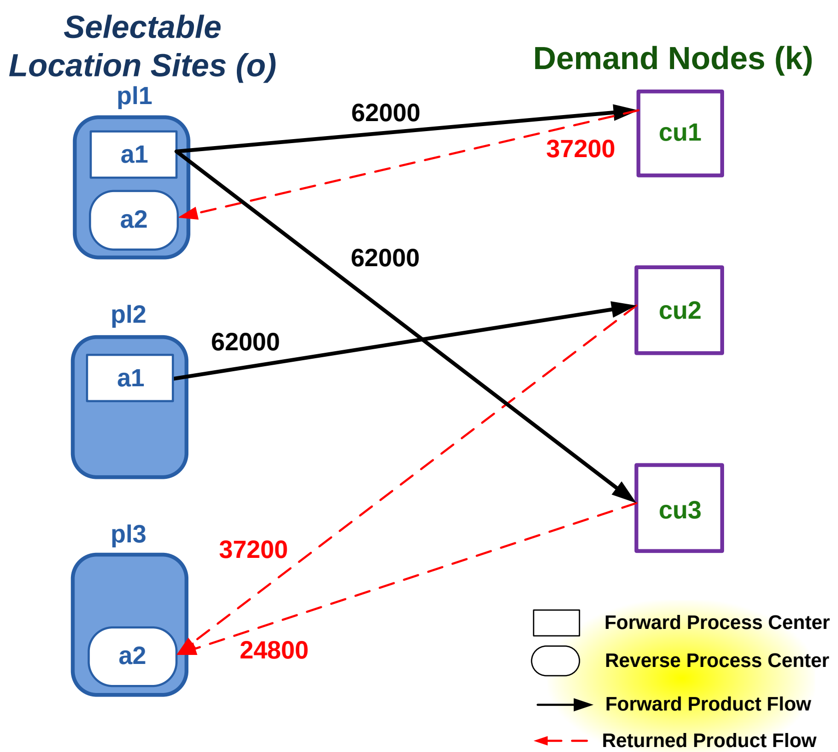


(b) in the last period (t=5)

Figure 4.4: Illustrative example of the optimal reverse dominant network (scenario R)



(a) in the first period (t=1)



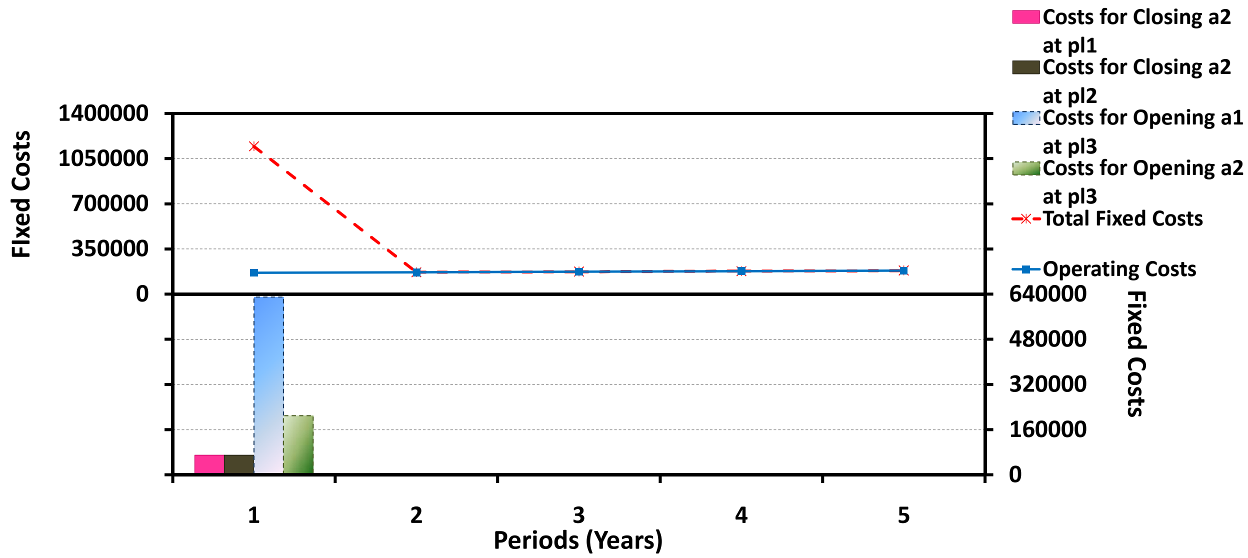
(b) in the last period (t=5)

FIGURE 4.5: Illustrative example of the optimal neither forward nor reverse dominant network (scenario N)

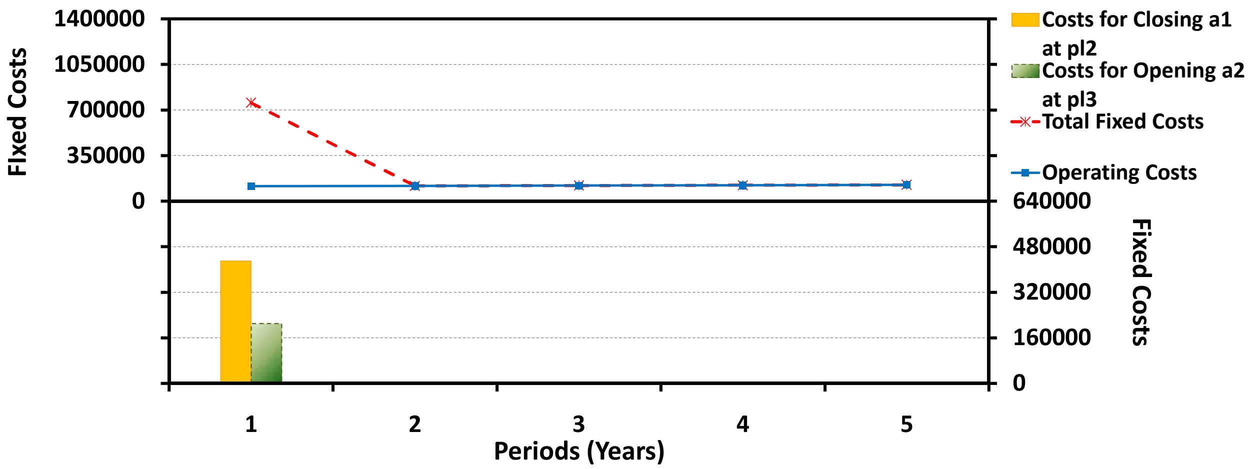
for the amount to be returned. Moreover, the reverse supply chain center a2 at the new location site pl3 is opened as processing and shipping costs for the amount returned to this location site are lower than such costs for the amount sent to other location sites. The network is thus comprised of one stand-alone forward facility (existing location site pl2), one stand-alone reverse facility (new location site pl3) and one bidirectional facility (existing location site pl1). All of the above mentioned network configurations are the same for all periods. We will discuss in greater detail below.

The variation in fixed costs is illustrated in Figure 4.6. For every scenario, it is obvious that there are additional costs related to closing and opening facilities in the first period (t=1). As already mentioned above, this is because the model selected to close some existing facilities and to open new facilities at the beginning of the planning horizon.

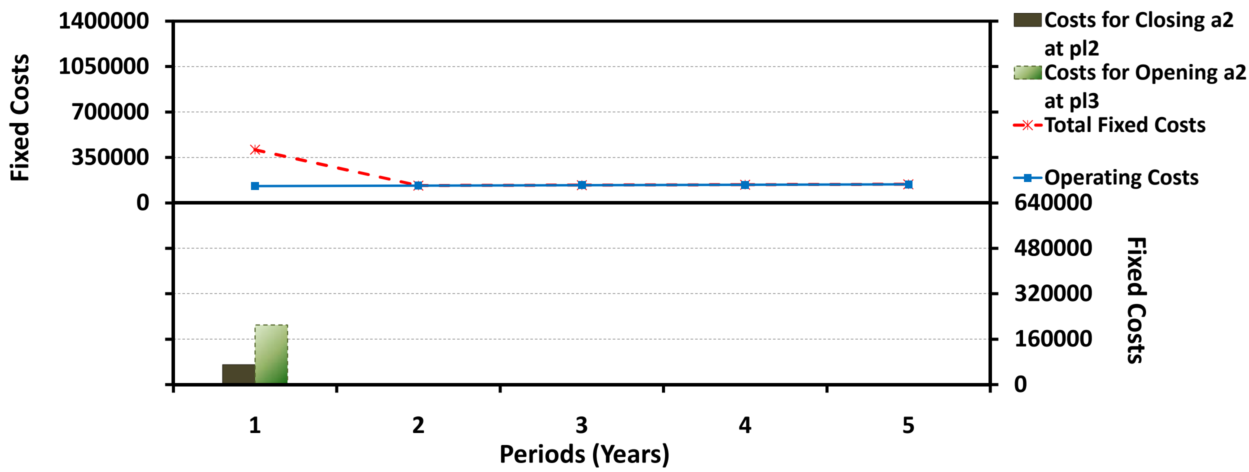
Figure 4.7 shows the flows between forward supply chain centers and demand nodes. In scenario F, forward supply chain centers located at selectable location sites (i.e., both existing and new location sites) are operating to fulfill the demand (see Figure 4.7(a)). We can see that the demand amount is mostly delivered from the existing location site pl1 to the demand node cu1 and from the new location site pl3 to the demand nodes cu2 and cu3 because their processing and shipping costs are much cheaper compared to the costs for processing and shipping from the existing location site pl2. For scenario R, only the forward supply chain center located at the existing location site pl1 is in operation to serve the demand of all demand nodes because processing and shipping costs from this existing location site for the forward distribution are the lowest costs (see Figure 4.7(b)). In scenario N, the forward flows between the forward supply chain centers at existing location sites pl1 and pl2 are operating to meet the demand. It can be seen that the demand is distributed from the existing location site pl1 to the demand nodes cu1 and cu3 and from the existing location site pl2 to the demand nodes cu2 (see Figure 4.7(c)). This is because their processing and shipping costs are much lower than the costs of processing and shipping the amount from the new location site pl3.



(a) Forward dominant case (scenario F)

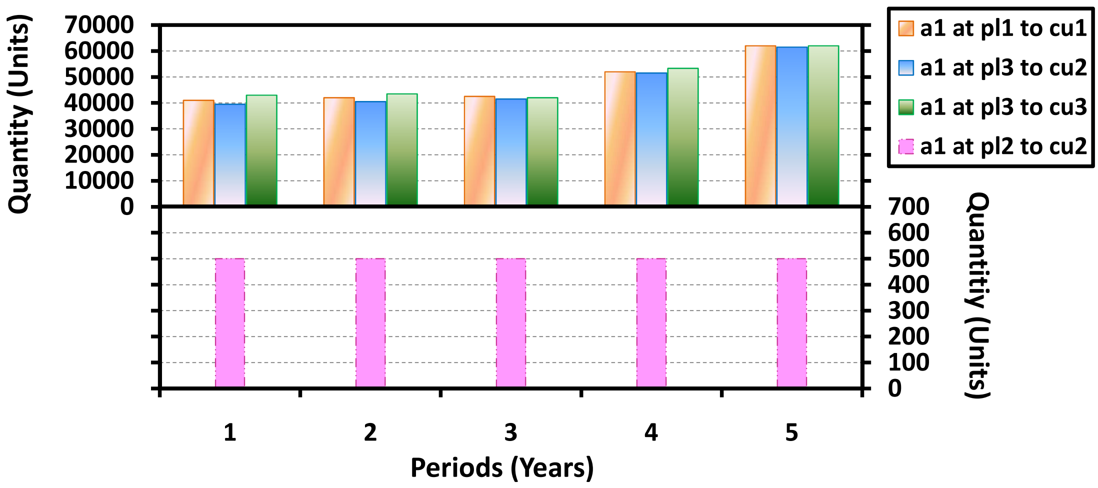


(b) Reverse dominant case (scenario R)

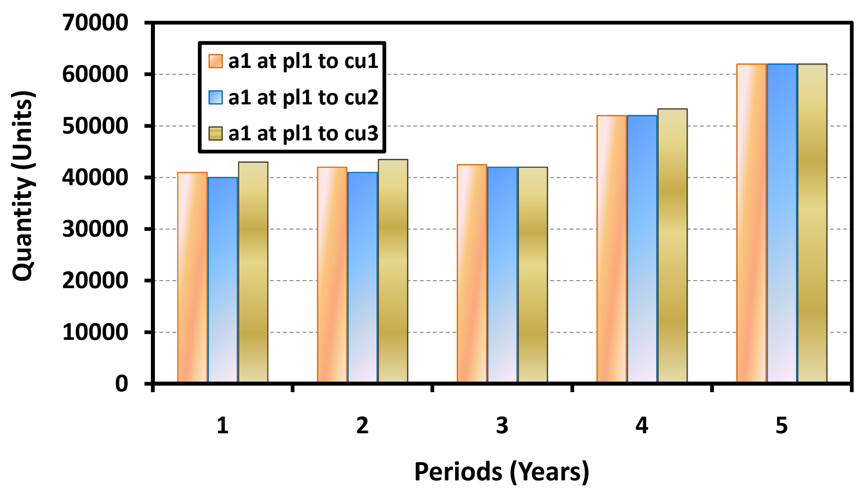


(c) Neither forward nor reverse dominant case (scenario N)

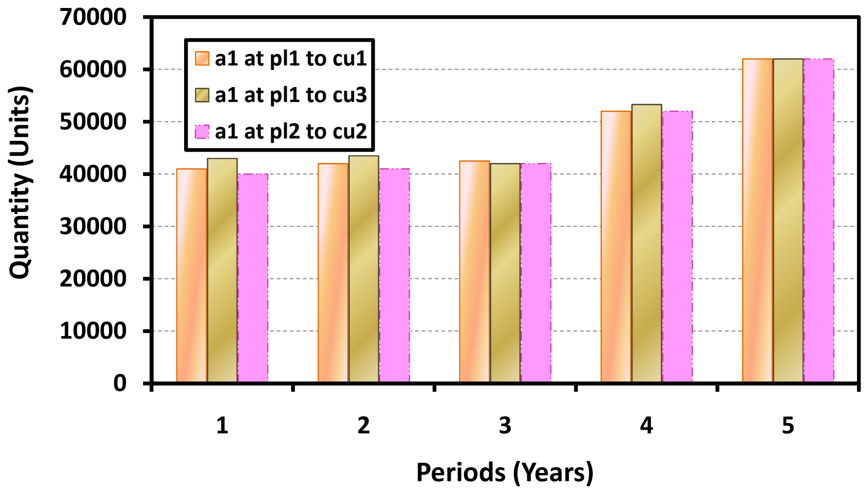
FIGURE 4.6: Fixed cost variation



(a) Forward dominant case (scenario F)

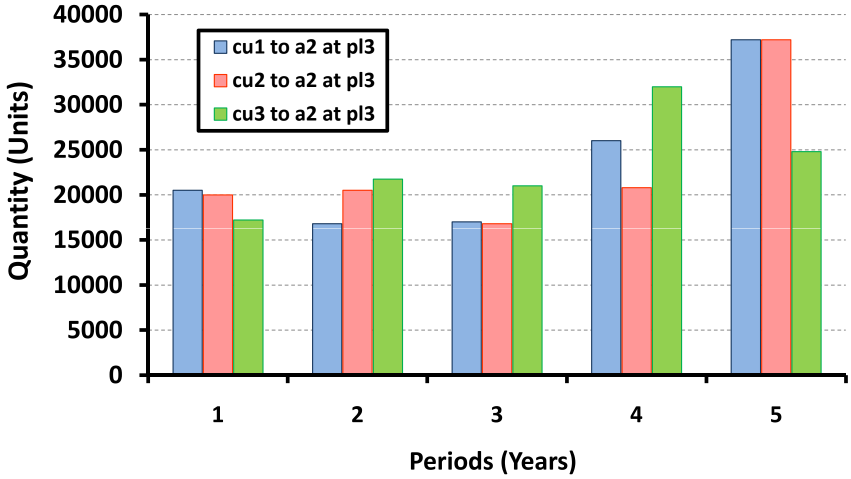


(b) Reverse dominant case (scenario R)

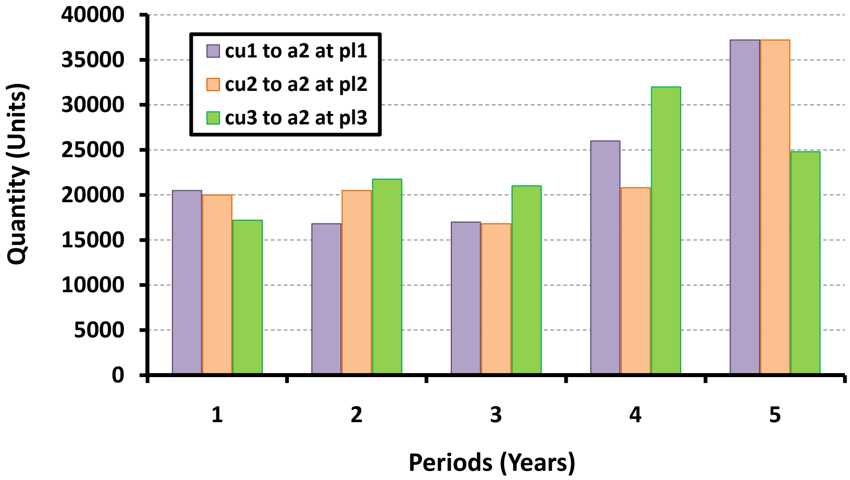


(c) Neither forward nor reverse dominant case (scenario N)

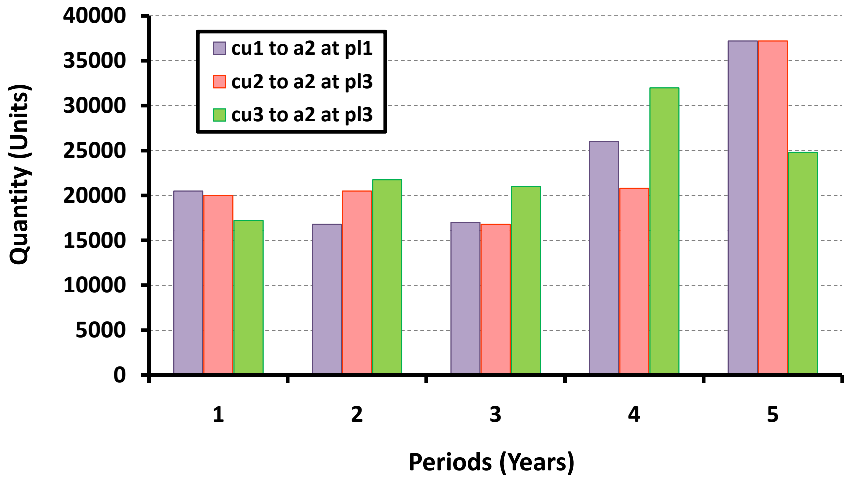
Figure 4.7: Flows between forward facilities



(a) Forward dominant case (scenario F)

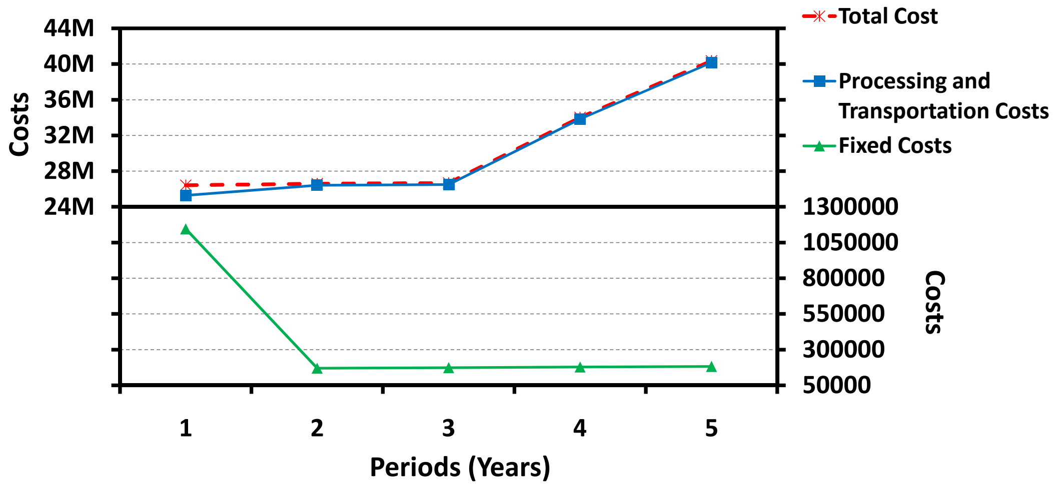


(b) Reverse dominant case (scenario R)

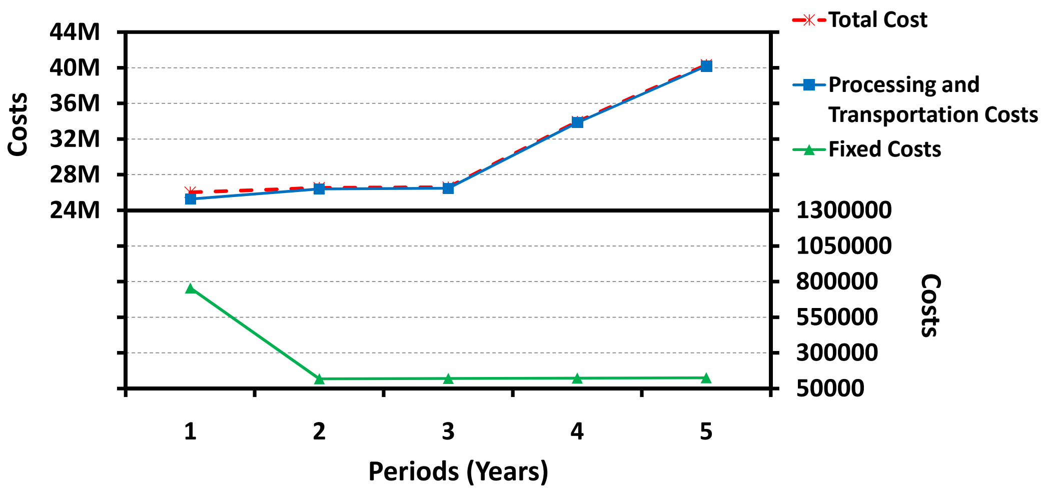


(c) Neither forward nor reverse dominant case (scenario N)

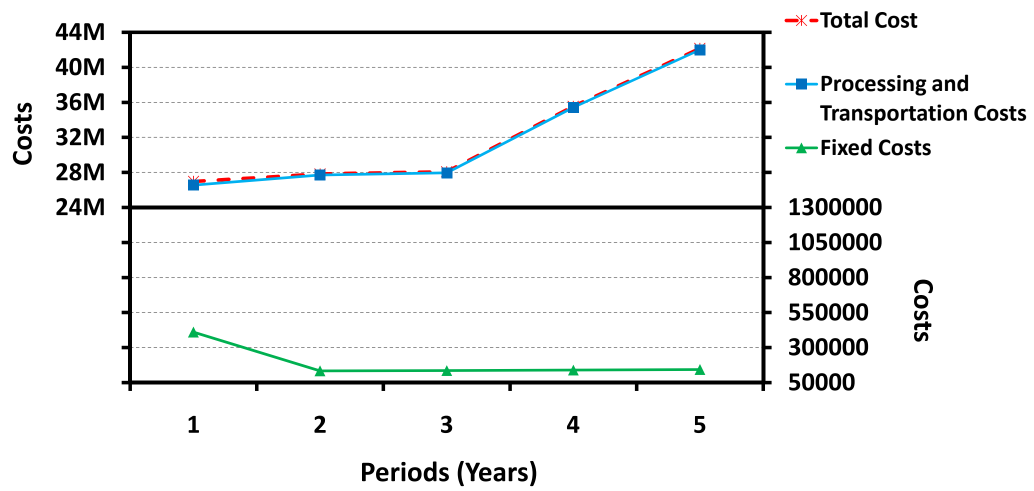
Figure 4.8: Flows between reverse facilities



(a) Forward dominant case (scenario F)



(b) Reverse dominant case (scenario R)



(c) Neither forward nor reverse dominant case (scenario N)

Figure 4.9: Total cost versus other costs

Figure 4.8 illustrates the returned flows between reverse supply chain centers and demand nodes. In scenario F, since the costs of processing and shipping the returned amount from demand nodes to the new location site pl3 are the least expensive, the returned amount from demand nodes are all sent to the reverse supply chain center located at the new location site pl3 (see Figure 4.8(a)). Whereas, in scenarios R and N, the returned amounts are shipped from the the demand node cu1 to the existing location site pl1, from the demand node cu2 to the existing location site pl2 and from the demand node cu3 to the new location site pl3 due to the low processing and shipping costs for the reverse supply chain process at these location sites (see Figures 4.8(b) and 4.8(c)).

Figure 4.9 depicts the change of the total cost with respect to other costs included in the total cost over the planning horizon. It can be noticed from the figure that scenario N has the highest total cost. This is because processing and shipping costs of scenario N are assumed to have the highest values as indicated by the values in Table 4.3 although this scenario has the lowest fixed costs as given in Table 4.4. According to a high volume of demand, fixed costs are much less than processing and transportation costs.

4.2 Dynamic Relocation and Expansion of Capacitated Facilities

4.2.1 Multiple Relocations and Expansions at Discrete Times

To be able to deal with unforeseen demand changes, two extensions of the previously described model in section 4.1.2, known as capacity *relocation* and *expansion* scenarios, are introduced in this section.

For the capacitated version the capacitated facility location problem, the possibility of relocating or expanding the facility capacity is frequently considered. In case that the interaction of facilities, distribution systems, consolidation, climate and/or government legislation are prone to fluctuate over time, *relocation of facilities* may therefore be

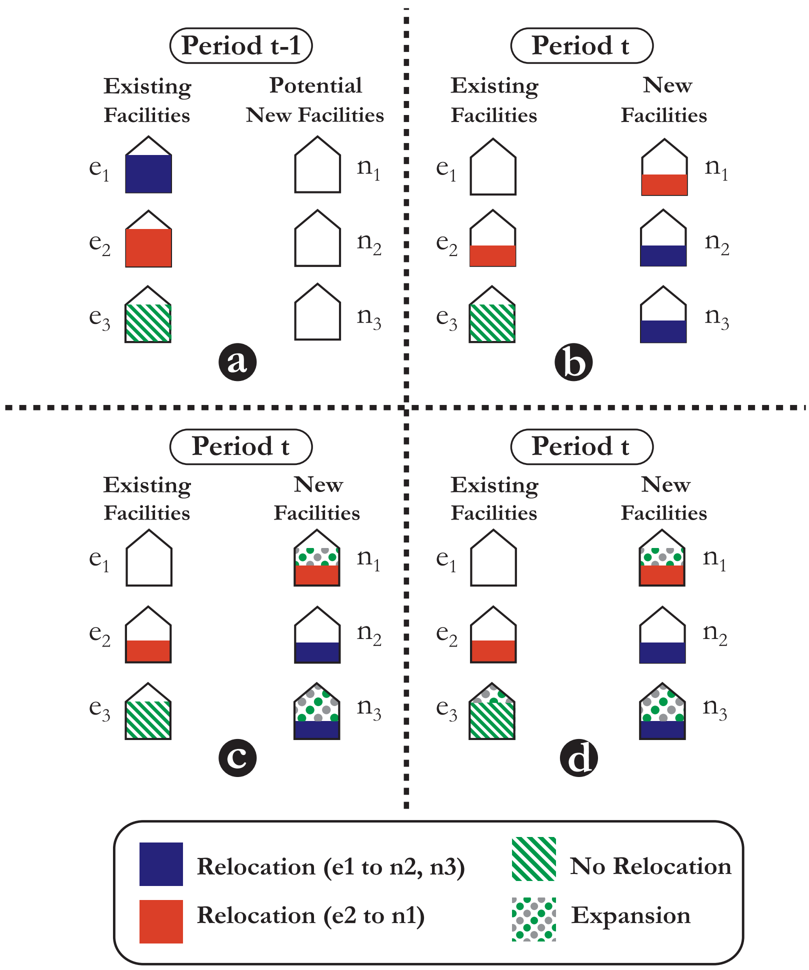


Figure 4.10: Capacity relocation and expansion scenarios (extended from [84])

necessary to avoid any potential disruption of activities in a firm [11]. However, it also needs to *expand the capacity of facilities* when a firm's sales volume is rising due to the increased demand [84].

Figure 4.10 illustrates the effect of capacity relocation and expansion. As depicted in Figure 4.10(a), facilities e_1, e_2 and e_3 are operated in a given period $t-1$. Potential sites for opening new facilities are n_1, n_2 and n_3. At the beginning of the subsequent period t, these new facilities will be operating in all potential sites. Relocation and/or expansion of the facility capacity occur during the beginning of this period.

In Figure 4.10(b), an existing facility is partly or entirely relocated to one or more new facilities. The total capacity of the existing facility e_1 is moved to facilities n_2 and n_3. As a result, operation of facility e_1 is shut down. Some part of the capacity of the existing facility e_2 is shifted to the new facility n_1. The existing facility e_2 is still operated but with decreased capacity. There is no capacity transferred from the existing facility e_3 to any new facility. Hence, the existing facility e_3 remains in operation with unchanged capacity. The possible scenarios of capacity expansion in combination with relocation are demonstrated in Figures 4.10(c) and (d), respectively.

All relocation scenarios shown in Figures 4.10(c) and (d) are the same as those in Figure 4.10(b). It can be seen from Figure 4.10(c) that the capacity of the new facilities n_1 and n_3 is increased by relocating from existing facilities to these new facilities and by establishing the additional capacity. The new facility n_3 reaches its maximum capacity, and cannot be extended in any later period. Figure 4.10(d) displays in particular the case of capacity expansion of existing and new facilities. The additional capacity is added at the existing facility e_3, as well as new facilities n_1 and n_3. The existing facility e_3 and new facility n_3 attain their maximum capacity, and therefore have not the capacity to consider further enlargement.

4.2.2 A Simple Relocation/Expansion Model for Hybrid Uni/Bidirectional Flows

4.2.2.1 Additional Notation

Based on the above-mentioned new problem settings, the following list describes the additional notation used in addition to that defined in this section.

Parameters:

$KI_{e,c}$: initial capacity of center $c \in \mathscr{C}$ at existing location site $e \in \mathscr{E}$

$KA^{max}_{o,c}$: maximum allowable additional capacity of center $c \in \mathscr{C}$ at selectable location site $o \in \mathscr{O}$

$CVE_{o,c,t}$: variable cost associated with expanding capacity of center $c \in \mathscr{C}$ at selectable location site $o \in \mathscr{O}$ in period $t \in \mathscr{T}$

$CVR_{e,n,c,t}$: variable cost associated with relocating capacity of center $c \in \mathscr{C}$ from existing location site $e \in \mathscr{E}$ to new location site $n \in \mathscr{N}$ in period $t \in \mathscr{T}$

Decision Variables:

$exp_{o,c,t}$: amount of capacity expanded at selectable location site $o \in \mathscr{O}$ for center $c \in \mathscr{C}$ in period $t \in \mathscr{T}$

$mov_{e,n,c,t}$: amount of capacity relocated from existing location site $e \in \mathscr{E}$ to new location site $n \in \mathscr{N}$ for processing at center $c \in \mathscr{C}$ in period $t \in \mathscr{T}$

$$\rho_{e,c} = \begin{cases} 1 & \text{if center } c \in \mathscr{C} \text{ is expanded at existing location site } e \in \mathscr{E} \text{ during the} \\ & \text{planning horizon,} \\ 0 & \text{otherwise} \end{cases}$$

Some modifications are required regarding the new formulation.

4.2.2.2 Formulation of the Dynamic Problem

4.2.2.2.1 Additional Variable Costs of Capacity Relocation and Expansion (TOC^3)

The costs in the following section are added to the objective function in the formulation of the previous section 4.1.2.2.

The first component in equation 4.14 is the variable costs of expanding the capacity $exp_{o,c,t}$ of one or more centers $c \in \mathscr{C}$ at selectable location sites $o \in \mathscr{O}$ in periods $t \in \mathscr{T}$.

$$TOC^3 = \sum_{o\in\mathscr{O}} \sum_{c\in\mathscr{C}} \sum_{t\in\mathscr{T}} CVE_{o,c,t} exp_{o,c,t} + \sum_{e\in\mathscr{E}} \sum_{n\in\mathscr{N}} \sum_{c\in\mathscr{C}} \sum_{t\in\mathscr{T}} CVR_{e,n,c,t} mov_{e,n,c,t} \tag{4.14}$$

The variable costs of relocating the capacity $mov_{e,n,c,t}$ from one or more centers $c \in \mathscr{C}$ at existing location sites $e \in \mathscr{E}$ to new location sites $n \in \mathscr{N}$ in periods $t \in \mathscr{T}$ are the second component.

4.2.2.2.2 Additional Constraints

The following new constraints[5] are required, in addition to constraints (4.4), (4.5) and (4.10) - (4.13).

4.2.2.2.2.1 Capacity Constraints

Capacity Relocation and Expansion Constraints

Constraints (4.15) and (4.16) limit the allowable capacity for expanding each center $c \in \mathscr{C}$ at any existing location site $e \in \mathscr{E}$, and the allowable capacity for relocating from each center $c \in \mathscr{C}$ at any existing location site $e \in \mathscr{E}$ to one or more new location sites $n \in \mathscr{N}$, respectively.

$$\sum_{t \in \mathscr{T}} exp_{e,c,t} \leq KA_{e,c}^{max} \rho_{e,c} \ , \quad \forall e \in \mathscr{E}, \ c \in \mathscr{C} \tag{4.15}$$

$$\sum_{n \in \mathscr{N}} \sum_{t \in \mathscr{T}} mov_{e,n,c,t} \leq KI_{e,c} \left(1 - \rho_{e,c}\right) \ , \quad \forall e \in \mathscr{E}, \ c \in \mathscr{C} \tag{4.16}$$

The combination of (4.15) and (4.16) ensures that each center $c \in \mathscr{C}$ at any existing location site $e \in \mathscr{E}$ can either have its capacity expanded or relocated to one or more new location sites $n \in \mathscr{N}$, but both changes cannot take place simultaneously.

Hence, if the capacity of center $c \in \mathscr{C}$ at that existing location site is relocated $\left(\rho_{e,c} = 0\right)$, that is, any capacity expansion is not allowed (4.15). If an existing capacity is expanded $\left(\rho_{e,c} = 1\right)$, no part of this capacity can be subsequently transferred (4.16).

Constraints (4.17) assure that an operating center $c \in \mathscr{C}$ at any existing location site $e \in \mathscr{E}$ can have its capacity relocated to a new location site $n \in \mathscr{N}$.

$$\sum_{n \in \mathscr{N}} \sum_{\tau=1}^{t} mov_{e,n,c,\tau} \leq KI_{e,c} \delta_{e,c,t} \ , \quad \forall e \in \mathscr{E}, \ c \in \mathscr{C}, \ t \in \mathscr{T} \tag{4.17}$$

The following constraints restrict the additional capacity allowed at any new location site $n \in \mathscr{N}$.

$$\sum_{e \in \mathscr{E}} \sum_{\tau=1}^{t} mov_{e,n,c,\tau} + \sum_{\tau=1}^{t} exp_{n,c,\tau} \leq KA_{n,c}^{max} \delta_{n,c,t} \ , \quad \forall n \in \mathscr{N}, \ c \in \mathscr{C}, \ t \in \mathscr{T} \tag{4.18}$$

[5] Our formulation of relocation and expansion conditions is developed from the model originally formulated by Melo et al. [84].

Constraints (4.18) impose that by period of time $t \in \mathscr{T}$, center $c \in \mathscr{C}$ at any new location site $n \in \mathscr{N}$ has been established for its capacity expansion and/or relocation from one or more existing location sites $e \in \mathscr{E}$ to that new location site.

Capacity Constraints of Forward Supply Chain Centers

Constraints (4.19) and (4.21) limit the maximum and minimum capacity of each forward supply chain center $f \in \mathscr{F}$.

Constraints (4.19) are the constraints ensuring that the processing and shipping quantity from each forward supply chain center $f \in \mathscr{F}$ of any existing location site $e \in \mathscr{E}$ must not exceed its available capacity.

$$\sum_{k \in \mathscr{K}} x_{e,k,f,t} \leq KI_{e,f}\delta_{e,f,t} + \sum_{\tau=1}^{t} exp_{e,f,\tau} - \sum_{n \in \mathscr{N}} \sum_{\tau=1}^{t} mov_{e,n,f,\tau} \ , \quad \forall e \in \mathscr{E},\ \ f \in \mathscr{F},\ \ t \in \mathscr{T} \tag{4.19}$$

This available capacity is limited by the sum of the initial capacity $(KI_{e,f})$ and the expanded capacity $\left(\sum_{\tau=1}^{t} exp_{e,f,\tau}\right)$ minus the capacity relocated to one or more new location sites $\left(\sum_{n\in\mathscr{N}} \sum_{\tau=1}^{t} mov_{e,n,f,\tau}\right)$.

Similarly, constraints (4.20) guarantee that the processing and shipping quantity from each forward supply chain center $f \in \mathscr{F}$ of any new location site $n \in \mathscr{N}$ must not above the available capacity of that forward supply chain center.

$$\sum_{k \in \mathscr{K}} x_{n,k,f,t} \leq \sum_{\tau=1}^{t} exp_{n,f,\tau} + \sum_{e \in \mathscr{E}} \sum_{\tau=1}^{t} mov_{e,n,f,\tau} \ , \quad \forall n \in \mathscr{N},\ \ f \in \mathscr{F},\ \ t \in \mathscr{T} \tag{4.20}$$

The available capacity for processing and shipping the units from each forward supply chain center $f \in \mathscr{F}$ of any new location site $n \in \mathscr{N}$ is the sum of the expanded capacity $\left(\sum_{\tau=1}^{t} exp_{n,f,\tau}\right)$ and the capacity relocated from one or more existing location sites $\left(\sum_{e\in\mathscr{E}} \sum_{\tau=1}^{t} mov_{e,n,f,\tau}\right)$.

Constraints (4.21) state that each forward supply chain center $f \in \mathscr{F}$ at any selectable location site $o \in \mathscr{O}$ must be operated above its minimum allowable capacity.

$$\sum_{k \in \mathscr{K}} x_{o,k,f,t} \geq KC^{min}_{o,f} \delta_{o,f,t} \ , \quad \forall o \in \mathscr{O}, \ f \in \mathscr{F}, \ t \in \mathscr{T} \tag{4.21}$$

Capacity Constraints of Reverse Supply Chain Centers

Constraints (4.22) and (4.24) restrict the maximum and minimum capacity of each reverse supply chain center $r \in \mathscr{R}$.

Constraints (4.22) make sure that the processing and shipping quantity from each reverse supply chain center $r \in \mathscr{R}$ of any existing location site $e \in \mathscr{E}$ must not above its available capacity.

$$\sum_{k \in \mathscr{K}} x_{k,e,r,t} \leq KI_{e,r} \delta_{e,r,t} + \sum_{\tau=1}^{t} exp_{e,r,\tau} - \sum_{n \in \mathscr{N}} \sum_{\tau=1}^{t} mov_{e,n,r,\tau} \ , \quad \forall e \in \mathscr{E}, \ r \in \mathscr{R}, \ t \in \mathscr{T} \tag{4.22}$$

This available amount of capacity is given by the sum of the initial capacity $(KI_{e,r})$ and the expanded capacity $\left(\sum_{\tau=1}^{t} exp_{e,r,\tau}\right)$ minus the capacity relocated to one or more new location sites $\left(\sum_{n \in \mathscr{N}} \sum_{\tau=1}^{t} mov_{e,n,r,\tau}\right)$.

The constraints below are specified in the same manner as constraints (4.22). These constraints guarantee that the processing and shipping quantity from each reverse supply chain center $r \in \mathscr{R}$ of any new location site $n \in \mathscr{N}$ must not be more than the available capacity of that reverse supply chain center.

$$\sum_{k \in \mathscr{K}} x_{k,n,r,t} \leq \sum_{\tau=1}^{t} exp_{n,r,\tau} + \sum_{e \in \mathscr{E}} \sum_{\tau=1}^{t} mov_{e,n,r,\tau} \ , \quad \forall n \in \mathscr{N}, \ r \in \mathscr{R}, \ t \in \mathscr{T} \tag{4.23}$$

The amount of capacity available for processing and shipping the units from each reverse supply chain center $r \in \mathscr{R}$ of any new location site $n \in \mathscr{N}$ is the sum of the expanded capacity $\left(\sum_{\tau=1}^{t} exp_{n,r,\tau}\right)$ and the capacity relocated from one or more existing location sites $\left(\sum_{e \in \mathscr{E}} \sum_{\tau=1}^{t} mov_{e,n,r,\tau}\right)$.

Constraints (4.24) are the constraints to assure that each reverse supply chain center $r \in \mathscr{R}$ at any selectable location site $o \in \mathscr{O}$ must not be operated at less than its minimum allowable capacity.

$$\sum_{k \in \mathscr{K}} x_{k,o,r,t} \geq KC^{min}_{o,r} \delta_{o,r,t} \ , \quad \forall o \in \mathscr{O}, \ r \in \mathscr{R}, \ t \in \mathscr{T} \tag{4.24}$$

4.2.2.2.2.2 Logical Constraints

The following constraints (4.25) together with constraints (4.10) guarantee that if each center $c \in \mathscr{C}$ at any existing location site $e \in \mathscr{E}$ is expanded, then it will remain in operation throughout the planning horizon.

On the other hand, if each center $c \in \mathscr{C}$ at any existing location site $e \in \mathscr{E}$ is not operated in the last period T, it must have been closed in one of the previous periods, and thus could not have its capacity expanded.

$$\rho_{e,c} \leq \delta_{e,c,T} \ , \quad \forall e \in \mathscr{E}, \ c \in \mathscr{C} \tag{4.25}$$

4.2.2.2.2.3 Non-Negativity and Integrity Constraints

Constraints (4.26) assure the non-negativity of decision variables $exp_{o,c,t}$ and $mov_{e,n,c,t}$. The binary integrality of decision variables $\rho_{e,c}$ is assured by constraints (4.27).

$$exp_{o,c,t}, \ mov_{e,n,c,t} \geq 0 \ , \quad \forall o \in \mathscr{O}, \ e \in \mathscr{E}, \ n \in \mathscr{N}, \ c \in \mathscr{C}, \ t \in \mathscr{T} \tag{4.26}$$

$$\rho_{e,c} \in \{0, 1\}, \ \forall e \in \mathscr{E}, \ c \in \mathscr{C} \tag{4.27}$$

4.2.3 An Example Problem of the Capacity Relocation and Expansion

4.2.3.1 Description of the Example Problem

For simple illustration of the model, the example network in section 4.1.3 is considered again. We generate new additional parameters and also change some parameter values to demonstrate the application of the model. In the same way as the previous two proposed models, this mixed-integer linear programming (MILP) model is implemented in GAMS 23.2.1 and solved using CPLEX 12.1.0[6].

Demand nodes	**Return amount in each period (year)**				
	1st yr.	**2nd yr.**	**3rd yr.**	**4th yr.**	**5th yr.**
cu1	20500	16800	17000	21000	25200
cu2	20000	20500	16800	16800	25200
cu3	17200	21750	21000	25980	16800

TABLE 4.5: Return amount from demand nodes ($RC_{k,t}$)

Centers at location sites	**Capacity expansion costs in each period (year)**				
	1st yr.	**2nd yr.**	**3rd yr.**	**4th yr.**	**5th yr.**
a1 at pl1	120	120	120	120	120
a1 at pl2	120	120	120	120	120
a1 at pl3	120	120	120	120	120
a2 at pl1	40	40	40	40	40
a2 at pl2	40	40	40	40	40
a2 at pl3	40	40	40	40	40

TABLE 4.6: Costs of expanding capacity of centers at existing location sites ($CVE_{o,c,t}$)

In order to evaluate the model, the data in Table 4.5 represents the parameter values of approximately 30% to 50% of demand returns to the supply chain. Tables 4.6 and 4.7 respectively show the costs for capacity expansion and relocation over a period of five years. We assume that expansion is much more expensive than relocation. The costs for processing and shipping the demand and return are given in Table 4.8[7].

[6] For the detailed GAMS code, see Appendix B.4 of this thesis.

[7] For additional parameters, see Appendix B.3. For demand value parameters, and other remaining parameters, see respectively Table 4.1 and Appendix B.1 of this thesis.

Relocation routes	Capacity relocation costs in each period (year)				
	1st yr.	2nd yr.	3rd yr.	4th yr.	5th yr.
a1 at pl1 to pl3	20	20	20	20	20
a1 at pl2 to pl3	24	24	24	24	24
a2 at pl1 to pl3	8	8	8	8	8
a2 at pl2 to pl3	10	10	10	10	10

Table 4.7: Costs of relocating capacity of centers from existing location sites to new location sites($CVR_{e,n,c,t}$)

Shipping routes	Processing/shipping costs in each period (year)					Shipping routes	Processing/shipping costs in each period (year)				
	1st yr.	2nd yr.	3rd yr.	4th yr.	5th yr.		1st yr.	2nd yr.	3rd yr.	4th yr.	5th yr.
pl1 to cu1	200	205	205	210	210	cu1 to pl1	11	12	13	14	15
pl1 to cu2	200	205	205	210	210	cu1 to pl2	21	22	23	24	25
pl1 to cu3	230	235	240	240	240	cu1 to pl3	8	8	10	10	11
pl2 to cu1	230	235	240	240	240	cu2 to pl1	11	12	13	14	15
pl2 to cu2	230	235	240	240	240	cu2 to pl2	15	16	17	18	19
pl2 to cu3	250	255	260	265	270	cu2 to pl3	8	8	10	10	11
pl3 to cu1	200	205	205	210	210	cu3 to pl1	11	12	13	14	15
pl3 to cu2	200	205	205	210	210	cu3 to pl2	15	16	17	18	19
pl3 to cu3	200	205	205	210	210	cu3 to pl3	8	8	10	10	11

Table 4.8: Costs of processing and shipping demand and return amount between location sites $\left(CP_{l,l',t}\right)$

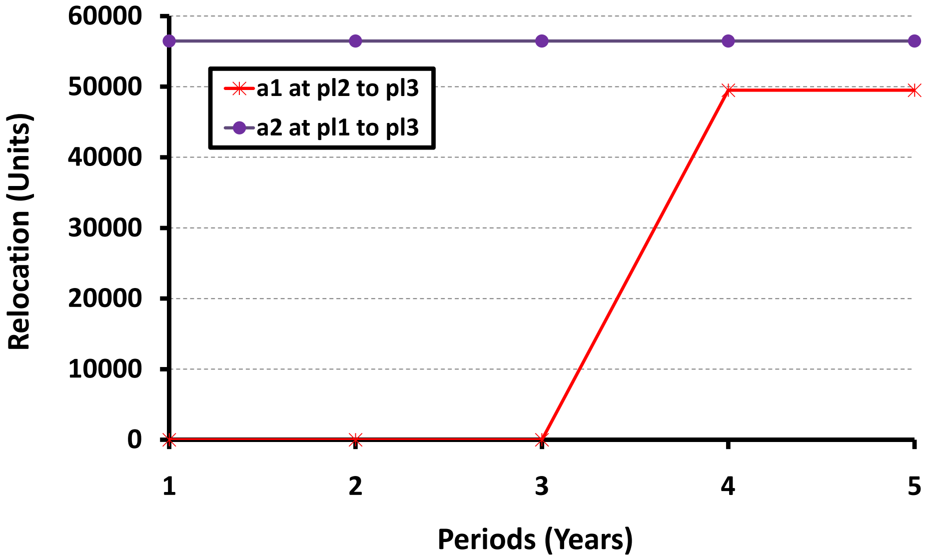


FIGURE 4.11: Capacity relocation

4.2.3.2 Numerical Results and Discussion

The relocation of capacity of supply chain process centers from existing location sites to new location sites as well as the capacity expansion of supply chain process centers at both existing and new location sites are shown in Figures 4.11 and 4.12, respectively. We observe that there are investments in expanding the capacity of the forward supply chain centers a1 at the existing location site pl1 and the new location site pl3 to meet the increasing demand over the planning horizon. The increase in demand increases the return and thus the reverse supply chain center a2 at the new location site pl3 is opened for expansion. There are also investments in expanding the capacity of the forward supply chain center a1 at the existing location site pl1 and opening the forward supply chain center a1 at the new location site pl3 for expansion to meet the increasing demand over the planning horizon.

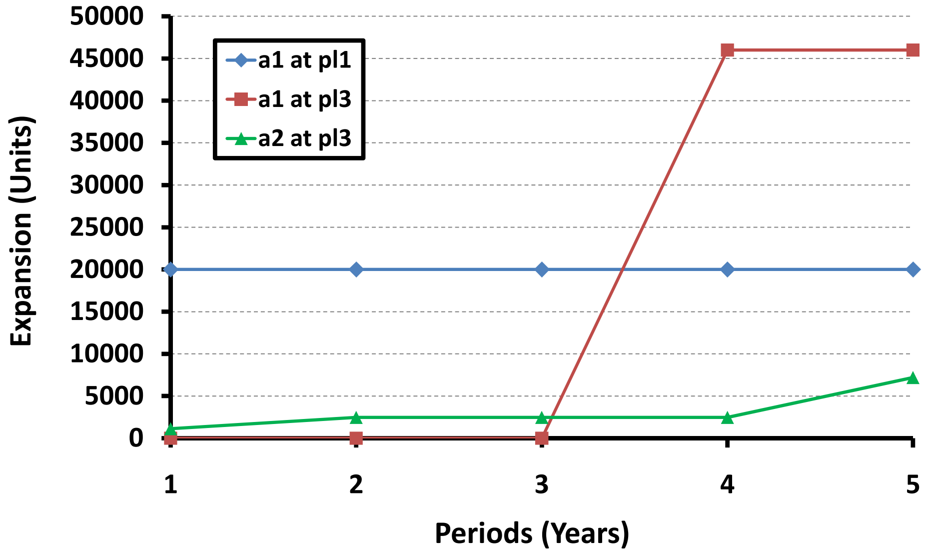


Figure 4.12: Capacity expansion

Figure 4.13 displays a comparison of the total fixed costs and all included costs related to closing, opening and operating facilities. It can be seen from the Figure that extra costs are added to the amount of fixed costs in the first and fourth one year periods. In order to be able to reduce processing and shipping costs in the early stage of the planning horizon, the model chose to close the reverse supply chain center a2 at the existing location site pl2, and to open the reverse supply chain center a2 at the new location site pl3. For the fourth period, the model selected to open the forward supply chain center a1 at the new location site pl3 to meet the increasing demand.

The optimal flows between the forward locations are demonstrated in Figure 4.14. For the entire time horizon, the forward flows occur from the existing location site pl1 to the demand nodes cu1 and cu2. In the first three periods, the forward flow also occurs from the existing location site pl2 to the demand node cu3, while the existing location site pl1 supplies to the demand node cu3 with the small volume. As the demand increases in the last two periods, the new location site pl3 fulfills the demand of the demand nodes cu1 and cu3 with the high volume during these periods, whereas the existing location site pl2 serves the low demand volume of the demand node cu1.

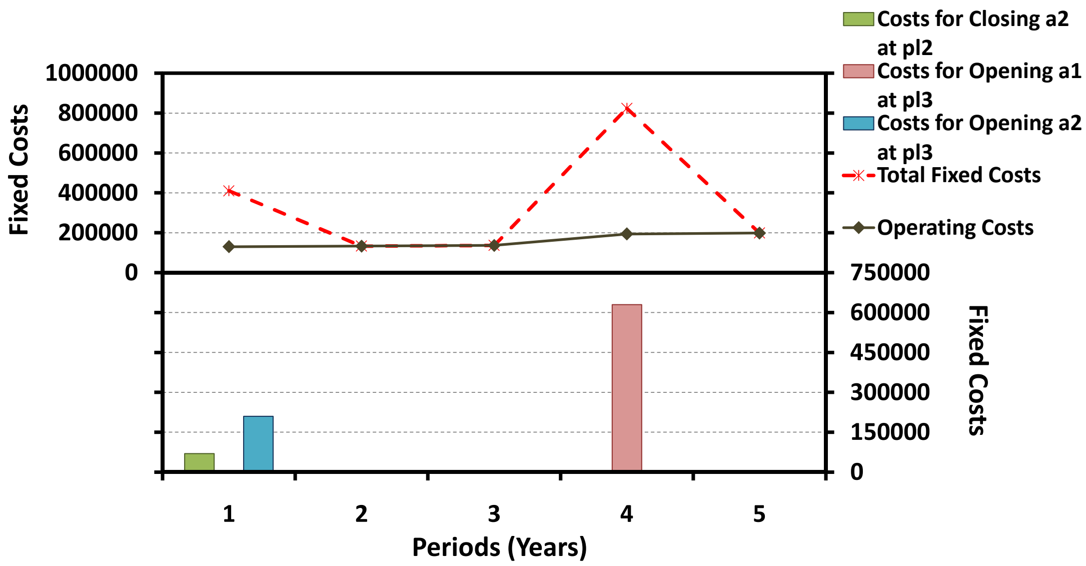


FIGURE 4.13: Fixed cost variation

Figure 4.15 depicts the optimal flows between the reverse facilities. In every planning period, the reverse flows occur from demand nodes cu1 and cu2 to the new location site pl3. During the first, second and third periods, the existing location site pl1 collects the low return volume from the demand node cu1. Because the demand is higher in the fourth and fifth periods, the existing location site pl1 collects a small volume of return from the demand node cu2 in the fourth period. Whereas the existing location site pl1 receives a high volume of return from the demand node cu3 in the fifth period, and the new location site pl3 receives a high volume of return from the demand node cu3 in the fourth and fifth periods.

Finally, Figure 4.16 illustrates the relationship between the total cost and other costs included in the total cost. The optimal solution shows that when the demand increases processing and shipping costs increase, and therefore the total cost increases. There are also extra costs added in the first and fourth periods due to the closing and opening of facilities.

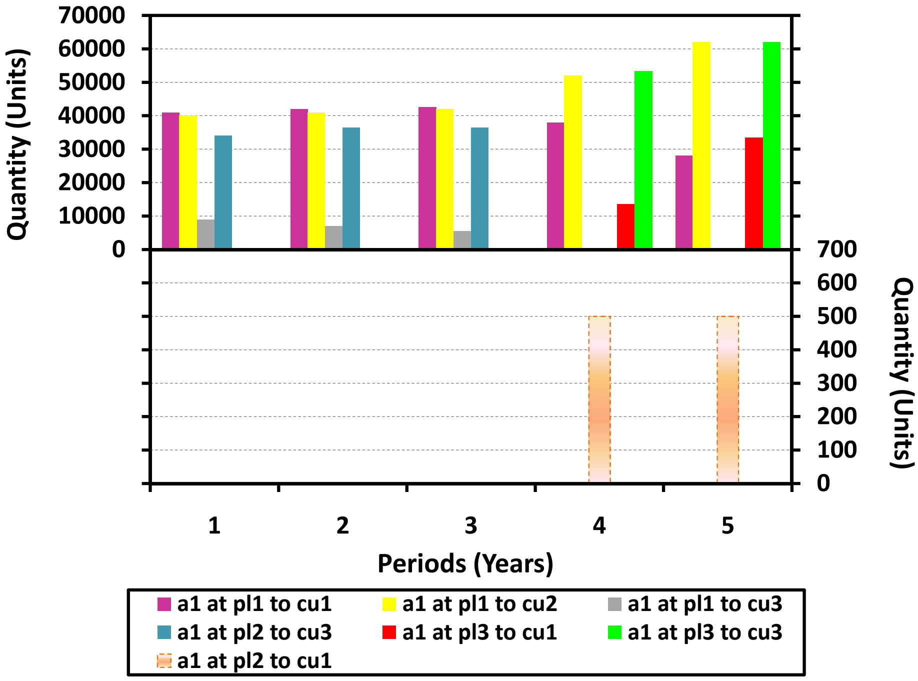


Figure 4.14: Flows between forward facilities

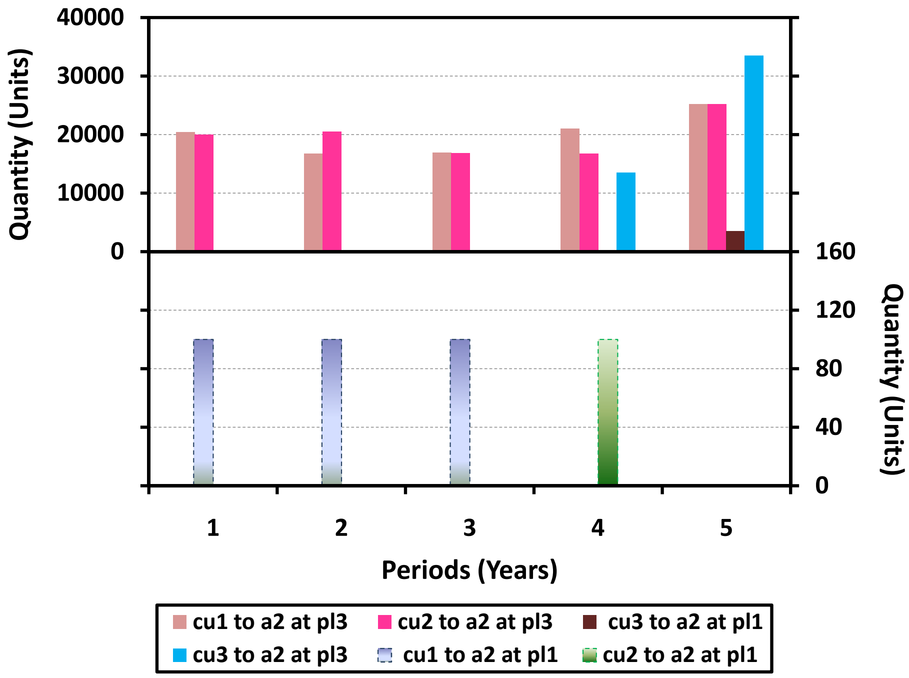


Figure 4.15: Flows between reverse facilities

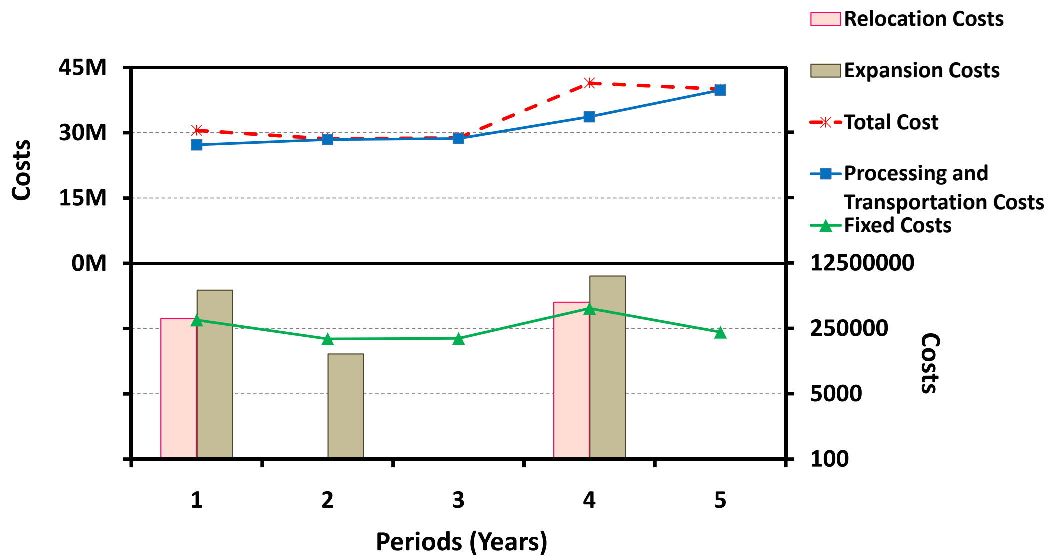


FIGURE 4.16: Total cost versus other costs

4.3 Literature Related to the Problems of Bidirectional Facilities, and Relocation and Expansion

This section gives a synthesis of the existing literature corresponding to the problems of bidirectional facilities, as well as capacity relocation and expansion. We will look at the research dedicated to these problems individually and some combination of them. Table 4.9 classifies the existing models related to these problems.

There are only three papers that consider the problem of hybrid uni/bidirectional facilities. This problem was firstly introduced by Lu et al. [76]. The authors presented a static (i.e., single period) two-level uncapacitated location problem. For this problem, the product demands of the customers can be met by producers or remanufacturing centers or a combination of them located at the same site. Later on, the problem of hybrid uni/bidirectional facilities was developed by Sahyouni et al. [107]. They extended a static version of the uncapacitated fixed-charge location model of Balinski [15] to include the location of bidirectional distribution centers in addition to unidirectional distribution centers. Their study shows that these models are most proper for products in the middle of their life cycle. Lee and Dong [71] then proposed dynamic (i.e., multi-period) capacitated facility location models for hybrid uni/bidirectional facilities. Instead of only handling stand-alone forward processing and collection facilities, a new type of intermediate depots, namely hybrid processing facilities, was also taken into consideration. Both forward products and returned products can be distributed via these hybrid facilities.

Problem aspects	**Article**		
Hybrid uni/bidirectional facilities	[71] Lee and Dong, 2009	[76] Lu and Bostel, 2007	[107] Sahyouni et al., 2007
Capacity relocation	[81] Melachrinousdis et al., 2005 [87] Melo et al., 2012	[82] Melachrinousdis and min, 2000	[86] Melo et al., 2011
Capacity expansion	[1] Aghezzaf, 2005 [10] Antunes and Peeters, 2001 [45] Fong and Srinivasan, 1986 [72] Lee and Luss, 1987 [96] Naraharisetti and Karimi, 2010 [120] Thanh et al., 2008 [128] Vila et al., 2006	[6] Alumur et al., 2012 [43] Fleischmann et al., 2006 [59] Hugo and Pistikopoulos, 2005 [90] Min and Ko, 2008 [113] Schultmann et al., 2003 [122] Troncoso and Garrido, 2005	[9] Antunes and Peeters, 2000 [44] Fong and Srinivasan, 1981 [66] Ko and Evan, 2007 [95] Naraharisetti et al., 2008 [118] Srivastava, 2008 [123] Ulstein et al., 2006
Capacity relocation and expansion	[53] Hammami et al., 2009	[84] Melo et al., 2006	

Table 4.9: Literature on the problems related to hybrid uni/bidirectional facilities, capacity relocation and expansion

Only four papers addressing the problems of capacity relocation have appeared. Melachrinousdis et al. [81] focused on the static capacity relocation problem in which the overall capacity available in one location is relocated at once to another location. Melachrinousdis and Min [82] concentrated on the dynamic capacity relocation of one single intermediate facility in a multi-objective context. Melo et al. [86, 87] extended their earlier dynamic facility model (Melo et al. [84]) that can only solve small and medium size instances. Extension of the previous model allowed dealing with the problems of realistic size associated with gradually relocating capacity from one facility to another site.

The literature devoted to capacity expansion is relatively sparse. The earliest attempts to incorporate capacity expansion conditions into the models are the papers proposed by Fong and Srinivasan [44, 45], and Lee and Luss [72]. Their papers studied the problem of determining in which periods of time the capacity of any facility should be expanded to meet the increasing demand. Hugo and Pistikopoulos [59], Ko and Evan [66], Min and Ko [90] and Srivastava [118] simultaneously considered capacity expansion and location decisions over the planning horizon of time periods. The case of modular capacity expansion was investigated by Alumur et al. [6], Antunes and Peeters [9, 10], Fleischmann et al. [43], Naraharisetti et al. [95], Naraharisetti and Karimi [96], Schultmann et al. [113], Thanh et al. [120], Troncoso and Garrido [122], Ulstein et al. [123], and Vila et al. [128]. This expansion was designed for installing the modules with pre-defined size. The authors combined capacity expansion with multi-period location decisions (except the paper of Schultmann et al. [113]). Aghezzaf et al. [1] limited capacity decisions to one specific layer. The possibility of expanding capacity can occur only for the upper layer facilities.

There are only two papers proposed by Hammami et al. [53] and Melo et al. [84] that concurrently considered a dynamic version of capacity relocation and expansion. Their models allowed for the gradual capacity relocation from one facility to another and capacity expansion acquired from an external source.

From the above it can be concluded that the research involving the integration of the problems of hybrid uni/bidirectional facilities, as well as capacity relocation and expansion has still not received attention in the literature. In this chapter, we therefore propose a mathematical modeling framework to tackle all these problems simultaneously.

5

Facility Relocation and Expansion in Product Recovery Network Design

5.1 A Relocation/Expansion Model for Product Recovery System Including Hybrid Uni/Bidirectional Flows

5.1.1 Network Design of a Closed-Loop Supply Chain System

As revealed in the previous chapter, the need for integrating, relocating and expanding forward and reverse logistics activities are the important key characteristics of the facility location problem in a closed-loop supply chain context. In this chapter, we explore this issue in more detail. We consider an extension of the facility location problem that allows for relocating and expanding hybrid uni/bidirectional facilities in a product recovery system, which leads to competitive advantages in the long term. The relocation and expansion involve joining forward and reverse logistics facilities to offer the ability of achieving greater speed to shelf, visibility, cost saving and pollution reduction as a result of possibly sharing of material handling equipment, adjustment of operations and infrastructure. The model developed in this chapter represents a mathematical relationship between various entities within the closed-loop supply chain network. In order to provide an easy understandable explanation for the proposed model, Figure 5.1 schematically illustrates the type of supply chain modeled in this chapter. The mathematical symbols firstly introduced in Figure 5.1 are provided along with a short description of each in section 5.1.3. The presented supply chain system consists of four critical processes: (1) production, (2) distribution, (3) collection and (4) disassembly and remanufacturing.

The production and disassembly-remanufacturing centers could be located at the same site (as bidirectional facility) or different places (as unidirectional facility). It is possible to locate both the distribution center and collection center at the same site or to locate the distribution center and the collection center at different intermediate sites, i.e. unidirectional or bidirectional intermediate site. In our framework, production centers have three alternatives for acquiring parts/components used to manufacture final products: (1) ordering the required parts/components from external suppliers, (2) re-processing the returned products and bringing those back 'as new' parts/components, and (3) outsourcing to subcontractors for disassembled and remanufactured parts/components. The manufactured products from production centers are initially transported to distribution centers and/or directly transported to customers. The distribution centers will then store the products until needed by customers. Whereas, the collection points, which receive the used goods from customers, are used as storage for the reverse channel, before the returned products are shipped to disassembly-remanufacturing centers and/or disassembly-remanufacturing subcontractors. Both disassembly-remanufacturing centers and disassembly-remanufacturing

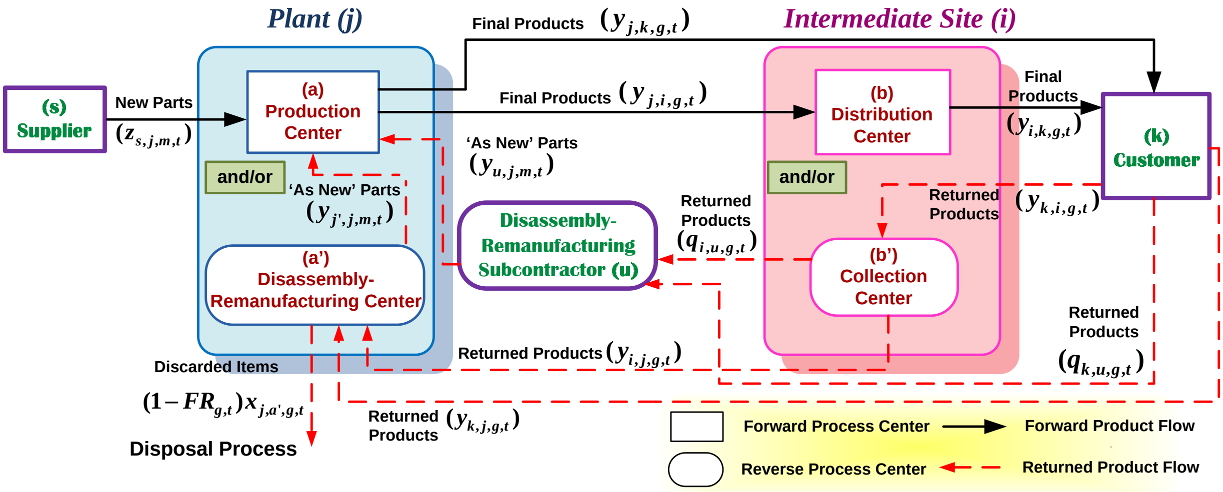


FIGURE 5.1: Configuration of the proposed model

subcontractors can also receive the returned products straight from customers. The disassembly-remanufacturing centers are responsible for some essential activities of recovering, in which the returns are disassembled and remanufactured, tested, sorted, as well as cleaned for reuse, repair and remanufacturing. Some discarded items from disassembly-remanufacturing centers will be sent for the disposal process.

5.1.2 Model Assumptions

The assumptions below are used to formulate the proposed mixed-integer linear programming (MILP) model for the dynamic (i.e. multi-period), multi-echelon, multi-commodity facility relocation/expansion problem in closed-loop supply chains that incorporate product recovery. To clearly define the assumptions of our model, some mathematical symbols listed in the next section are also mentioned in this section. These assumptions are classified into the following categories: products, supply chain structure, supply chain processes, relocation and expansion, closing and opening of facilities, as well as economic aspects.

5.1.2.1 Products

A1: The final product $g \in \mathscr{G}$ is produced by either the remanufacturer with reusable parts/components $m \in \mathscr{M}$ or the manufacturer with new parts/components $m \in \mathscr{M}$.

A2: Reusable parts/components $m \in \mathscr{M}$ have the same quality standards as new parts/components $m \in \mathscr{M}$.

5.1.2.2 Supply Chain Structure

B1: The system consists of multiple external suppliers $s \in \mathscr{S}$, multiple plant sites $j \in \mathscr{J}$, multiple intermediate sites $i \in \mathscr{I}$, multiple customers $k \in \mathscr{K}$ and multiple disassembly-remanufacturing subcontractors $u \in \mathscr{U}$.

B2: The external supplier $s \in \mathscr{S}$ provides new parts/components $m \in \mathscr{M}$ for manufacturing at the production center $a \in \mathscr{F}$ of any plant site $j \in \mathscr{J}$.

B3: Within each plant site $j \in \mathscr{J}$, there are the production center $a \in \mathscr{F}$ and/or the disassembly-remanufacturing center $a \in \mathscr{R}$.

B4: Each intermediate site $i \in \mathscr{I}$ has the distribution center $b \in \mathscr{F}$ and/or the collection center $b \in \mathscr{R}$.

B5: The production center $a \in \mathscr{F}$ at any plant site $j \in \mathscr{J}$ is the center where final products $g \in \mathscr{G}$ are manufactured prior to being sent to the distribution center $b \in \mathscr{F}$ at any intermediate site $i \in \mathscr{I}$, and/or directly to any customer $k \in \mathscr{K}$.

B6: The disassembly-remanufacturing center $a \in \mathscr{R}$ at any plant site $j \in \mathscr{J}$ is the center where reusable parts/components $m \in \mathscr{M}$ are disassembled and remanufactured prior to being delivered to the production center $a \in \mathscr{F}$ at any plant site $j \in \mathscr{J}$.

B7: The distribution center $b \in \mathscr{F}$ at any intermediate site $i \in \mathscr{I}$ is the center where final products $g \in \mathscr{G}$ are stored before being transported to any customer $k \in \mathscr{K}$.

B8: The collection center $b \in \mathscr{R}$ at any intermediate site $i \in \mathscr{I}$ is the center where returned final products $g \in \mathscr{G}$ are stored before being sent for disassembling and remanufacturing at the disassembly-remanufacturing center $a \in \mathscr{R}$ of any plant site $j \in \mathscr{J}$ and/or by the disassembly-remanufacturing subcontractor $u \in \mathscr{U}$.

B9: Each customer $k \in \mathscr{K}$ purchases the final products $g \in \mathscr{G}$ from the distribution center $b \in \mathscr{F}$ at any intermediate site $i \in \mathscr{I}$, and/or directly from the production center $a \in \mathscr{F}$ at any plant site $j \in \mathscr{J}$.

B10: Each customer $k \in \mathscr{K}$ returns the used final products $g \in \mathscr{G}$ to the collection center $b \in \mathscr{R}$ at any intermediate site $i \in \mathscr{I}$, and/or directly to the disassembly-remanufacturing center $a \in \mathscr{R}$ at any plant site $j \in \mathscr{J}$. It is also possible for any customer $k \in \mathscr{K}$ to transfer the used final products $g \in \mathscr{G}$ to the external disassembly-remanufacturing subcontractor $u \in \mathscr{U}$.

B11: Each disassembly-remanufacturing subcontractor $u \in \mathscr{U}$ is an external plant of the network in which subcontracted reusable parts/components $m \in \mathscr{M}$ are recovered, and are directly delivered to the production center $a \in \mathscr{F}$ at any plant site $j \in \mathscr{J}$.

5.1.2.3 Supply Chain Processes

C1: The manufacturing process at the production center $a \in \mathscr{F}$ of any plant site $j \in \mathscr{J}$ was created for assembling parts/components $m \in \mathscr{M}$ into the final product $g \in \mathscr{G}$.

C2: The disassembly-remanufacturing process at the disassembly-remanufacturing center $a \in \mathscr{R}$ of any plant site $j \in \mathscr{J}$ was created for disassembling and remanufacturing the used final product $g \in \mathscr{G}$ into reusable parts/components $m \in \mathscr{M}$ and discarding non-reusable part/component remains.

C3: The distribution center $b \in \mathscr{F}$ at any intermediate site $i \in \mathscr{I}$ could have only the stocks of final products $g \in \mathscr{G}$ distributed from the production center $a \in \mathscr{F}$ at any plant site $j \in \mathscr{J}$ in its storage.

C4: The collection center $b \in \mathscr{R}$ at any intermediate site $i \in \mathscr{I}$ could have only the stocks of final products $g \in \mathscr{G}$ returned from customer $k \in \mathscr{K}$ in its storage.

5.1.2.4 Closing and Opening of Facilities

E1: It is possible that center $c \in \mathscr{C}$ for any supply chain process at any existing location site $e \in \mathscr{E}$ and its existing location site may be closed. There are also potential locations for opening new location sites $n \in \mathscr{N}$ for center $c \in \mathscr{C}$.

E2: It is assumed that the opened/closed status of a facility changes no more than once during the planning horizon.

5.1.2.5 Relocation and Expansion

D1: All types of centers $c \in \mathscr{C}$ at any existing location site $e \in \mathscr{E}$ can be partly or totally relocated to one or more new location sites $n \in \mathscr{N}$.

D2: It is possible to establish the additional new capacity at any existing location site $e \in \mathscr{E}$ for all types of centers $c \in \mathscr{C}$, if there is available free space.

D3: For any new location site $n \in \mathscr{N}$, the additional new capacity can be established for all types of centers $c \in \mathscr{C}$.

D4: It is assumed that if the capacity for each of center $c \in \mathscr{C}$ is added, this added capacity is a permanent increase.

5.1.2.6 Economic Aspects

F1: Transportation cost is calculated with respect to the distance between location sites $l \in \mathscr{L}$ and $l' \in \mathscr{L}$.

F2: It is assumed that the value of assets will last forever, and thus their value is not depreciated.

F3: The primary goal is to maximize the net present value (NPV) of a time series of cash flows for the entire supply chain.

5.1.3 Notation

5.1.3.1 Index Sets

$\mathscr{L}$: set of location sites, indexed by $l \in \mathscr{L}$

$\mathscr{O} \subset \mathscr{L}$: set of selectable location sites, indexed by $o \in \mathscr{O}$

$\mathscr{E} \subset \mathscr{O}$: set of existing location sites, indexed by $e \in \mathscr{E}$

$\mathscr{N} \subset \mathscr{O}$: set of potential new location sites, indexed by $n \in \mathscr{N}$

$\mathscr{J} \subset \mathscr{O}$: set of plant sites for production and disassembly-remanufacturing centers, indexed by $j \in \mathscr{J}$

$\mathscr{I} \subset \mathscr{O}$: set of intermediate sites for distribution and collection centers, indexed by $i \in \mathscr{I}$

$\mathscr{S} \subset \mathscr{L}$: set of locations of external suppliers, indexed by $s \in \mathscr{S}$

$\mathscr{K} \subset \mathscr{L}$: set of locations of customers, indexed by $k \in \mathscr{K}$

$\mathscr{U} \subset \mathscr{L}$: set of locations of external subcontractors for disassembly-remanufacturing process, indexed by $u \in \mathscr{U}$

$\mathscr{C}$: set of center types for supply chain processes, indexed by $c \in \mathscr{C}$

$\mathscr{F} \subset \mathscr{C}$: set of center types for forward supply chain processes, indexed by $f \in \mathscr{F}$

$\mathscr{R} \subset \mathscr{C}$: set of center types for reverse supply chain processes, indexed by $r \in \mathscr{R}$

$\mathscr{A} \subset \mathscr{C}$: set of center types at plant sites, indexed by $a \in \mathscr{A}$

$\mathscr{B} \subset \mathscr{C}$: set of center types at intermediate sites, indexed by $b \in \mathscr{B}$

$\mathscr{P}$: set of product types, indexed by $p \in \mathscr{P}$

$\mathscr{G} \subset \mathscr{P}$: set of final products, indexed by $g \in \mathscr{G}$

$\mathscr{M} \subset \mathscr{P}$: set of parts/components, indexed by $m \in \mathscr{M}$

$\mathscr{T}$: set of periods in the planning horizon, indexed by $t \in \mathscr{T}$

Let $\mathscr{L}$ be the set of all location sites, which are classified in so-called selectable and non-selectable location sites. Selectable location sites form the set $\mathscr{O}$, which is a subset of $\mathscr{L}$. These location sites include existing location sites (the set $\mathscr{E}$) and potential new location sites (the set $\mathscr{N}$). At the beginning of the planning horizon, all existing location sites in the set $\mathscr{E}$ are in operation. Capacity can be subsequently shifted from these location sites to potential new location sites in the set $\mathscr{N}$. The set of selectable location sites $\mathscr{L}$ also includes plant sites (the set $\mathscr{J}$) as well as intermediate sites (the set $\mathscr{I}$), which can be either existing or potential new location sites. Note that $\mathscr{E} \cap \mathscr{N} = \emptyset$, $\mathscr{J} \cap \mathscr{I} = \emptyset$, $\mathscr{J} \cup \mathscr{I} = \mathscr{E} \cup \mathscr{N}$ and $\mathscr{O} = (\mathscr{E} \cup \mathscr{N}) \cap (\mathscr{J} \cup \mathscr{I})$.

The second classification group of location sites, the so-called non-selectable location sites form the set $\mathscr{L} \setminus \mathscr{O}$, which includes external suppliers (the set $\mathscr{S}$), customers (the set $\mathscr{K}$) and external subcontractors for the disassembly-remanufacturing process (the set $\mathscr{U}$). These location sites must remain in operation over the time horizon.

Set $\mathscr{C}$ contains all types of centers for supply chain processes. These are categorized into two groups: (1) center types for forward supply chain processes and (2) center types for reverse supply chain processes. Center types for forward supply chain processes form the set $\mathscr{F}$, a subset of $\mathscr{C}$. Whereas, center types for reverse supply chain processes form the set $\mathscr{R}$, which is also a subset of $\mathscr{C}$. In the set of all center types $\mathscr{C}$, center types at plant sites ($\mathscr{A}$) and center types at intermediate sites ($\mathscr{B}$) are also included. Observe that $\mathscr{F} \cap \mathscr{R} = \emptyset$, $\mathscr{A} \cap \mathscr{B} = \emptyset$, $\mathscr{F} \cup \mathscr{R} = \mathscr{A} \cup \mathscr{B}$ and $\mathscr{C} = (\mathscr{F} \cup \mathscr{R}) \cap (\mathscr{A} \cup \mathscr{B})$.

Furthermore, let $\mathscr{P}$ belong to the set of all product types ranging from final products (the set $\mathscr{G}$), to parts/components (the set $\mathscr{M}$), $\mathscr{G} \cap \mathscr{M} = \emptyset$ and $\mathscr{P} = \mathscr{G} \cup \mathscr{M}$. The set of planning time periods, denoted by $\mathscr{T} = \{1, ..., T\}$, is a set of consecutive and integer time periods. There are totally $|\mathscr{T}|$ planning periods. That is $|\mathscr{T}|=T$.

5.1.3.2 Parameters

5.1.3.2.1 Capacity of Location Sites

KO_o^{max} : maximum allowable capacity of selectable location site $o \in \mathscr{O}$

$KI_{o,c}$: initial capacity of center $c \in \mathscr{C}$ at selectable location site $o \in \mathscr{O}$

$KC_{o,c}^{max}$: maximum allowable capacity of center $c \in \mathscr{C}$ at selectable location site $o \in \mathscr{O}$

$KC_{o,c}^{min}$: minimum allowable capacity of center $c \in \mathscr{C}$ at selectable location site $o \in \mathscr{O}$

$KM_{o,c}$: fixed expanding and/or relocating size for capacity of center $c \in \mathscr{C}$ at selectable location site $o \in \mathscr{O}$

$KS^{max}_{s,m,t}$: maximum available capacity of external supplier $s \in \mathscr{S}$ for part/component $m \in \mathscr{M}$ in period $t \in \mathscr{T}$

$KU^{max}_{u,g,t}$: maximum available capacity of disassembly-remanufacturing subcontractor $u \in \mathscr{U}$ for returned final product $g \in \mathscr{G}$ in period $t \in \mathscr{T}$

5.1.3.2.2 Selling Prices

$SC_{o,k,g,t}$: variable price of selling one unit of final product $g \in \mathscr{G}$ from selectable location site $o \in \mathscr{O}$ to customer $k \in \mathscr{K}$ in period $t \in \mathscr{T}$

5.1.3.2.3 Costs

$CB_{s,j,m,t}$: variable cost of purchasing one unit of part/component $m \in \mathscr{M}$ from external supplier $s \in \mathscr{S}$ by plant site $j \in \mathscr{J}$ in period $t \in \mathscr{T}$

$CP_{j,a,g,t}$: variable cost of processing one unit of final product $g \in \mathscr{G}$ by center $a \in \mathscr{A}$ at plant site $j \in \mathscr{J}$ in period $t \in \mathscr{T}$

$CS_{l,u,g,t}$: variable cost of subcontracting one unit of returned final product $g \in \mathscr{G}$ from location site $l \in \mathscr{L}$ by external subcontractor $u \in \mathscr{U}$ in period $t \in \mathscr{T}$

$CT_{l,l',p,t}$: variable cost of shipping one unit of product $p \in \mathscr{P}$ from location site $l \in \mathscr{L}$ to location site $l' \in \mathscr{L}$ in period $t \in \mathscr{T}$

$CF_{o,t}$: fixed cost of operating selectable location site $o \in \mathscr{O}$ in period $t \in \mathscr{T}$

$CC_{e,t}$: fixed cost of closing existing location site $e \in \mathscr{E}$ in period $t \in \mathscr{T}$

$CO_{n,t}$: fixed cost of opening new location site $n \in \mathscr{N}$ in period $t \in \mathscr{T}$

$CFF_{o,c,t}$: fixed cost of operating center $c \in \mathscr{C}$ at selectable location site $o \in \mathscr{O}$ in period $t \in \mathscr{T}$

$CVE_{o,c,t}$: variable cost associated with expanding capacity of center $c \in \mathscr{C}$ at selectable location site $o \in \mathscr{O}$ in period $t \in \mathscr{T}$

$CVR_{e,n,c,t}$: variable cost associated with relocating capacity of center $c \in \mathscr{C}$ from existing location site $e \in \mathscr{E}$ to new location site $n \in \mathscr{N}$ in period $t \in \mathscr{T}$

$CFC_{e,c,t}$: fixed cost of closing center $c \in \mathscr{C}$ at existing location site $e \in \mathscr{E}$ in period $t \in \mathscr{T}$

$CFO_{n,c,t}$: fixed cost of opening center $c \in \mathscr{C}$ at new location site $n \in \mathscr{N}$ in period $t \in \mathscr{T}$

$CDP_{j,a,g,t}$: variable disposal cost per unit of returned final product $g \in \mathscr{G}$ discarded from center $a \in \mathscr{A}$ at plant site $j \in \mathscr{J}$ in period $t \in \mathscr{T}$

5.1.3.2.4 Other Parameters

$DP_{k,g,t}$: demand of final product $g \in \mathscr{G}$ by customer $k \in \mathscr{K}$ in period $t \in \mathscr{T}$

$RC_{k,g,t}$: fraction of final product $g \in \mathscr{G}$ returned from customer $k \in \mathscr{K}$ in period $t \in \mathscr{T}$

$AM_{m,g}$: amount of part/component $m \in \mathscr{M}$ for assembling one unit of final product $g \in \mathscr{G}$

$RM_{m,g}$: amount of part/component $m \in \mathscr{M}$ obtained from disassembling and remanufacturing one unit of returned final product $g \in \mathscr{G}$

$FR_{g,t}$: fraction of returned final product $g \in \mathscr{G}$ satisfying the quality specifications in period $t \in \mathscr{T}$

$FC_{o,c}$: fraction of capacity of center $c \in \mathscr{C}$ allowed in each selectable location site $o \in \mathscr{O}$

$UJ_{j,a,g}$: unit capacity consumption factor of final product $g \in \mathscr{G}$ processed at center $a \in \mathscr{A}$ of plant site $j \in \mathscr{J}$ in period $t \in \mathscr{T}$

$UI_{l,i,b,g}$: unit capacity consumption factor of final product $g \in \mathscr{G}$ shipped from location site $l \in \mathscr{L}$ to center $b \in \mathscr{B}$ at intermediate site $i \in \mathscr{I}$ in period $t \in \mathscr{T}$

IR : interest rate for the time value of money

5.1.3.3 Decision Variables

5.1.3.3.1 Non-Negative Integer

$x_{j,a,g,t}$: amount of final product $g \in \mathscr{G}$ processed by center $a \in \mathscr{A}$ at plant site $j \in \mathscr{J}$ in period $t \in \mathscr{T}$

$y_{l,l',p,t}$: amount of product $p \in \mathscr{P}$ shipped from location site $l \in \mathscr{L}$ to location site $l' \in \mathscr{L}$ in period $t \in \mathscr{T}$

$z_{s,j,m,t}$: amount of part/component $m \in \mathscr{M}$ purchased from external supplier $s \in \mathscr{S}$ by plant site $j \in \mathscr{J}$ in period $t \in \mathscr{T}$

$q_{l,u,g,t}$: amount of returned final product $g \in \mathscr{G}$ subcontracted from location site $l \in \mathscr{L}$ by external subcontractor $u \in \mathscr{U}$ in period $t \in \mathscr{T}$

$w_{o,c,t}$: number of fixed sizes for expanding center $c \in \mathscr{C}$ at selectable location site $o \in \mathscr{O}$ in period $t \in \mathscr{T}$

$v_{e,n,c,t}$: number of fixed sizes for relocating from existing location site $e \in \mathscr{E}$ to new location site $n \in \mathscr{N}$ for center $c \in \mathscr{C}$ in period $t \in \mathscr{T}$

$exp_{o,c,t}$: total amount of the capacity expanded for center $c \in \mathscr{C}$ at selectable location site $o \in \mathscr{O}$ in period $t \in \mathscr{T}$

$mov_{o,o',c,t}$: total amount of the capacity relocated from selectable location site $o \in \mathscr{O}$ to selectable location site $o' \in \mathscr{O}$ for center $c \in \mathscr{C}$ in period $t \in \mathscr{T}$

5.1.3.3.2 Binary

$$\varphi_{o,t} = \begin{cases} 1 & \text{if selectable location site } o \in \mathscr{O} \text{ is operated in period } t \in \mathscr{T}, \\ 0 & \text{otherwise} \end{cases}$$

$$\delta_{o,c,t} = \begin{cases} 1 & \text{if center } c \in \mathscr{C} \text{ is operated at selectable location site } o \in \mathscr{O} \text{ in period } t \in \mathscr{T}, \\ 0 & \text{otherwise} \end{cases}$$

$$\rho_{e,c} = \begin{cases} 1 & \text{if center } c \in \mathscr{C} \text{ is expanded at existing location site } e \in \mathscr{E} \text{ during the planning horizon}, \\ 0 & \text{otherwise} \end{cases}$$

5.1.4 Formulation of the Model

The proposed mixed-integer linear programming (MILP) model represents a complex mathematical relationship between different entities. Hence, before detailing the model, it was decided to provide a simple overview of this model (see Table 5.1), as well as the relation of our assumptions as presented in section 5.1.2 to the model formulation (see Table 5.2). The following is the full mathematical formulation of the model.

5.1.4.1 Objective Function

The objective function is to maximize the net present value (NPV) of cash flows to overlook profitable opportunity for the long-term investment. The NPV here includes the time value of money and profit (= total revenue - total cost). The objective function is formulated as below:

$$\textbf{MAX NPV} = \sum_{t \in \mathscr{T}} \left(\frac{\left(\overbrace{\sum_{o \in \mathscr{O}} \sum_{k \in \mathscr{K}} \sum_{g \in \mathscr{G}} SC_{o,k,g,t} y_{o,k,g,t}}^{\text{Total Revenue}} - \overbrace{TOC_t^{total}}^{\text{Total Cost}} \right)}{(1+IR)^t} \right) \tag{5.1}$$

The following equation is the sum of all costs (i.e. the total cost) in period $t \in \mathscr{T}$.

$$TOC_t^{total} = TOC_t^1 + TOC_t^2 + TOC_t^3 + TOC_t^4 + TOC_t^5 + TOC_t^6\ , \quad \forall t \in \mathscr{T} \tag{5.2}$$

	Description	Equation No.
Objective function	• Maximize the net present value (NPV) of cash flows	5.1
Constraints		
Forward supply chain	• Ensure enough parts/components $m \in \mathscr{M}$ for manufacturing process	5.10
	• Control the shipments between forward facilities to ensure enough final products $g \in \mathscr{G}$ to meet the customer demands	5.11 - 5.13
Reverse supply chain	• Control the shipments of returned final products $g \in \mathscr{G}$ between reverse facilities	5.14 - 5.16
	• Control the shipments of reusable parts/components $m \in \mathscr{M}$ from disassembly-remanufacturing process	5.17 and 5.18
Capacity, relocation and expansion	• Decide on the capacity relocation and expansion at any existing location site $e \in \mathscr{E}$	5.19 - 5.22
	• Decide on the capacity increase at any new location site $n \in \mathscr{N}$	5.23 and 5.24
	• Limit respectively the size for relocating and expanding capacity	5.25 - 5.26
	• Limit the maximum capacity for forward and reverse supply chain processes	5.27, 5.28, 5.30 and 5.31
	• Specify the minimum capacity for forward and reverse supply chain processes	5.29 and 5.32
	• Limit respectively the capacity of external suppliers and disassembly-remanufacturing subcontractors	5.33 and 5.34
	• Establish the capacity expansion condition	5.40
Closing and opening of facilities	• Establish the conditions for closing and opening of facilities	5.35 - 5.39

TABLE 5.1: Overview of the model explanation

Assumptions	Equation No.	Assumptions	Equation No.	Assumptions	Equation No.
A1	5.10	**B10**	5.14	**E1**	5.35 - 5.39
B5	5.10 and 5.11	**B11**	5.18	**D1**	5.21
B6	5.16 and 5.17	**C1**	5.10	**D2**	5.19
B7	5.12	**C2**	5.9 and 5.17	**D3**	5.23
B8	5.15	**C3**	5.12	**D4**	5.40
B9	5.13	**C4**	5.15	**F2**	5.1

Table 5.2: Connections between assumptions and model formulation

5.1.4.2 Total Cost $\left(TOC_t^{total}\right)$

The total cost is an important factor in optimizing supply chain. The profit rises as the total cost declines. Various costs associated with the network are shown in the constraints below.

5.1.4.2.1 Variable Purchasing, Processing, Subcontracting and Transportation Costs (TOC_t^1)

The first component in equation 5.3 is the costs of purchasing all the parts/components $m \in \mathscr{M}$ from external suppliers $s \in \mathscr{S}$ in period $t \in \mathscr{T}$ $\left(z_{s,j,m,t}\right)$. The second component is the costs of processing all the final products $g \in \mathscr{G}$ by centers $a \in \mathscr{A}$ at plant sites $j \in \mathscr{J}$ in period $t \in \mathscr{T}$ $\left(x_{j,a,g,t}\right)$.

$$TOC_t^1 = \sum_{s\in\mathscr{S}} \sum_{j\in\mathscr{J}} \sum_{m\in\mathscr{M}} CB_{s,j,m,t} z_{s,j,m,t} + \sum_{j\in\mathscr{J}} \sum_{a\in\mathscr{A}} \sum_{g\in\mathscr{G}} CP_{j,a,g,t} x_{j,a,g,t}$$
$$+ \sum_{l\in\mathscr{L}} \sum_{u\in\mathscr{U}} \sum_{g\in\mathscr{G}} CS_{l,u,g,t} q_{l,u,g,t} + \sum_{l\in\mathscr{L}} \sum_{l'\in\mathscr{L}} \sum_{p\in\mathscr{P}} CT_{l,l',p,t} y_{l,l',p,t}\ , \quad \forall t \in \mathscr{T} \qquad (5.3)$$

The third component is the costs of disassembling and remanufacturing all the reusable parts/components $m \in \mathscr{M}$ by external subcontractors $u \in \mathscr{U}$ in period $t \in \mathscr{T}$ $\left(q_{l,u,g,t}\right)$. The last component is the costs of transporting all types of products $p \in \mathscr{P}$

from location sites $l \in \mathscr{L}$ to location sites $l' \in \mathscr{L}$ in period $t \in \mathscr{T}$ $\left(y_{l,l',p,t}\right)$.

5.1.4.2.2 Variable Costs of Capacity Relocation and Expansion (TOC_t^2)

In equation 5.4, the first component is the variable costs of expanding the capacity $exp_{o,c,t}$ of one or more centers $c \in \mathscr{C}$ at selectable location sites $o \in \mathscr{O}$ in period $t \in \mathscr{T}$.

$$TOC_t^2 = \sum_{o \in \mathscr{O}} \sum_{c \in \mathscr{C}} CVE_{o,c,t} exp_{o,c,t} + \sum_{e \in \mathscr{E}} \sum_{n \in \mathscr{N}} \sum_{c \in \mathscr{C}} CVR_{e,n,c,t} mov_{e,n,c,t} \;, \quad \forall t \in \mathscr{T} \tag{5.4}$$

The costs of relocating the capacity $mov_{e,n,c,t}$ from one or more centers $c \in \mathscr{C}$ at existing location sites $e \in \mathscr{E}$ to new location sites $n \in \mathscr{N}$ in period $t \in \mathscr{T}$ is the second component.

5.1.4.2.3 Fixed Costs of Operating Facilities (TOC_t^3)

The first component in the following equation is the costs of operating one or more selectable location sites $o \in \mathscr{O}$ in period $t \in \mathscr{T}$. The costs of operating one or more centers $c \in \mathscr{C}$ at selectable location sites $o \in \mathscr{O}$ in period $t \in \mathscr{T}$ are the second component.

$$TOC_t^3 = \sum_{o \in \mathscr{O}} CF_{o,t} \varphi_{o,t} + \sum_{o \in \mathscr{O}} \sum_{c \in \mathscr{C}} CFF_{o,c,t} \delta_{o,c,t} \;, \quad \forall t \in \mathscr{T} \tag{5.5}$$

5.1.4.2.4 Fixed Costs of Closing Facilities (TOC_t^4)

The costs of closing one or more existing location sites $e \in \mathscr{E}$, and closing one or more centers $c \in \mathscr{C}$ at existing location sites $e \in \mathscr{E}$ in the first period are correspondingly the first and second components in equation 5.6.

$$TOC_1^4 = \sum_{e \in \mathscr{E}} CC_{e,1} \left(1 - \varphi_{e,1}\right) + \sum_{e \in \mathscr{E}} \sum_{c \in \mathscr{C}} CFC_{e,c,1} \left(1 - \delta_{e,c,1}\right) \tag{5.6}$$

$$TOC_t^4 = \sum_{e \in \mathscr{E}} CC_{e,t} \left(\varphi_{e,t-1} - \varphi_{e,t}\right) + \sum_{e \in \mathscr{E}} \sum_{c \in \mathscr{C}} CFC_{e,c,t} \left(\delta_{e,c,t-1} - \delta_{e,c,t}\right) \ , \quad \forall t \in \mathscr{T} \setminus \{1\} \tag{5.7}$$

In equation (5.7), the first and second components are the costs of closing existing location sites $e \in \mathscr{E}$, and closing one or more centers $c \in \mathscr{C}$ at existing location sites $e \in \mathscr{E}$ in a later period $t \in \mathscr{T} \setminus \{1\}$, respectively.

5.1.4.2.5 Fixed Costs of Opening Facilities (TOC_t^5)

The first and second components in the equation below are respectively the costs of opening one or more new location sites $n \in \mathscr{N}$, and opening one or more centers $c \in \mathscr{C}$ at new location sites $n \in \mathscr{N}$ in period $t \in \mathscr{T}$.

$$TOC_t^5 = \sum_{n \in \mathscr{N}} CO_{n,t} \left(\varphi_{n,t} - \varphi_{n,t-1}\right) + \sum_{n \in \mathscr{N}} \sum_{c \in \mathscr{C}} CFO_{n,c,t} \left(\delta_{n,c,t} - \delta_{n,c,t-1}\right) \ , \quad \forall t \in \mathscr{T} \tag{5.8}$$

5.1.4.2.6 Variable Disposal Costs (TOC_t^6)

The disposal costs in period $t \in \mathscr{T}$ (5.9) are computed based on a fraction $\left(1 - FR_{g,t}\right)$ of returned products from the disassembly-remanufacturing process that plant sites $j \in \mathscr{J}$ send for disposal.

$$TOC_t^6 = \sum_{j \in \mathscr{J}} \sum_{a \in \mathscr{A}} \sum_{g \in \mathscr{G}} CDP_{j,a,g,t} \left(1 - FR_{g,t}\right) x_{j,a,g,t} \ , \quad \forall t \in \mathscr{T} \tag{5.9}$$

Subject to constraints (5.10) - (5.36).

5.1.4.3 Constraints

In this section, the constraints are divided into five categories: forward flow constraints, reverse flow constraints, capacity constraints, logical constraints, and non-negativity and integrity constraints.

5.1.4.3.1 Forward Flow Constraints

Constraints (5.10) provide the required quantity of each part/component $m \in \mathscr{M}$ for manufacturing the final product $g \in \mathscr{G}$ at the production center $a \in \mathscr{F}$ of any plant site $j \in \mathscr{J}$.

$$\sum_{s \in \mathscr{S}} z_{s,j,m,t} + \sum_{j' \in \mathscr{J}} y_{j',j,m,t} + \sum_{u \in \mathscr{U}} y_{u,j,m,t} = \sum_{g \in \mathscr{G}} x_{j,a,g,t} AM_{m,g} \;, \quad \forall j \in \mathscr{J} \;,\; a \in \mathscr{F},\; m \in \mathscr{M},\; t \in \mathscr{T} \tag{5.10}$$

These constraints make sure that the summation of the number of units to product in period $t \in \mathscr{T}$ $\left(\sum_{g \in \mathscr{G}} x_{j,a,g,t}\right)$ multiplied by the quantity of each part/component $m \in \mathscr{M}$ needed to produce one unit of final product $g \in \mathscr{G}$ $(AM_{m,g})$, is equal to the total amount of each part/component $m \in \mathscr{M}$ delivered from one or more external suppliers $s \in \mathscr{S}$ in period $t \in \mathscr{T}$ $\left(\sum_{s \in \mathscr{S}} z_{s,j,m,t}\right)$, one or more plant sites $j' \in \mathscr{J}$ by their disassembly-remanufacturing centers in period $t \in \mathscr{T}$ $\left(\sum_{j' \in \mathscr{J}} y_{j',j,m,t}\right)$ and one or more disassembly-remanufacturing subcontractors $u \in \mathscr{U}$ in period $t \in \mathscr{T}$ $\left(\sum_{u \in \mathscr{U}} y_{u,j,m,t}\right)$.

The constraints below assure the connection between the manufacturing process at each production center $a \in \mathscr{F}$, and the outbound flow to distribution centers and directly to customers.

$$x_{j,a,g,t} = \sum_{i \in \mathscr{I}} y_{j,i,g,t} + \sum_{k \in \mathscr{K}} y_{j,k,g,t} \;, \quad \forall j \in \mathscr{J},\; a \in \mathscr{F} \;,\; g \in \mathscr{G},\; t \in \mathscr{T} \tag{5.11}$$

These constraints are the constraints ensuring that the amount of each final product $g \in \mathscr{G}$ manufactured in period $t \in \mathscr{T}$ $\left(x_{j,a,g,t}\right)$ is equal to all the amount distributed to one or more intermediate sites $i \in \mathscr{I}$ for further distribution process in period $t \in \mathscr{T}$ $\left(\sum_{i \in \mathscr{I}} y_{j,i,g,t}\right)$, and directly to one or more customers $k \in \mathscr{K}$ in period $t \in \mathscr{T}$ $\left(\sum_{k \in \mathscr{K}} y_{j,k,g,t}\right)$.

Constraints (5.12) guarantee that the distribution center $b \in \mathscr{F}$ at any intermediate site $i \in \mathscr{I}$ must receive a sufficient amount of each final product $g \in \mathscr{G}$ from the manufacturing process to meet the demands.

$$\sum_{j\in\mathscr{J}} y_{j,i,g,t} = \sum_{k\in\mathscr{K}} y_{i,k,g,t}\ , \quad \forall i\in\mathscr{I}\ ,\ g\in\mathscr{G},\ t\in\mathscr{T} \tag{5.12}$$

The inbound flow from the manufacturing process at one or more plant sites $j \in \mathscr{J}$ to the distribution center located at any intermediate site $i \in \mathscr{I}$ in period $t \in \mathscr{T}$ $\left(\sum_{j\in\mathscr{J}} y_{j,i,g,t}\right)$ must be equal to the outbound flow to one or more customers $k \in \mathscr{K}$ in period $t \in \mathscr{T}$ $\left(\sum_{k\in\mathscr{K}} y_{i,k,g,t}\right)$.

Constraints 5.13 satisfy the demand requirement of any customer $k \in \mathscr{K}$ in period $t \in \mathscr{T}$.

$$\sum_{j\in\mathscr{J}} y_{j,k,g,t} + \sum_{i\in\mathscr{I}} y_{i,k,g,t} = DP_{k,g,t}\ , \quad \forall k\in\mathscr{K}\ ,\ g\in\mathscr{G},\ t\in\mathscr{T} \tag{5.13}$$

The above constraints ensure that the total sales volume of each final product $g \in \mathscr{G}$ for any customer $k \in \mathscr{K}$ must be equal to the demands of that customer $(DP_{k,g,t})$.

5.1.4.3.2 Reverse Flow Constraints

Constraints 5.14 require that the predefined return rate of each final product $g \in \mathscr{G}$ is used as the return amount (i.e., the left hand side of constraints 5.14) from each customer $k \in \mathscr{K}$.

$$\left(\sum_{j\in\mathscr{J}} y_{j,k,g,t} + \sum_{i\in\mathscr{I}} y_{i,k,g,t}\right) RC_{k,g,t} = \sum_{i\in\mathscr{I}} y_{k,i,g,t} + \sum_{j\in\mathscr{J}} y_{k,j,g,t} + \sum_{u\in\mathscr{U}} q_{k,u,g,t}\ , \tag{5.14}$$
$$\forall k\in\mathscr{K},\ g\in\mathscr{G},\ t\in\mathscr{T}$$

This return amount is computed based on a fraction $(RC_{k,g,t})$ of each final product $g \in \mathscr{G}$ returned from a customer $k \in \mathscr{K}$.

Conditions 5.15 and 5.16 are established to assure the connection between the collection center and associated inbound and outbound flows to and from the collection center.

The return volume of each final product $g \in \mathscr{G}$ from all customers $k \in \mathscr{K}$ to the collection center for further disassembly and remanufacturing is assured by constraints 5.15.

$$\sum_{k \in \mathscr{K}} y_{k,i,g,t} = \sum_{j \in \mathscr{J}} y_{i,j,g,t} + \sum_{u \in \mathscr{U}} q_{i,u,g,t} \ , \quad \forall i \in \mathscr{I}, \ g \in \mathscr{G}, \ t \in \mathscr{T} \tag{5.15}$$

Constraints 5.15 are the constraints to ensure that returned final products $g \in \mathscr{G}$ from one or more customers $k \in \mathscr{K}$ to the collection center located at any intermediate site $i \in \mathscr{I}$ in period $t \in \mathscr{T}$ $\left(\sum_{k \in \mathscr{K}} y_{k,i,g,t}\right)$ must be equal to returned final products $g \in \mathscr{G}$ that leave from the collection center to one or more disassembly-remanufacturing centers located at plant sites $j \in \mathscr{J}$ in period $t \in \mathscr{T}$ $\left(\sum_{j \in \mathscr{J}} y_{i,j,g,t}\right)$ and to one or more disassembly-remanufacturing subcontractors $u \in \mathscr{U}$ in period $t \in \mathscr{T}$ $\left(\sum_{u \in \mathscr{U}} q_{i,u,g,t}\right)$.

The volume of each final product $g \in \mathscr{G}$ returned for the disassembly-remanufacturing process at any plant site $j \in \mathscr{J}$ is ensured by constraints 5.16.

$$\sum_{k \in \mathscr{K}} y_{k,j,g,t} + \sum_{i \in \mathscr{I}} y_{i,j,g,t} = x_{j,a,g,t} \ , \quad \forall j \in \mathscr{J}, \ a \in \mathscr{R}, \ g \in \mathscr{G}, \ t \in \mathscr{T} \tag{5.16}$$

The inbound flow from one or more customers $k \in \mathscr{K}$ $\left(\sum_{k \in \mathscr{K}} y_{k,j,g,t}\right)$, and from one or more collection centers located at intermediate sites $i \in \mathscr{I}$ $\left(\sum_{i \in \mathscr{I}} y_{i,j,g,t}\right)$ to the disassembly-remanufacturing center $a \in \mathscr{R}$ located at any plant site $j \in \mathscr{J}$ in period $t \in \mathscr{T}$ must be equal to the amount of disassembled and remanufactured units in period $t \in \mathscr{T}$ $\left(x_{j,a,g,t}\right)$.

Likewise, constraints 5.17 establish the requirement for the total outgoing flow of reusable parts/components $m \in \mathscr{M}$ from the disassembly-remanufacturing center $a \in \mathscr{R}$.

$$\begin{aligned} &\sum_{g \in \mathscr{G}} \left[FR_{g,t} \left(x_{j,a,g,t} RM_{m,g}\right)\right] = \sum_{j' \in \mathscr{J}} y_{j,j',m,t} \ , \\ &\forall j \in \mathscr{J}, \ a \in \mathscr{R}, \ m \in \mathscr{M}, \ t \in \mathscr{T} \end{aligned} \tag{5.17}$$

These constraints stipulate that reusable parts/components $m \in \mathscr{M}$ that leave from the disassembly-remanufacturing center located at any plant site $j \in \mathscr{J}$ in period

$t \in \mathscr{T}$ $\left(\sum_{j' \in \mathscr{J}} y_{j,j',m,t}\right)$ must be equal to the reusable quantity, i.e. the number of parts/components $m \in \mathscr{M}$ obtained from disassembling and remanufacturing the returned final products $g \in \mathscr{G}$ in period $t \in \mathscr{T}$ $\left(\sum_{g \in \mathscr{G}} x_{j,a,g,t} RM_{m,g}\right)$ multiplied by a fraction $FR_{g,t}$ of part/component satisfying the quality specifications in period $t \in \mathscr{T}$.

Finally, the flow of reusable parts/components $m \in \mathscr{M}$ from disassembling and remanufacturing by any external subcontractor $u \in \mathscr{U}$ is ensured by the following constraints.

$$\sum_{g \in \mathscr{G}} \left\{ FR_{g,t} \left[\left(\sum_{k \in \mathscr{K}} q_{k,u,g,t} + \sum_{i \in \mathscr{I}} q_{i,u,g,t} \right) RM_{m,g} \right] \right\} = \sum_{j \in \mathscr{J}} y_{u,j,m,t} \ , \qquad (5.18)$$
$$\forall u \in \mathscr{U}, \ m \in \mathscr{M}, \ t \in \mathscr{T}$$

Constraints (5.18) enforce that the reusable items, which are the number of parts/components $m \in \mathscr{M}$ disassembled and remanufactured from returned final products $g \in \mathscr{G}$ that are sent from one or more customers $k \in \mathscr{K}$, and from one or more intermediates sites $i \in \mathscr{I}$ by the collection process at their collection centers to any disassembly-remanufacturing subcontractor $u \in \mathscr{U}$ in period $t \in \mathscr{T}$ (i.e., the left hand side of constraints (5.18)) multiplied by a fraction $FR_{g,t}$, must be equal to all the reusable parts/components $m \in \mathscr{M}$ left from that subcontractor to one or more plant sites $j \in \mathscr{J}$ for the manufacturing process at their production centers in period $t \in \mathscr{T}$ $\left(\sum_{j \in \mathscr{J}} y_{u,j,m,t}\right)$.

5.1.4.3.3 Capacity Constraints

5.1.4.3.3.1 Capacity Relocation and Expansion Constraints

Constraints (5.19) - (5.26) ensure that only feasible capacity relocation and expansion can take place during the planning horizon.

It is possible to expand the capacity at some existing location sites $e \in \mathscr{E}$. Constraints (5.19) limit the available capacity for further expansion at each center $c \in \mathscr{C}$ of any existing location site $e \in \mathscr{E}$.

$$\sum_{t \in \mathscr{T}} exp_{e,c,t} \leq \left(KC^{max}_{e,c} - KI_{e,c}\right) \rho_{e,c} \ , \quad \forall e \in \mathscr{E}, \ c \in \mathscr{C} \qquad (5.19)$$

The expanded capacity $\sum_{t\in\mathscr{T}} exp_{e,c,t}$ of each center $c \in \mathscr{C}$ must not exceed the maximum capacity of that center allowed at any existing location site $e \in \mathscr{E}$ $\left(KC_{e,c}^{max}\right)$ minus the initial capacity of that center for processing the final products at its existing location site $(KI_{e,c})$.

Constraints (5.20) restrict the full expanded capacity at any existing location site $e \in \mathscr{E}$.

$$\sum_{c\in\mathscr{C}} \left[FC_{e,c} \left(\sum_{\tau=1}^{t} exp_{e,c,\tau} + KI_{e,c}\rho_{e,c} \right) \right] \leq KO_e^{max} \varphi_{e,t} \ , \qquad \forall e \in \mathscr{E}, \ t \in \mathscr{T} \tag{5.20}$$

The maximum allowable capacity of any existing location site $e \in \mathscr{E}$ $\left(KO_e^{max}\right)$ must be greater than or equal to the expanded capacity of all centers $c \in \mathscr{C}$ located at that existing location site plus the initial capacity of all centers $c \in \mathscr{C}$ at that existing location site.

It can be noticed that a fraction $FC_{e,c}$ is determined as the amount of capacity of each center $c \in \mathscr{C}$ allowed for its existing location site $e \in \mathscr{E}$. Observe that $(2 - FC_{e,c})\, KC_{e,c}^{max} \leq KO_e^{max}$.

Constraints (5.21) limit the allowable capacity that can be relocated from each center $c \in \mathscr{C}$ at any existing location site $e \in \mathscr{E}$ to one or more new location sites $n \in \mathscr{N}$.

$$\sum_{n\in\mathscr{N}} \sum_{t\in\mathscr{T}} mov_{e,n,c,t} \leq KI_{e,c} \left(1 - \rho_{e,c}\right) \ , \quad \forall e \in \mathscr{E}, \ c \in \mathscr{C} \tag{5.21}$$

Center $c \in \mathscr{C}$ cannot relocate the capacity over its initial capacity $(KI_{e,c})$.

Moreover, constraints (5.19) together with (5.21) make sure that an existing capacity can either relocate to new sites $\left(\rho_{e,c} = 0\right)$ or expand its capacity $\left(\rho_{e,c} = 1\right)$.

Constraints (5.22) make sure that a center $c \in \mathscr{C}$ at any existing location site $e \in \mathscr{E}$ can have its capacity relocated to new location site $n \in \mathscr{N}$, if it is operating.

$$\sum_{n\in\mathscr{N}} \sum_{\tau=1}^{t} mov_{e,n,c,\tau} \leq KI_{e,c}\delta_{e,c,t} \ , \quad \forall e \in \mathscr{E}, \ c \in \mathscr{C}, \ t \in \mathscr{T} \tag{5.22}$$

Constraints (5.23) impose that by period $t \in \mathscr{T}$ center $c \in \mathscr{C}$ has been established at the new location site $n \in \mathscr{N}$ for expanding the additional capacity and/or relocating the capacity from one or more existing location sites $e \in \mathscr{E}$.

$$\sum_{\tau=1}^{t} exp_{n,c,\tau} + \sum_{e \in \mathscr{E}} \sum_{\tau=1}^{t} mov_{e,n,c,\tau} \leq KC_{n,c}^{max} \delta_{n,c,t} \ , \quad \forall n \in \mathscr{N}, \ c \in \mathscr{C}, \ t \in \mathscr{T} \tag{5.23}$$

The expanded capacity $\sum_{\tau=1}^{t} exp_{n,c,\tau}$ of each center $c \in \mathscr{C}$ at any new location site $n \in \mathscr{N}$ and the capacity $\sum_{e \in \mathscr{E}} \sum_{\tau=1}^{t} mov_{e,n,c,\tau}$ relocated from one or more existing location sites $e \in \mathscr{E}$ to that new location site must not exceed its maximum capacity, which is the maximum allowable capacity of that center at its new location site $\left(KC_{n,c}^{max}\right)$.

The additional capacity allowed at any new location site $n \in \mathscr{N}$ is restricted by constraints (5.24).

$$\sum_{c \in \mathscr{C}} \left[FC_{n,c} \left(\sum_{\tau=1}^{t} exp_{n,c,\tau} + \sum_{e \in \mathscr{E}} \sum_{\tau=1}^{t} mov_{e,n,c,\tau} \right) \right] \leq KO_{n}^{max} \varphi_{n,t} \ , \quad \forall n \in \mathscr{N}, \ t \in \mathscr{T} \tag{5.24}$$

This set of constraints assures that the maximum capacity allowable at any new location site $n \in \mathscr{N}$ $\left(KO_{n}^{max}\right)$ must be higher than or equal to the sum of the capacity of centers $c \in \mathscr{C}$ expanded at that new location site and the capacity relocated from one or more existing location sites $e \in \mathscr{E}$ to that new location site.

It can be seen that a fraction $FC_{n,c}$ is used as the amount of capacity of each center $c \in \mathscr{C}$ allowed for its new location site $n \in \mathscr{N}$. Note that $(2 - FC_{n,c})\, KC_{n,c}^{max} \leq KO_{n}^{max}$.

For each time period $t \in \mathscr{T}$, the allowable amount of capacity added to every center $c \in \mathscr{C}$ of any selectable location site $o \in \mathscr{O}$ is bounded by constraints (5.25) and (5.26).

Constraints (5.25) limit the allowable expansion amount of capacity for every center $c \in \mathscr{C}$ at any selectable location site $o \in \mathscr{O}$ in each period $t \in \mathscr{T}$.

$$exp_{o,c,t} = w_{o,c,t} KM_{o,c} \ , \quad \forall o \in \mathscr{O}, \ c \in \mathscr{C}, \ t \in \mathscr{T} \tag{5.25}$$

The expanded capacity $exp_{o,c,t}$ is confined by the size of fixed capacity for expansion and/or relocation $KM_{o,c}$ multiplied by a number of fixed-capacity sizes for expanding $w_{o,c,t}$ in each period $t \in \mathscr{T}$.

Constraints 5.26 define the allowable amount of capacity for relocating from every center $c \in \mathscr{C}$ at any existing location site $e \in \mathscr{E}$ to whatever new location site $n \in \mathscr{N}$ in each period $t \in \mathscr{T}$.

$$mov_{e,n,c,t} = v_{e,n,c,t} KM_{e,c} \;, \quad \forall e \in \mathscr{E},\; n \in \mathscr{N},\; c \in \mathscr{C},\; t \in \mathscr{T} \tag{5.26}$$

The relocated capacity $mov_{e,n,c,t}$ is restricted by the size of fixed capacity for expansion and/or relocation $KM_{e,c}$ multiplied by the number of fixed-capacity sizes for relocating $v_{e,n,c,t}$ in each period $t \in \mathscr{T}$.

5.1.4.3.3.2 Capacity Constraints of Plant Sites

Inequality 5.27 and 5.28 assure that the capacity for processing all final products $g \in \mathscr{G}$ at any plant site $j \in \mathscr{J}$ is not exceeded.

Constraints 5.27 ensure that the processing amount of each center $a \in \mathscr{A}$ at any existing plant site $j \in \mathscr{E}$ must not be above its available capacity.

$$\sum_{g \in \mathscr{G}} UJ_{j,a,g}\, x_{j,a,g,t} \leq KI_{j,a}\delta_{j,a,t} + \sum_{\tau=1}^{t} exp_{j,a,\tau} - \sum_{j' \in \mathscr{N}} \sum_{\tau=1}^{t} mov_{j,j',a,\tau} \;, \quad \forall j \in \mathscr{E},\; a \in \mathscr{A},\; t \in \mathscr{T} \tag{5.27}$$

This available capacity is limited by the sum of the initial capacity ($KI_{j,a}$) and the expanded capacity $\left(\sum_{\tau=1}^{t} exp_{j,a,\tau}\right)$ minus the capacity relocated to one or more new plant sites $\left(\sum_{j' \in \mathscr{N}} \sum_{\tau=1}^{t} mov_{j,j',a,\tau}\right)$.

Likewise, constraints 5.28 guarantee that the processing amount at each center $a \in \mathscr{A}$ of any new plant site $j \in \mathscr{N}$ must not exceed the available capacity of that center.

$$\sum_{g \in \mathscr{G}} UJ_{j,a,g}\, x_{j,a,g,t} \leq \sum_{\tau=1}^{t} exp_{j,a,\tau} + \sum_{j' \in \mathscr{E}} \sum_{\tau=1}^{t} mov_{j',j,a,\tau} \;, \quad \forall j \in \mathscr{N},\; a \in \mathscr{A},\; t \in \mathscr{T} \tag{5.28}$$

The capacity available for processing the final products at each center $a \in \mathscr{A}$ of any new plant site $j \in \mathscr{N}$ is the sum of the expanded capacity $\left(\sum_{\tau=1}^{t} exp_{j,a,\tau}\right)$ and the capacity relocated from one or more existing plant sites $\left(\sum_{\tau=1}^{t} mov_{j',j,a,\tau}\right)$.

Constraints 5.29 impose that each center $a \in \mathscr{A}$ at any plant site $j \in \mathscr{J}$ must be operated above its minimum allowable capacity.

$$\sum_{g \in \mathscr{G}} UJ_{j,a,g}\, x_{j,a,g,t} \geq KC_{j,a}^{min} \delta_{j,a,t} \ , \quad \forall j \in \mathscr{J}, \ a \in \mathscr{A}, \ t \in \mathscr{T} \tag{5.29}$$

It should be noted from constraints 5.27 - 5.29 that the processing amount is the summation of all final products to be processed multiplied by $UJ_{j,a,g}$, which is a unit factor of measuring the capacity consumed for each final product $g \in \mathscr{G}$ at any center $a \in \mathscr{A}$.

5.1.4.3.3.3 Capacity Constraints of Intermediate Sites

Conditions 5.30 and 5.31 ensure that the inbound flow of all final products $g \in \mathscr{G}$ to any intermediate site $i \in \mathscr{I}$ must not exceed the maximum capacity of that intermediate site.

Constraints 5.30 stipulate that the delivery of all final products $g \in \mathscr{G}$ to each center $b \in \mathscr{B}$ at any existing intermediate site $i \in \mathscr{E}$ cannot be more than the capacity obtainable for that center.

$$\sum_{l \in \mathscr{L}} \sum_{g \in \mathscr{G}} UI_{l,i,b,g}\, y_{l,i,g,t} \leq KI_{i,b} \delta_{i,b,t} + \sum_{\tau=1}^{t} exp_{i,b,\tau} - \sum_{i' \in \mathscr{N}} \sum_{\tau=1}^{t} mov_{i,i',b,\tau} \ , \quad \forall i \in \mathscr{E}, \ b \in \mathscr{B}, \ t \in \mathscr{T} \tag{5.30}$$

This obtainable capacity is restricted by the sum of the initial capacity $(KI_{i,b})$ and the expanded capacity $\left(\sum_{\tau=1}^{t} exp_{i,b,\tau}\right)$ minus the capacity shifted to one or more new intermediate sites $\left(\sum_{i' \in \mathscr{N}} \sum_{\tau=1}^{t} mov_{i,i',b,\tau}\right)$.

Constraints 5.31 enforce that the quantity of all final products $g \in \mathscr{G}$ sent to each center $b \in \mathscr{B}$ at any new intermediate site $i \in \mathscr{N}$ cannot exceed its obtainable capacity.

$$\sum_{l \in \mathscr{L}} \sum_{g \in \mathscr{G}} UI_{l,i,b,g}\, y_{l,i,g,t} \leq \sum_{\tau=1}^{t} exp_{i,b,\tau} + \sum_{i' \in \mathscr{E}} \sum_{\tau=1}^{t} mov_{i',i,b,\tau} \ , \quad \forall i \in \mathscr{N}, \ b \in \mathscr{B}, \ t \in \mathscr{T} \tag{5.31}$$

The capacity obtainable for the quantity sent to each center $b \in \mathscr{B}$ at any new intermediate site $i \in \mathscr{N}$ is the sum of the expanded capacity $\left(\sum_{\tau=1}^{t} exp_{i,b,\tau}\right)$ and the capacity shifted from one or more existing intermediate sites $\left(\sum_{i' \in \mathscr{E}} \sum_{\tau=1}^{t} mov_{i',i,b,\tau}\right)$.

Constraints (5.32) guarantee that the amount of final products $g \in \mathscr{G}$ transported to each center $b \in \mathscr{B}$ at any intermediate site $i \in \mathscr{I}$ must be greater than the minimum allowable capacity of that center.

$$\sum_{l \in \mathscr{L}} \sum_{g \in \mathscr{G}} UI_{l,i,b,g}\, y_{l,i,g,t} \geq KC_{i,b}^{min} \delta_{i,b,t} \ , \quad \forall i \in \mathscr{I}, \ b \in \mathscr{B}, \ t \in \mathscr{T} \tag{5.32}$$

It should be observed from constraints (5.30) - (5.32) that the amount delivered is the summation of all final products to be delivered multiplied by $UJ_{l,i,b,g}$, which is a unit factor of measuring the capacity consumed for each final product $g \in \mathscr{G}$ at any center $b \in \mathscr{B}$.

5.1.4.3.3.4 Capacity Constraints of External Suppliers

Constraints (5.33) indicate the maximum available capacity of each external supplier $s \in \mathscr{S}$. Each external supplier $s \in \mathscr{S}$ cannot deliver its parts/components $m \in \mathscr{M}$ $\left(z_{s,j,m,t}\right)$ to all the plant sites $j \in \mathscr{S}$ for manufacturing the final products more than its maximum capacity $KS_{s,m,t}^{max}$.

$$\sum_{j \in \mathscr{J}} z_{s,j,m,t} \leq KS_{s,m,t}^{max} \ , \quad \forall s \in \mathscr{S}, \ m \in \mathscr{M}, \ t \in \mathscr{T} \tag{5.33}$$

5.1.4.3.3.5 Capacity Constraints of External Disassembly-Remanufacturing Subcontractors

For disassembly-remanufacturing subcontractors $u \in \mathscr{U}$, their subcontracting to retrieve reusable parts/components cannot exceed their maximum available capacity $KU_{u,g,t}^{max}$.

$$\sum_{k \in \mathscr{K}} y_{k,u,g,t} + \sum_{i \in \mathscr{I}} y_{i,u,g,t} \leq KU_{u,g,t}^{max} \ , \quad \forall u \in \mathscr{U}, \ g \in \mathscr{G}, \ t \in \mathscr{T} \tag{5.34}$$

5.1.4.3.4 Logical Constraints

Condition (5.35) ensures that there is no center $c \in \mathscr{C}$ operated at the selectable location site $o \in \mathscr{O}$, if the selectable location site $o \in \mathscr{O}$ is not active.

$$\varphi_{o,t} \geq \delta_{o,c,t} \ , \quad \forall o \in \mathscr{O}, \ c \in \mathscr{C}, \ t \in \mathscr{T} \tag{5.35}$$

Hence, if the binary variable $\varphi_{o,t}$ is equal to 0, $\delta_{o,c,t}$ must be equal to 0.

The facility configuration constraints 5.36 - 5.39 allow each facility to change its status (opened or closed) at most once.

In constraints 5.36, if the existing location site $e \in \mathscr{E}$ is closed $\big(\varphi_{e,t}$ is 0$\big)$, it cannot be reopened in later time periods $\big(\varphi_{e,t+1}$ must be 0$\big)$.

$$\varphi_{e,t} \geq \varphi_{e,t+1} \ , \quad \forall e \in \mathscr{E}, \ t \in \mathscr{T} \setminus \{T\} \tag{5.36}$$

Similarly, once the new location site $n \in \mathscr{N}$ is opened, it will remain in operation until the end of the planning horizon 5.37. In other words, if $\varphi_{n,t}$ is 1, $\varphi_{n,t+1}$ must be 1.

$$\varphi_{n,t} \leq \varphi_{n,t+1} \ , \quad \forall n \in \mathscr{N}, \ t \in \mathscr{T} \setminus \{T\} \tag{5.37}$$

Constraints 5.38 state that once center $c \in \mathscr{C}$ at the existing location site $e \in \mathscr{E}$ is closed $\big(\delta_{e,c,t}$ is 0$\big)$, it cannot be reopened in subsequent periods $\big(\delta_{e,c,t+1}$ must be 0$\big)$.

$$\delta_{e,c,t} \geq \delta_{e,c,t+1} \ , \quad \forall e \in \mathscr{E}, \ c \in \mathscr{C}, \ t \in \mathscr{T} \setminus \{T\} \tag{5.38}$$

Constraints 5.39 assure that if center $c \in \mathscr{C}$ at the new location site $n \in \mathscr{N}$ is established $\big(\delta_{n,c,t}$ is 1$\big)$, it will remain in operation until the end of the planning horizon $\big(\delta_{n,c,t+1}$ must be 1$\big)$.

$$\delta_{n,c,t} \leq \delta_{n,c,t+1} \ , \quad \forall n \in \mathscr{N}, \ c \in \mathscr{C}, \ t \in \mathscr{T} \setminus \{T\} \tag{5.39}$$

Constraints 5.40 together with constraints 5.38 guarantee that if center $c \in \mathscr{C}$ at the existing location site $e \in \mathscr{E}$ is expanded, then it will remain in operation throughout the whole planning horizon.

$$\rho_{e,c} \leq \delta_{e,c,T} \ , \quad \forall e \in \mathscr{E}, \ c \in \mathscr{C} \tag{5.40}$$

Contrarily, if center $c \in \mathscr{C}$ at the existing location site $e \in \mathscr{E}$ is not operated in the last period T, it must have been closed in one of the previous periods, and therefore could not have its capacity expanded.

5.1.4.3.5 Non-Negativity and Integrity Constraints

Constraints (5.41) enforce the non-negativity condition on the decision variables. Lastly, the binary decision variable constraints are (5.42).

$$x_{j,a,g,t},\ y_{l,l',p,t},\ z_{s,j,m,t},\ q_{l,u,g,t},\ w_{o,c,t},\ v_{e,n,c,t},\ exp_{o,c,t},\ mov_{o,o',c,t} \geq 0$$
$$\text{and integer },\ \ \forall l \in \mathscr{L},\ l' \in \mathscr{L}, o \in \mathscr{O},\ o' \in \mathscr{O},\ e \in \mathscr{E},\ n \in \mathscr{N},\ j \in \mathscr{J}, \tag{5.41}$$
$$s \in \mathscr{S}, u \in \mathscr{U},\ c \in \mathscr{C}, a \in \mathscr{A},\ p \in \mathscr{P},\ g \in \mathscr{G},\ m \in \mathscr{M},\ t \in \mathscr{T}$$

$$\varphi_{o,t},\ \delta_{o,c,t},\ \rho_{e,c} \in \{0,1\}\ ,\ \ \forall o \in \mathscr{O},\ e \in \mathscr{E},\ c \in \mathscr{C},\ t \in \mathscr{T} \tag{5.42}$$

5.1.5 A Case Study on Different Values of Product Demands and Returns

5.1.5.1 Description of the Example Case

The capabilities of the proposed model are highlighted through a case study of a fictitious closed-loop supply chain network comprising several existing and new facilities. During the planning horizon, existing facilities at sites can be closed, and potential new facilities can be opened from a set of candidate locations. There are also a number of suppliers, customers and subcontractors at fixed locations. The network consists of three external suppliers (su1, su2 and su3), two existing plant sites (pl1 and pl2), one potential new plant site (pl3), one existing intermediate site (in1), one potential new intermediate site (in2), three customers (cu1, cu2 and cu3) and one disassembly-remanufacturing subcontractor (ou1). Before the planning horizon starts, the existing plant sites pl1 and pl2 have both the production center (a1) and the disassembly-remanufacturing center (a2), and the existing intermediate site in1 has both the distribution center (b1) and the collection center (b2). It is possible to open the production center a1 and the disassembly-remanufacturing center a2 at the new plant site pl3, and the distribution center b1 and the collection center b2 at the new intermediate site in2. There are three kinds of parts/components (m1, m2 and m3), which are converted into two types of final products (g1 and g2). In the same way as performed on the previously proposed models in Chapters 3 and 4, this present model is implemented and solved in GAMS 23.2.1 in a Pentium IV 2.66 GHz personal computer with 1 GB RAM. The code CPLEX is employed for solving the problem[1].

In order to evaluate the model, nine different scenarios are considered. We present scenarios looking at changes in product demands and returns. Tables 5.3 and 5.4 give the scenario parameter data of varying customers' product demands and return rates from customers over 10 year periods. The scenarios considered are as follows:

1. Scenarios for decreasing product demands

    - *Scenario DL:* The first scenario to consider is the effect of decreasing product demands and low rates of returns (see Tables 5.3(a) and 5.4(a)).
    - *Scenario DM:* Similar to the first scenario in terms of decreasing product demands but medium rates of returns are considered (see Tables 5.3(a) and 5.4(b)).
    - *Scenario DH:* Similar to the first scenario in terms of decreasing product demands but high rates of returns are considered (see Tables 5.3(a) and 5.4(c)).

2. Scenarios for relatively stable product demands

    - *Scenario SL:* The scenario to be investigated is the effect of relatively stable product demands and low rates of returns (see Tables 5.3(b) and 5.4(a)).
    - *Scenario SM:* Similar to scenario NL in terms of relatively stable product demands but medium rates of returns are investigated (see Tables 5.3(b) and 5.4(b)).

[1] For the detailed GAMS code, see Appendix C.2 of this thesis.

- *Scenario SH:* Similar to scenario NL in terms of relatively stable product demands but high rates of returns are investigated (see Tables 5.3(b) and 5.4(c)).

3. Scenarios for increasing product demands

- *Scenario IL:* This scenario considers the effect of increasing product demands and low rates of returns (see Tables 5.3(c) and 5.4(a)).
- *Scenario IM:* Similar to scenario IL in terms of decreasing product demands but medium rates of returns are taken into consideration (see Tables 5.3(c) and 5.4(b)).
- *Scenario IH:* Similar to scenario IL in terms of decreasing product demands but high rates of returns are taken into consideration (see Tables 5.3(c) and 5.4(c)).

Demands in Table 5.3 are assumed to be deterministic and known before. Table 5.3(a) represents the decrease in demands. Demands gradually decrease by 5%- 20% each year. Table 5.3(b) contains demand parameters that are relatively stable, averaging approximately 10% of demand values is different from one period to another. Table 5.3(c) considers in case that demands of approximately 5%- 15% gradually increase every year. Table 5.4 provides the return rate data, which are defined in terms of the percentage of products returned from customers. Low rates of returns are presented in Table 5.4(a). Product demands of 10%- 30% are assumed to return to the supply chain. Table 5.4(b) represents medium rates of returns. Product returns of 40%- 60% from customers are assumed. In Table 5.4(c), high rates of returns are assumed to be 70%- 90%[2].

[2] For the remaining data associated with the problem see Appendix C.1.

Customers	Final products	Demands in each period (year)									
		1st yr.	**2nd yr.**	**3rd yr.**	**4th yr.**	**5th yr.**	**6th yr.**	**7th yr.**	**8th yr.**	**9th yr.**	**10th yr.**
cu1	g1	11000	10000	10000	10000	10000	10000	10000	9500	9000	8500
	g2	10000	10000	9000	9000	7000	7000	7000	7000	7000	7000
cu2	g1	10000	10000	9000	9000	8000	7500	6500	6500	5500	5500
	g2	10000	11000	10500	10000	10000	9000	8000	7000	6200	5200
cu3	g1	12000	10000	9000	9000	8500	7500	7000	6800	6500	6000
	g2	11000	9000	9000	8000	7000	7000	6000	5600	5100	5000

(a) Decreasing product demands

Customers	Final products	Demands in each period (year)									
		1st yr.	**2nd yr.**	**3rd yr.**	**4th yr.**	**5th yr.**	**6th yr.**	**7th yr.**	**8th yr.**	**9th yr.**	**10th yr.**
cu1	g1	11000	11000	11000	11000	11000	11000	11000	11000	11000	11000
	g2	10000	11000	11500	11000	11000	10000	10000	11000	11200	12000
cu2	g1	10000	10000	11000	11000	11000	11000	11000	10000	11000	11000
	g2	10000	11000	11000	11000	11000	11000	11000	13000	11000	10000
cu3	g1	12000	12500	11000	11800	11000	11000	13000	12500	10000	12000
	g2	11000	11000	11000	11500	11000	11000	12000	11000	12000	11000

(b) Relatively stable product demands

Customers	Final products	Demands in each period (year)									
		1st yr.	**2nd yr.**	**3rd yr.**	**4th yr.**	**5th yr.**	**6th yr.**	**7th yr.**	**8th yr.**	**9th yr.**	**10th yr.**
cu1	g1	10000	11000	12000	13000	14000	14500	15000	15500	16000	18000
	g2	10000	11000	11500	12000	12000	12500	13000	14000	17000	18000
cu2	g1	10000	11000	12000	12400	13000	13500	14000	15000	16000	17000
	g2	10000	11000	12000	13000	13500	14000	15000	16000	17000	18000
cu3	g1	10000	11500	12000	13800	14000	15000	15500	16500	17000	18000
	g2	10000	11000	11500	12500	13000	14000	15000	16000	16500	17000

(c) Increasing product demands

Table 5.3: Product demands of customers ($DC_{k,g,t}$)

Customers	Final products	Return rates in each period (year)									
		1st yr.	2nd yr.	3rd yr.	4th yr.	5th yr.	6th yr.	7th yr.	8th yr.	9th yr.	10th yr.
cu1	g1	0.2	0.1	0.3	0.2	0.3	0.2	0.1	0.2	0.3	0.2
	g2	0.1	0.2	0.2	0.3	0.1	0.2	0.3	0.2	0.3	0.2
cu2	g1	0.2	0.2	0.1	0.2	0.3	0.1	0.2	0.3	0.2	0.3
	g2	0.2	0.1	0.2	0.2	0.2	0.2	0.3	0.2	0.1	0.2
cu3	g1	0.1	0.2	0.2	0.3	0.1	0.3	0.2	0.1	0.1	0.2
	g2	0.2	0.1	0.1	0.2	0.3	0.3	0.2	0.3	0.3	0.2

(a) Low rates of returns

Customers	Final products	Return rates in each period (year)									
		1st yr.	2nd yr.	3rd yr.	4th yr.	5th yr.	6th yr.	7th yr.	8th yr.	9th yr.	10th yr.
cu1	g1	0.5	0.4	0.4	0.5	0.6	0.4	0.6	0.5	0.5	0.4
	g2	0.4	0.4	0.5	0.6	0.5	0.5	0.4	0.6	0.6	0.5
cu2	g1	0.5	0.5	0.4	0.4	0.6	0.4	0.6	0.5	0.5	0.6
	g2	0.5	0.4	0.4	0.6	0.5	0.5	0.4	0.5	0.6	0.5
cu3	g1	0.4	0.5	0.5	0.6	0.4	0.5	0.4	0.6	0.5	0.6
	g2	0.4	0.6	0.4	0.5	0.5	0.6	0.4	0.5	0.5	0.4

(b) Medium rates of returns

Customers	Final products	Return rates in each period (year)									
		1st yr.	2nd yr.	3rd yr.	4th yr.	5th yr.	6th yr.	7th yr.	8th yr.	9th yr.	10th yr.
cu1	g1	0.8	0.8	0.9	0.8	0.7	0.9	0.8	0.8	0.9	0.7
	g2	0.7	0.7	0.8	0.7	0.8	0.7	0.8	0.7	0.7	0.9
cu2	g1	0.8	0.7	0.7	0.9	0.8	0.9	0.8	0.9	0.9	0.8
	g2	0.8	0.9	0.7	0.9	0.7	0.8	0.7	0.8	0.8	0.7
cu3	g1	0.9	0.7	0.8	0.8	0.9	0.8	0.9	0.7	0.7	0.8
	g2	0.7	0.8	0.7	0.8	0.8	0.7	0.8	0.9	0.8	0.7

(c) High rates of returns

TABLE 5.4: Return rates of products from customers ($RC_{k,g,t}$)

5.1.5.2 Numerical Results and Discussion

The results obtained from the proposed model are presented in this section. Figures 5.2-5.8 depict the optimal supply chain configurations. The network structures for only three different demand level scenarios DL, SL and IL in some periods during a time-planning horizon are illustrated as the example network structures. The resulting networks with shipment routes and forward and reverse product flows into and out from facilities are also demonstrated.

Figures 5.2-5.4 show the optimal networks with decreasing demands and low rates of returns (scenario DL) in the first, second and fifth periods, respectively. During the first period (t=1), the disassembly-remanufacturing center a2 at the existing plant site pl2 and the distribution center b1 at the existing intermediate site in1 are closed, while both distribution and collection centers b1 and b2 are opened at the new intermediate site in2. This is because disassembly and remanufacturing costs of the existing plant site pl2 are higher than these costs of the existing plant site pl1. Notice that a major volume of the production is carried out at the plant site pl1 due to the high production costs (especially for final product g2) in the plant site pl2. Moreover, the costs for the shipment to and from distribution and collection centers b1 and b2 at the new intermediate site in2 are much cheaper than shipping costs to and from these centers at the existing intermediate site in1. It is also profitable to distribute some of final products g1 and g2 directly from the production center a1 at the existing plant site pl1 to customers. Since demands gradually decrease over the time horizon, the production center a1 at the existing plant site pl2 and the collection center b2 at the existing intermediate site in1 are closed in the second period (t=2) and the fifth period (t=5), respectively (see Figures 5.3 and 5.4). As can be seen, it is profitable to distribute some of final products g2 from the production center a1 at the existing plant site pl1 directly to the customer cu3 in the second period (t=2), as well as to distribute some of final products g1 and g2 from the production center a1 at the existing plant site pl1 directly to customers and to return products g1 from the customer cu2 directly to the disassembly-remanufacturing center a2 at the existing plant site pl1 in the fifth period (t=5). The network in the fifth period thus consists of one stand-alone reverse facility (existing intermediate site in1) and two bidirectional facilities (existing plant site pl1 and new intermediate site in2). The network structures are the same as in the fifth period for all subsequent periods.

The optimal networks with relatively stable demands and low rates of returns (scenario SL) in the first and last periods are respectively exhibited in Figures 5.5 and 5.6. As can be seen from Figure 5.5, the existing plant site pl2 and the existing intermediate site in1 are closed, and the new intermediate site in2 is opened due to the high processing and operating costs at the plant site pl2 and the high transportation costs between the intermediate site in1 and other location sites. It is also profitable to return products g1 directly from customers cu2 and cu3 to the disassembly-remanufacturing center a2 at the existing plant site pl1 in the first period (t=1) and from the customer cu2 to the disassembly-remanufacturing center a2 at the existing plant site pl1 in the last period (t=10). The network structures are the same as in the first period for all subsequent periods. Hence, the network in any period is comprised of two bidirectional facilities (existing plant site pl1 and new intermediate site in2).

In Figures 5.7-5.8, the optimal networks with increasing demands and low rates of returns (scenario IL) in the first and last periods are respectively illustrated. These figures show that the disassembly-remanufacturing center a2 located at the existing plant site pl2 is closed resulting from the high processing costs at this center. Additionally, both distribution and collection centers b1 and b2 are opened at the new intermediate site in2. According to the high transportation costs for the amount sent to and from the existing intermediate site in1, a major amount of the distribution and collection are carried out from the new intermediate site in2. In case of increasing demands, a rather large amount of final products are manufactured by using parts/components that are recovered from the disassembly-remanufacturing subcontractor in addition to using new parts/components from suppliers and recovered parts/components from the disassembly-remanufacturing center. It is also profitable to return products g1 directly from the customer cu2 to the subcontractor ou1 for disassembly and remanufacturing process in the first period (t=1) and the last period (t=10) and to distribute some of final products g1 and g2 from the production center a1 at the existing plant site pl1 directly to the customer cu3 in the last period. The network structures are the same as in the first period for all subsequent periods. The network in any period therefore contains one stand-alone forward facility (existing plant site pl2) and three bidirectional facilities (existing plant site pl1, and existing and new intermediate sites in1 and in2).

As can be observed from Figures 5.2-5.8, since a low number of products are returned, the larger amount of parts/components used to manufacture final products are received from external suppliers. It can be noticed from these figures that new parts/-components m3 are never transported from the external supplier su2 to any production center due to the high purchasing costs for parts/components m3 from this supplier. The model decided not to open the potential new plant site pl3 for both production and disassembly-remanufacturing centers a1 and a2 due to the high production costs at this site and a small number of products returned to the supply chain.

Figure 5.9 shows the capacity expansion at both existing and new location sites in case of gradually decreasing demands throughout the planning horizon. To fulfill the demands and return amount from customers, the capacity of the production and disassembly-remanufacturing centers a1 and a2 at the existing plant site pl1 and the distribution and collection centers b1 and b2 at the new intermediate site in2 is expanded because the existing plant site pl2 and the existing intermediate site in1 are closed during the planning horizon (all scenarios). In scenario DH, there are also investments on the capacity expansion of the disassembly-remanufacturing center a2 at new plant site pl3 to serve a large amount of returned products.

Figure 5.10 shows the capacity expansion at both existing and new location sites in case of relatively stable demands. For scenarios SL and SM, there are investments on the capacity expansion of production and disassembly-remanufacturing centers a1 and a2 at the plant site pl1 and distribution and collection centers b1 and b2 at the new intermediate site in2 to serve the demand and return volume due to the close of the existing plant site pl2 and the existing intermediate site in1 during the planning period (all scenarios). In scenario SH, it is more profitable to open the disassembly-remanufacturing center a2 at the new plant site pl3 instead of expanding the capacity of the disassembly-remanufacturing center a2 at the existing plant site pl1.

Note that no existing location site has its capacity relocated to any new location in case of decreasing and relatively stable demands. This is because the existing plant site pl2 and the existing intermediate site in1 are closed during the planning periods. Only the existing plant site pl1, the new plant site pl3 and the new intermediate site in2 are operating to serve the demands and returns.

Figures 5.11 and 5.12 show the capacity expansion and relocation at both existing and new location sites in case demands are gradually increasing over the planning horizon. There are investments in the capacity relocation from some existing facilities due to their high processing and shipping costs. For all scenarios, the capacity of the distribution and collection centers b1 and b2 are relocated from the existing intermediate site in1 to the new intermediate site in2. Since returns increase in scenarios IM and IH, the capacity of the disassembly-remanufacturing center a2 is relocated from the existing plant site pl1 to the new plant site pl3. There are also investments in expanding the capacity of the production center a1 at the existing plant site pl1 and the distribution center b1 at the intermediate site in2 to meet increasing demands (all scenarios). For scenario IL, the capacity of the disassembly-remanufacturing center a2 at the plant site pl1 is expanded. In scenarios IM and IH, it is more profitable to open the disassembly-remanufacturing center a2 at the new plant site pl3 and the collection center b2 at the new intermediate site in2 for the capacity expansion. The model selected to close the disassembly-remanufacturing a2 at the existing plant site pl2 due to high operating costs at this site.

In term of costs, Figures 5.13-5.15 illustrate the total cost in comparison with others including costs for the scenarios considered in this case study. It is clearly understood from the results in all scenarios that when demands increase, the total cost of the supply chain system increases, and when return rates increase, the costs of the disassembly-remanufacturing decrease for the same amount of demands. This is because we assume that purchased one unit of new part/component is the most expensive, followed by subcontracted one unit of reusable part/component and recovered one unit of part/component from the disassembly-remanufacturing process at the plant site. Even though transportation costs increase when return rates increase, processing costs

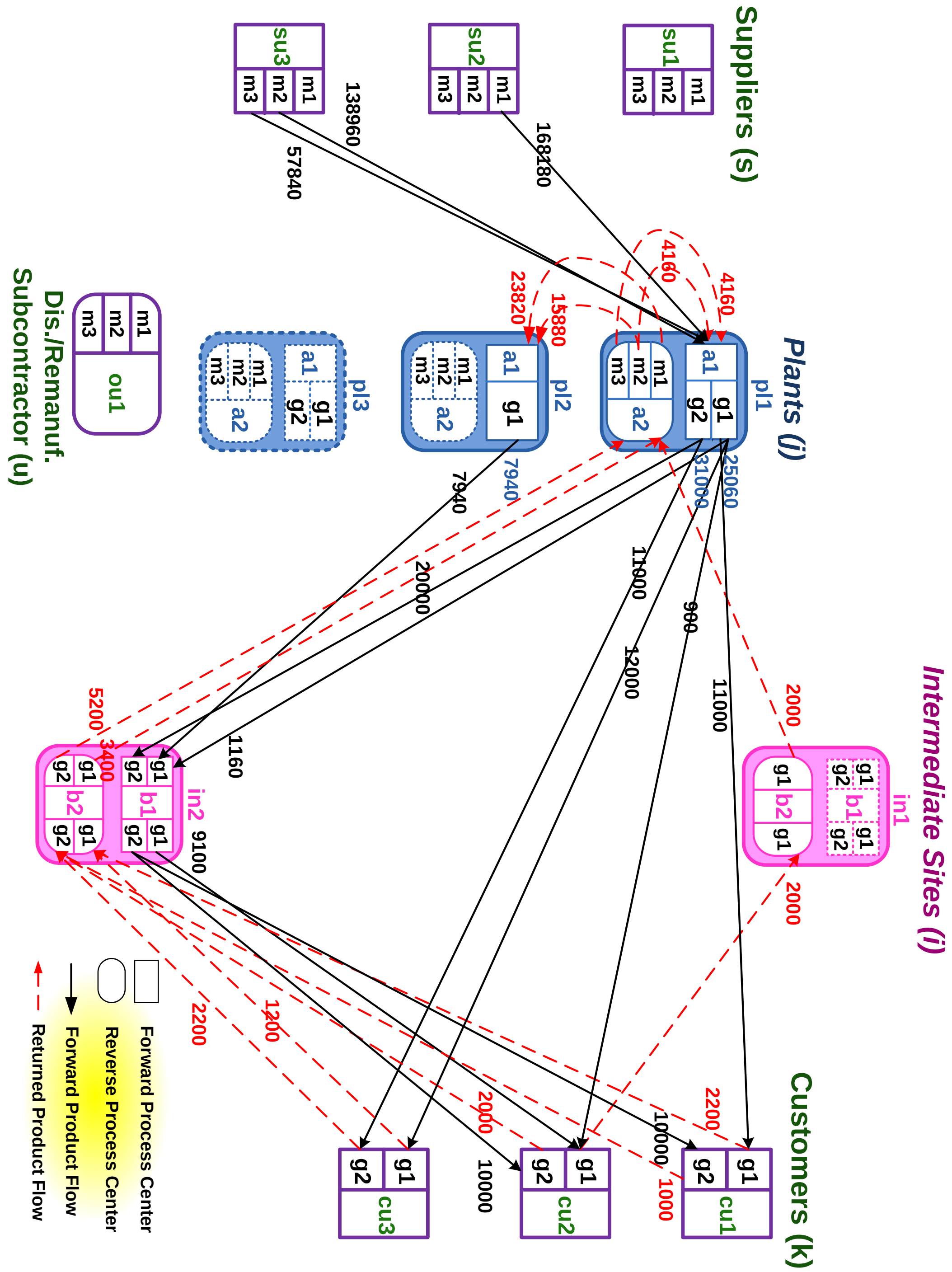


Figure 5.2: Illustrative example of the optimal network in the first period (scenario DL)

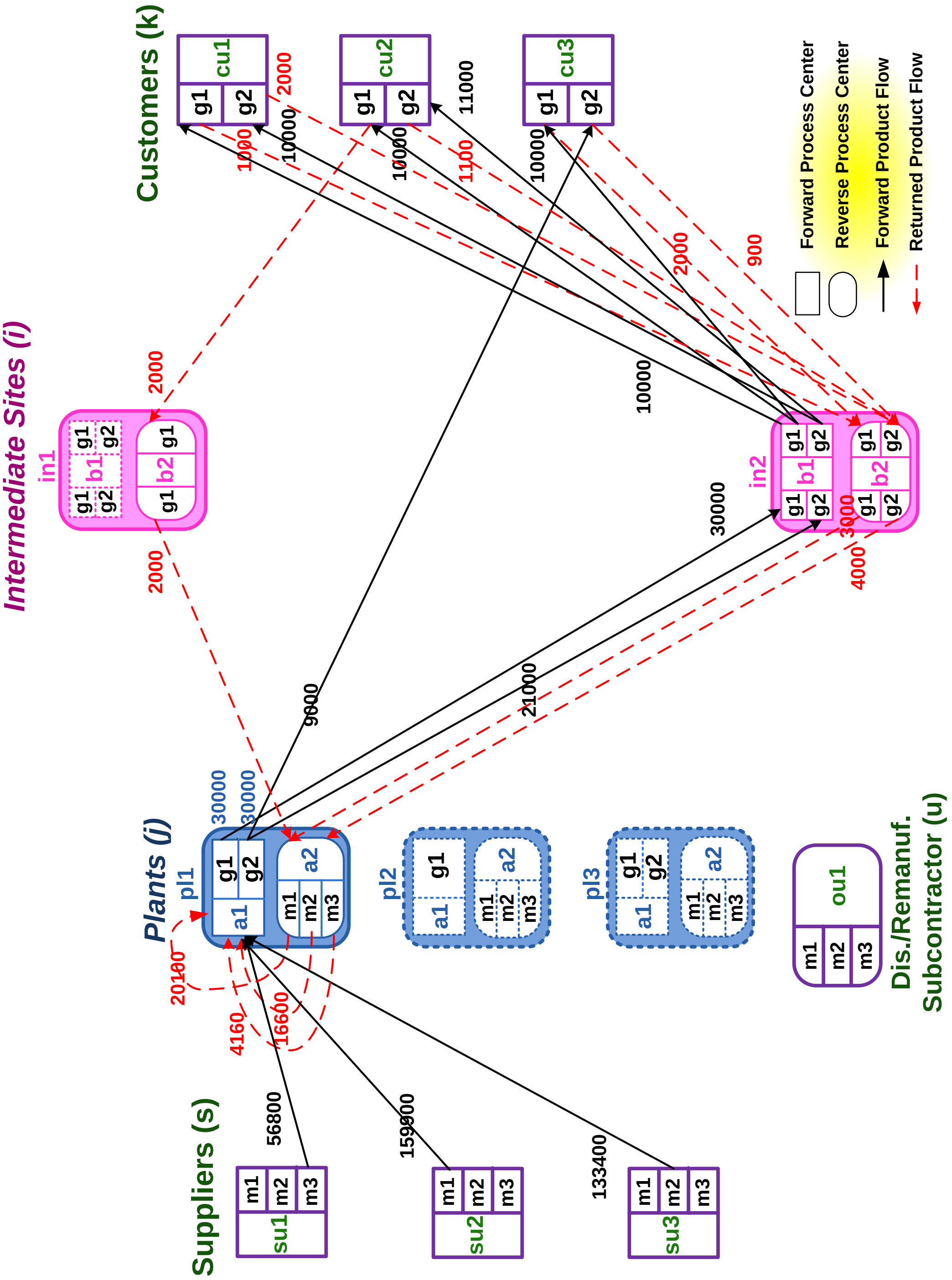


Figure 5.3: Illustrative example of the optimal network in the second period (scenario DL)

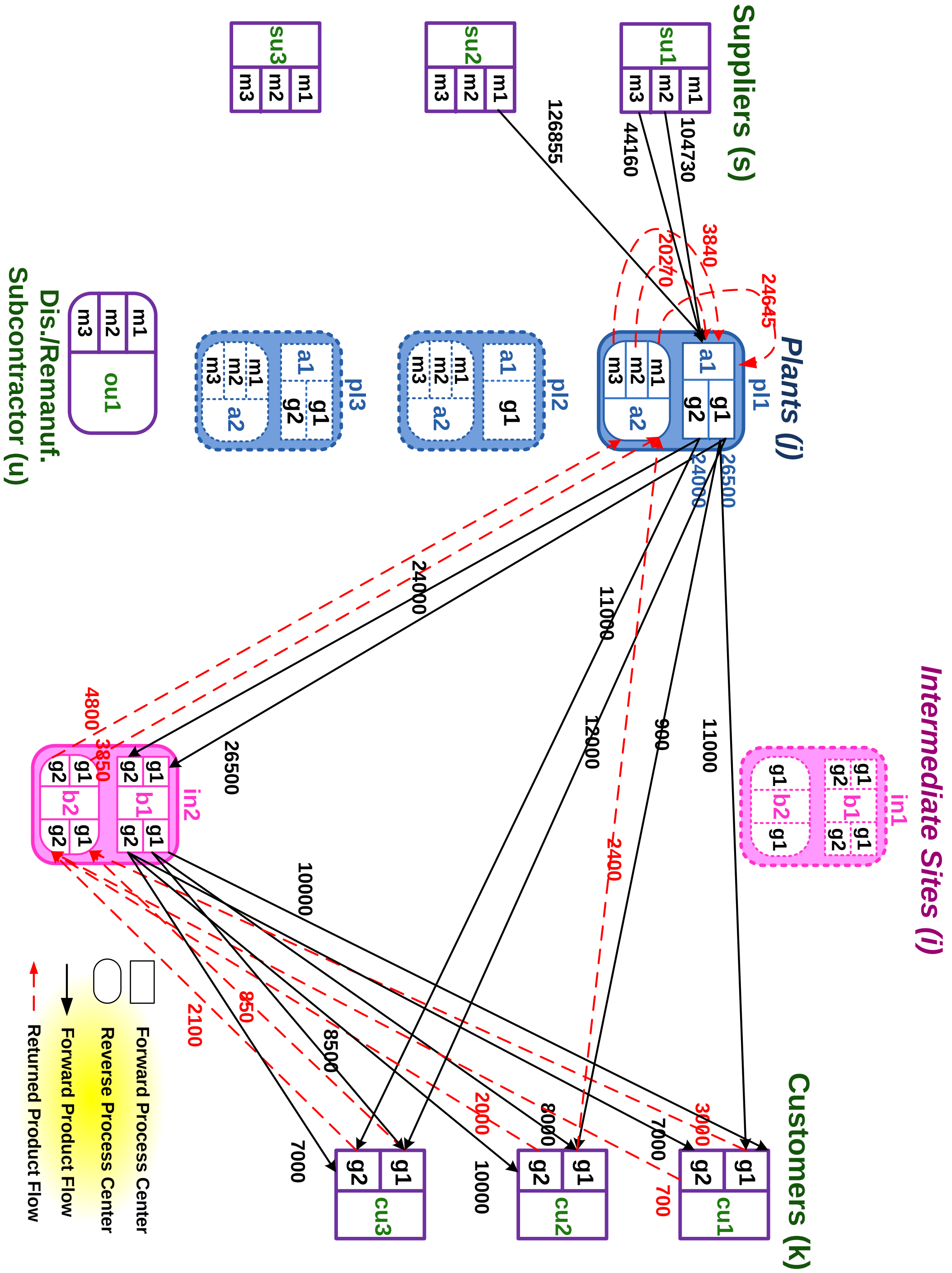


Figure 5.4: Illustrative example of the optimal network in the fifth period (scenario DL)

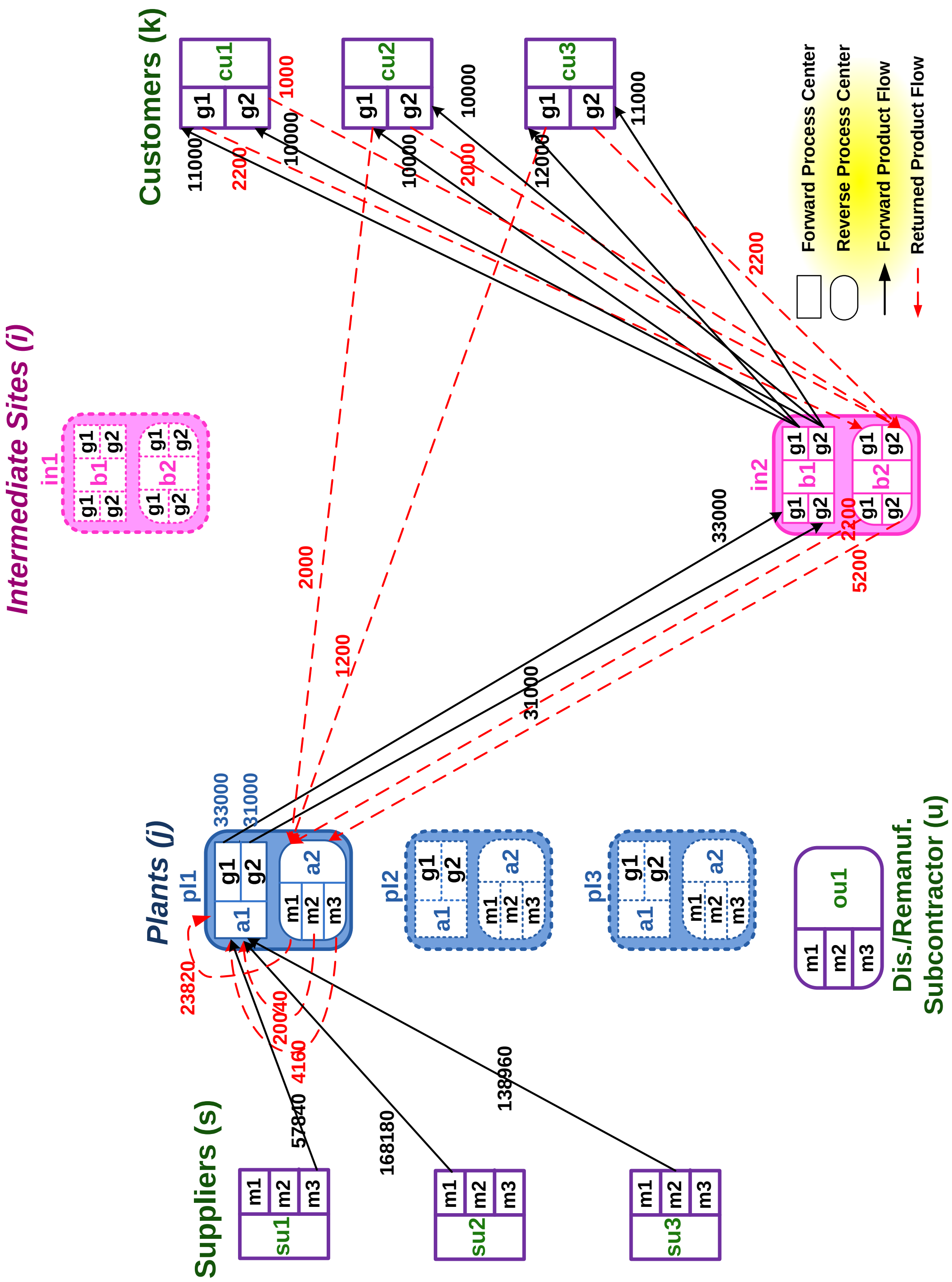


Figure 5.5: Illustrative example of the optimal network in the first period (scenario SL)

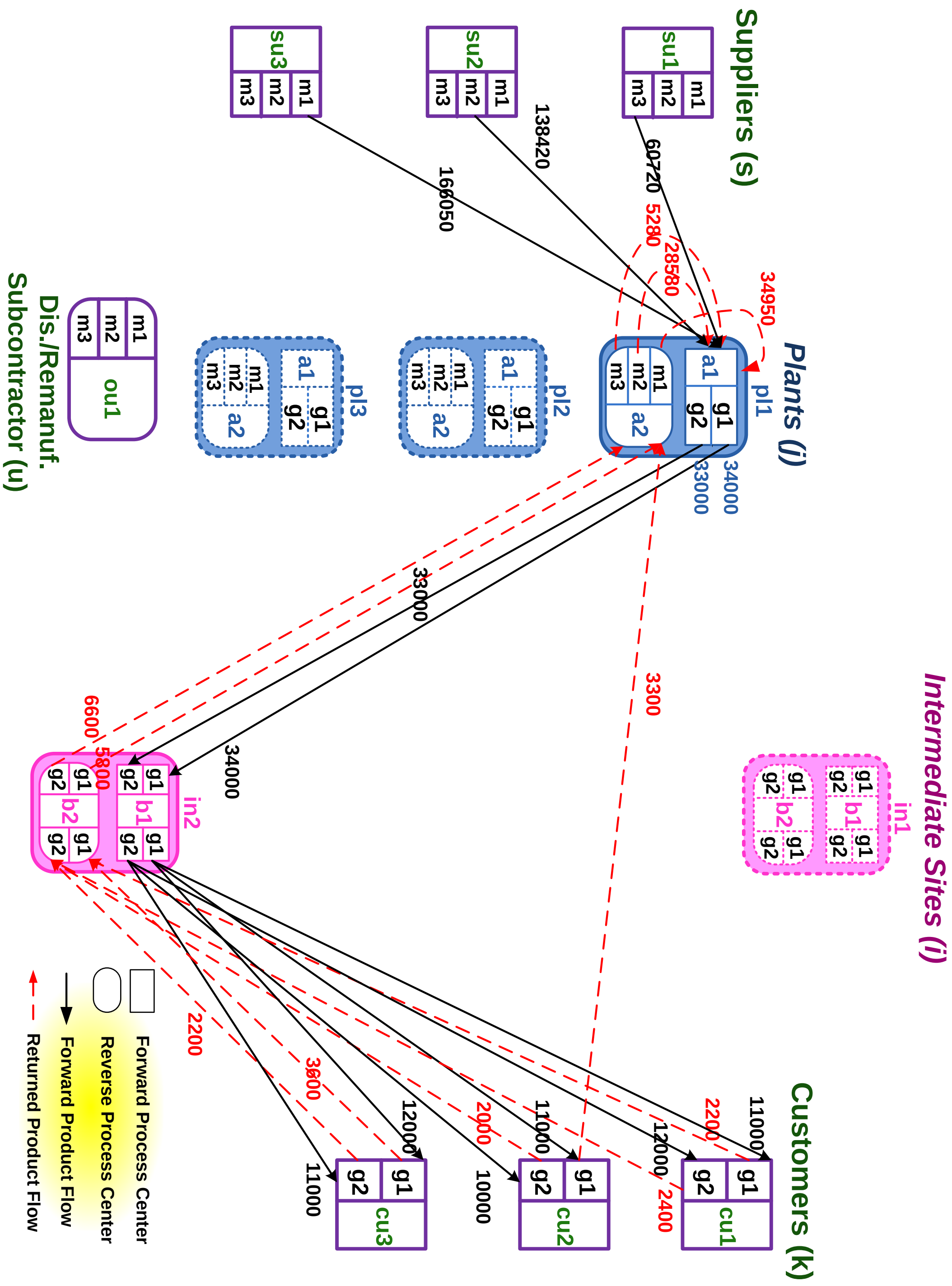


Figure 5.6: Illustrative example of the optimal network in the last period (scenario SL)

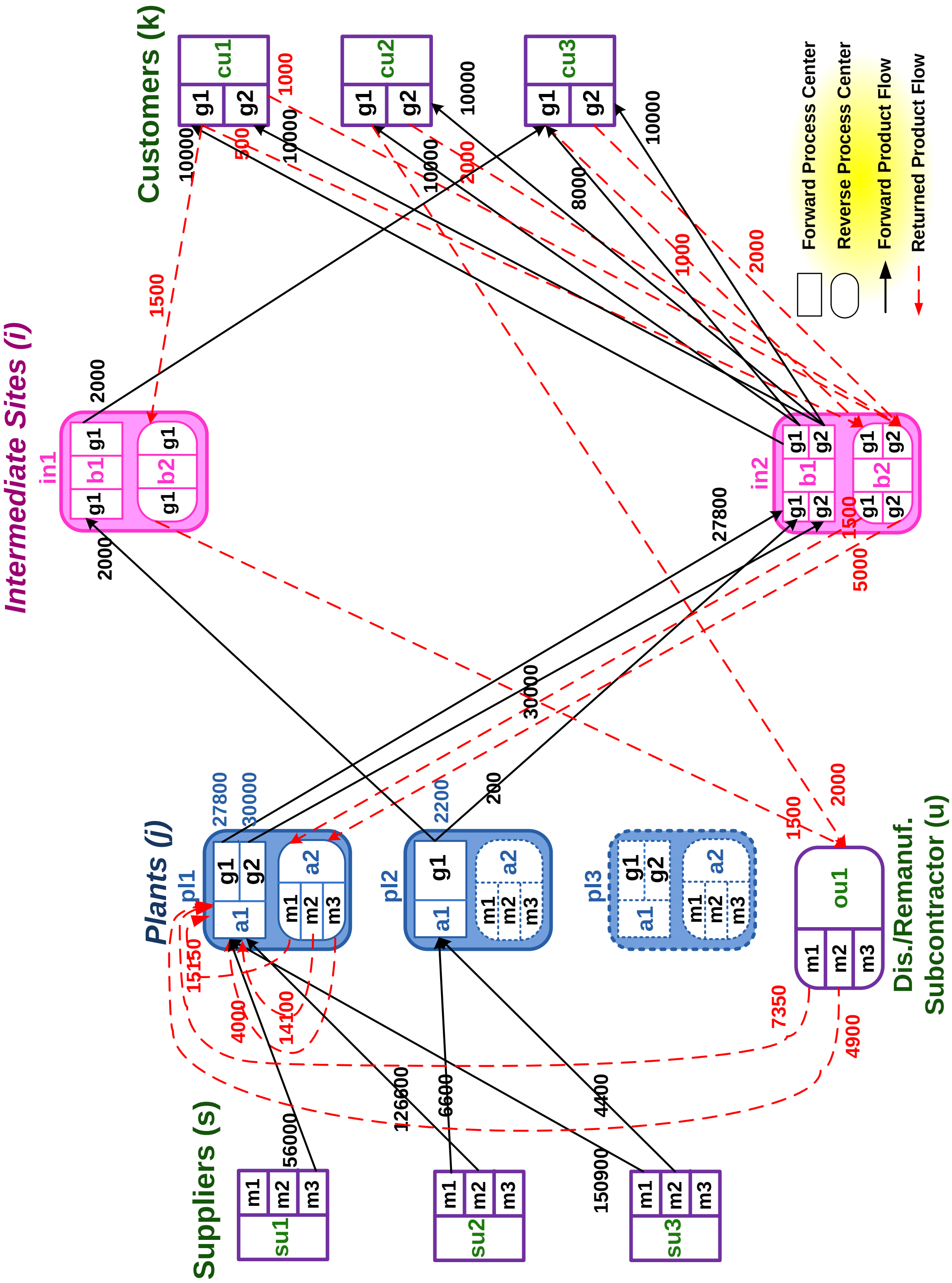


FIGURE 5.7: Illustrative example of the optimal network in the first period (scenario IL)

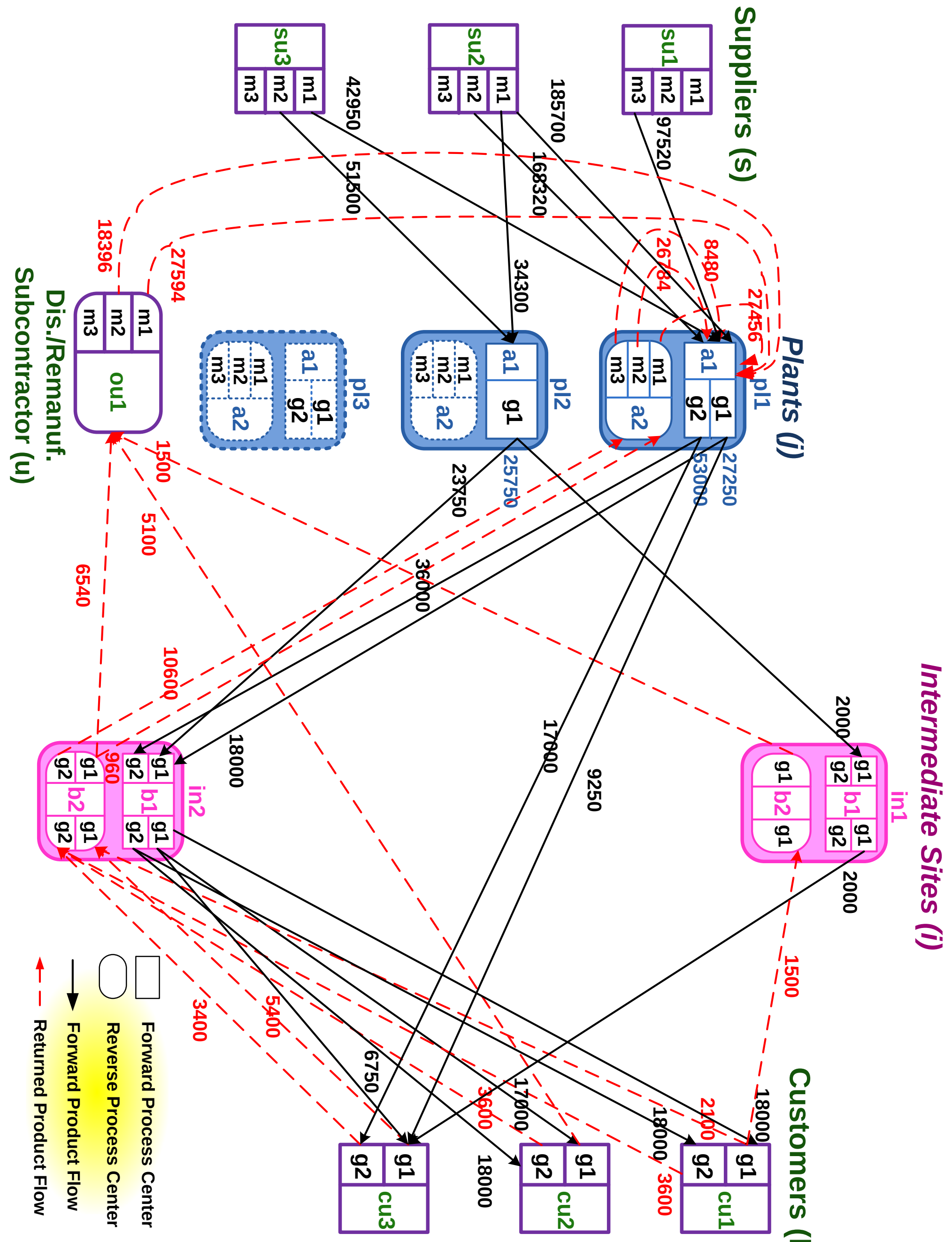
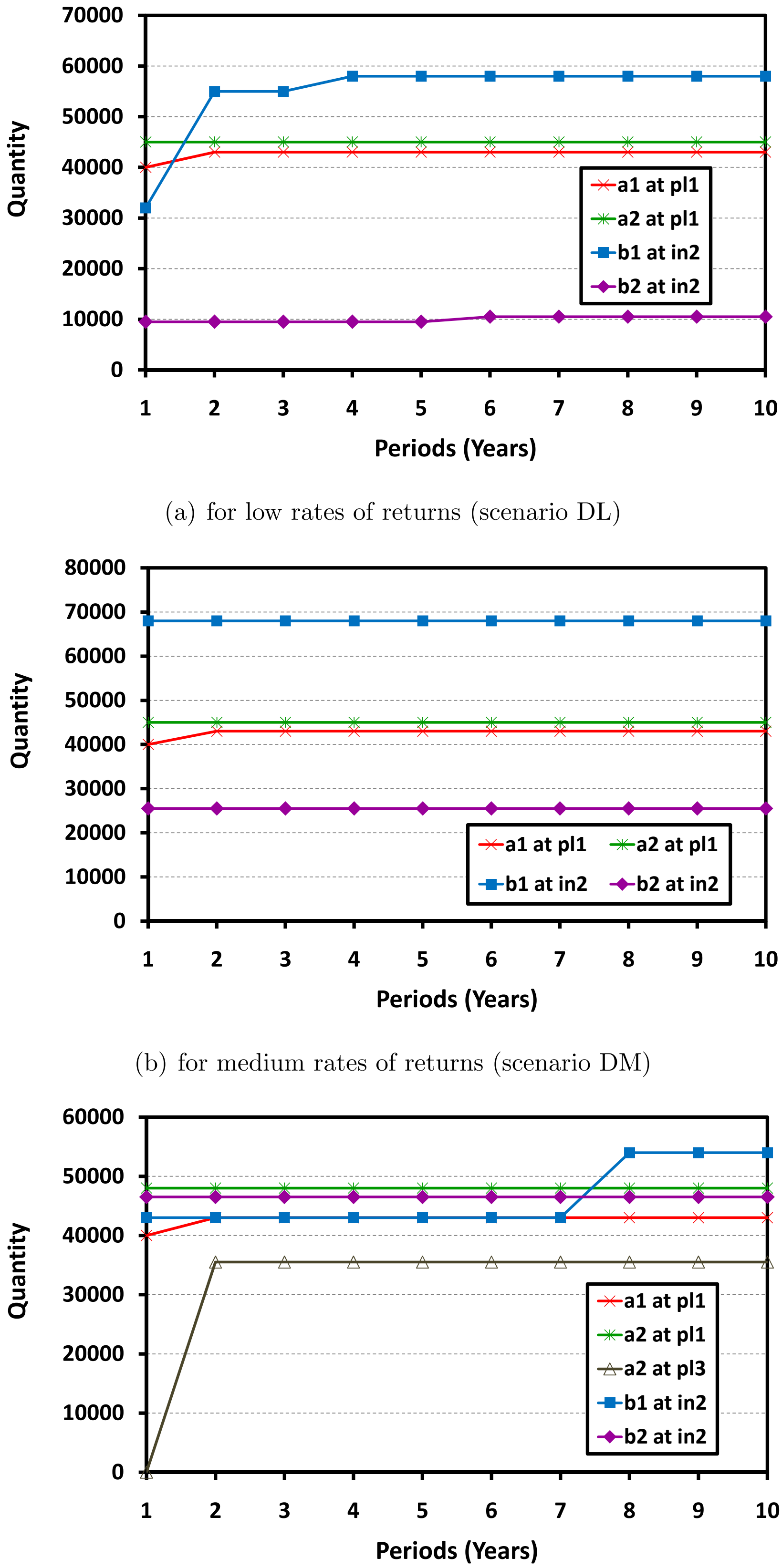


FIGURE 5.8: Illustrative example of the optimal network in the last period (scenario II)

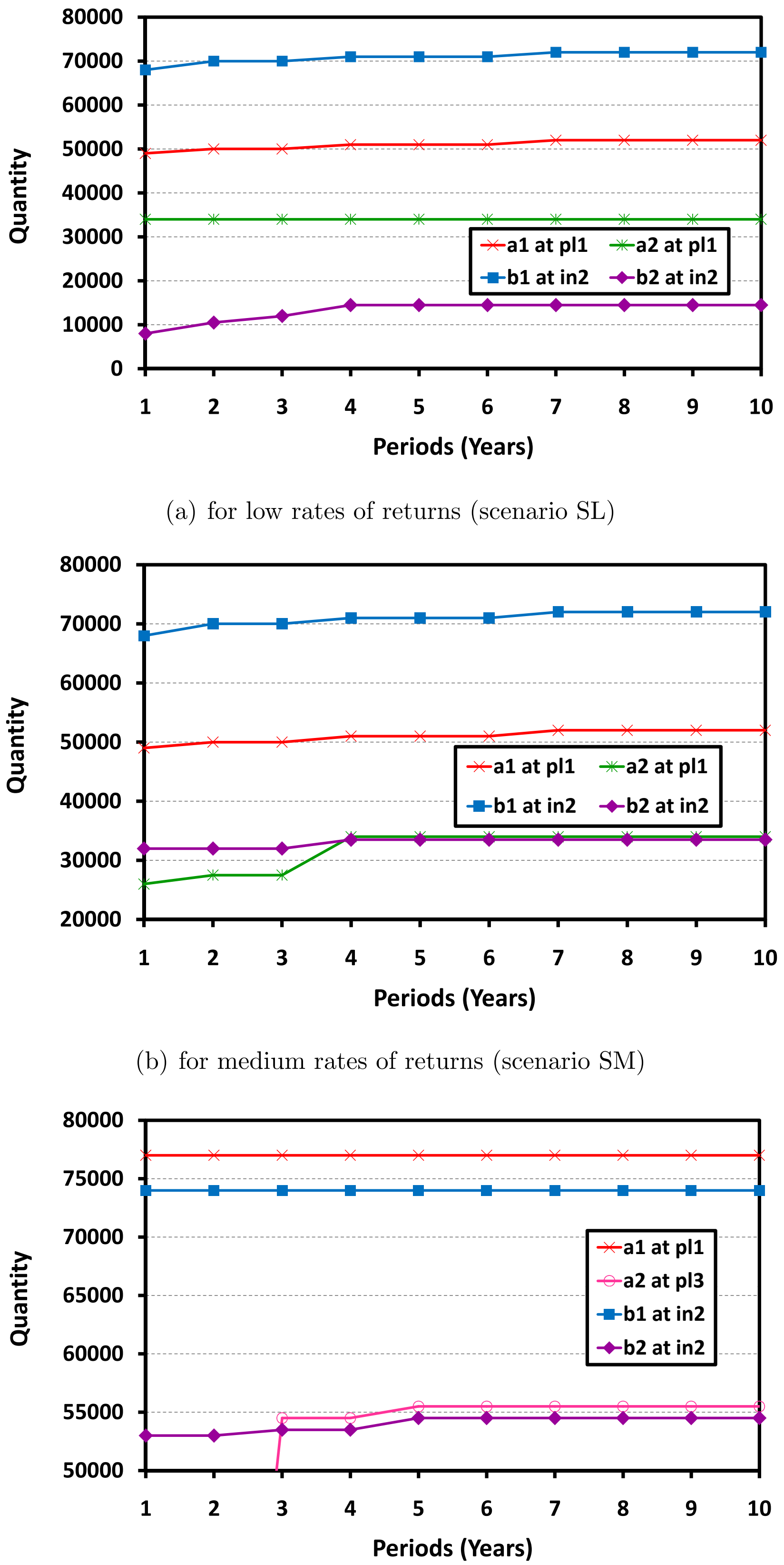


(a) for low rates of returns (scenario DL)

(b) for medium rates of returns (scenario DM)

(c) for high rates of returns (scenario DH)

Figure 5.9: Expansion (decreasing product demands)

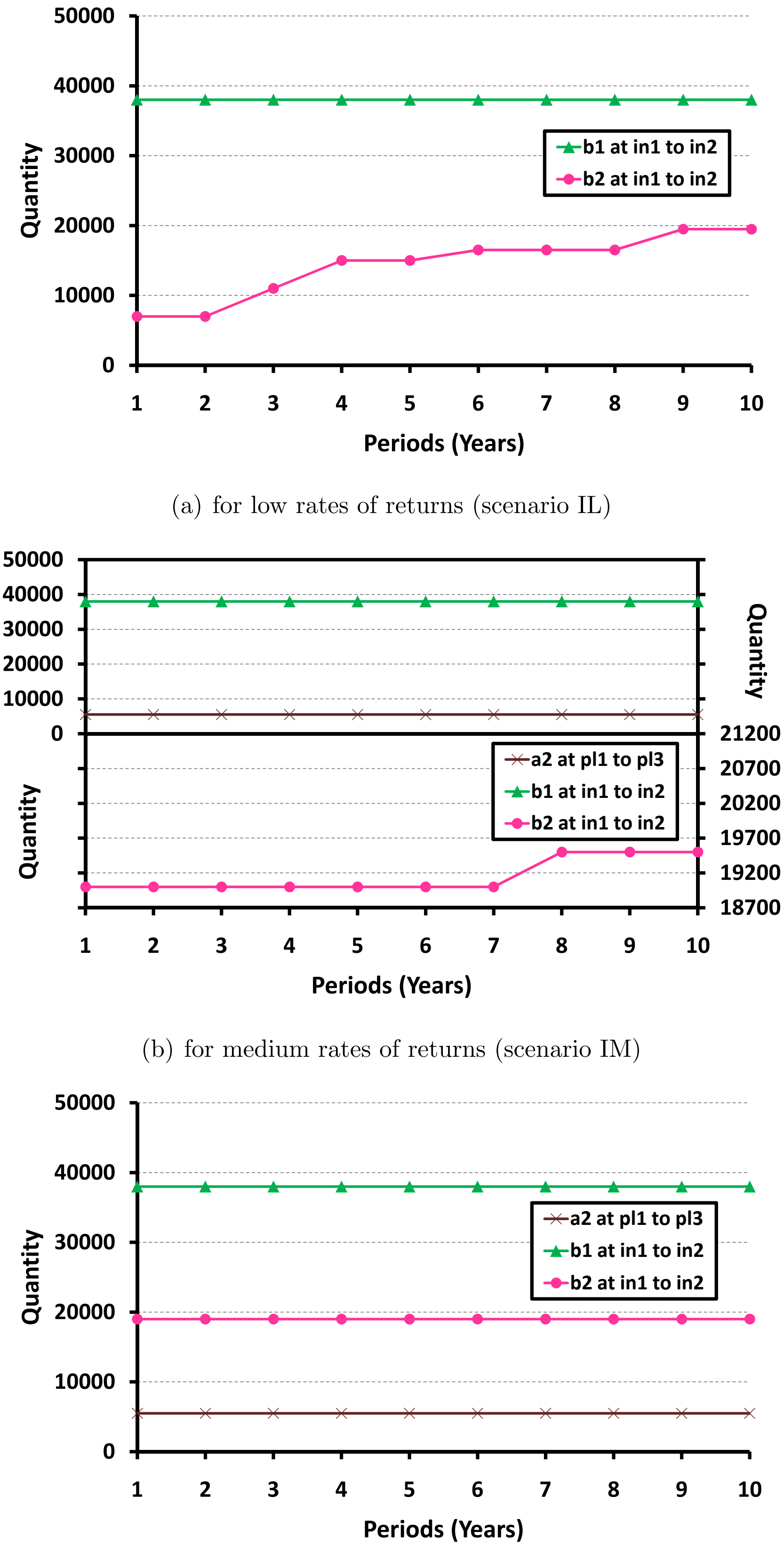


(a) for low rates of returns (scenario SL)

(b) for medium rates of returns (scenario SM)

(c) for high rates of returns (scenario SH)

Figure 5.10: Expansion (relatively stable product demands)

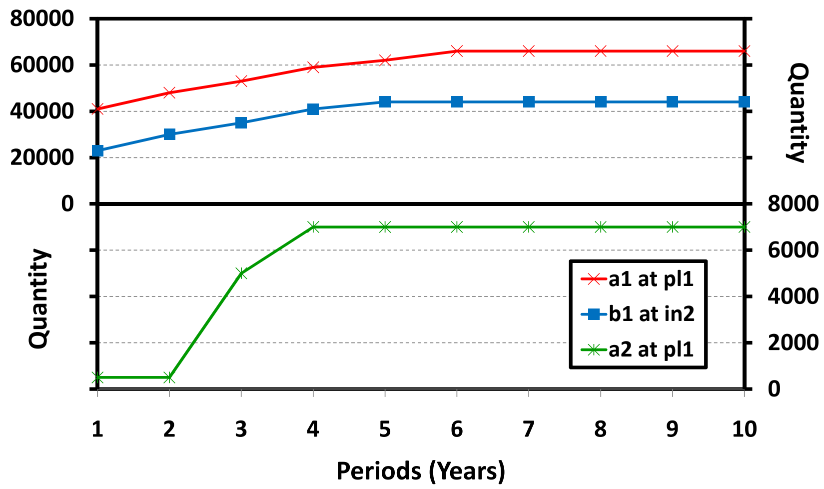


(a) for low rates of returns (scenario IL)

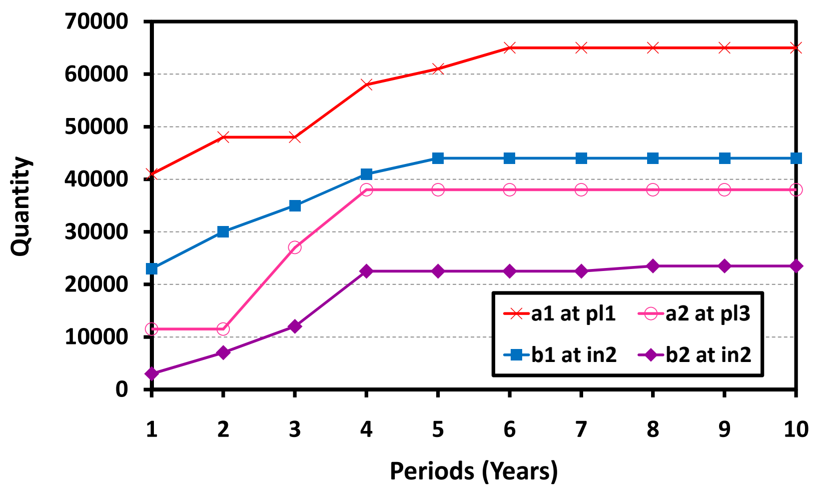
(b) for medium rates of returns (scenario IM)

(c) for high rates of returns (scenario IH)

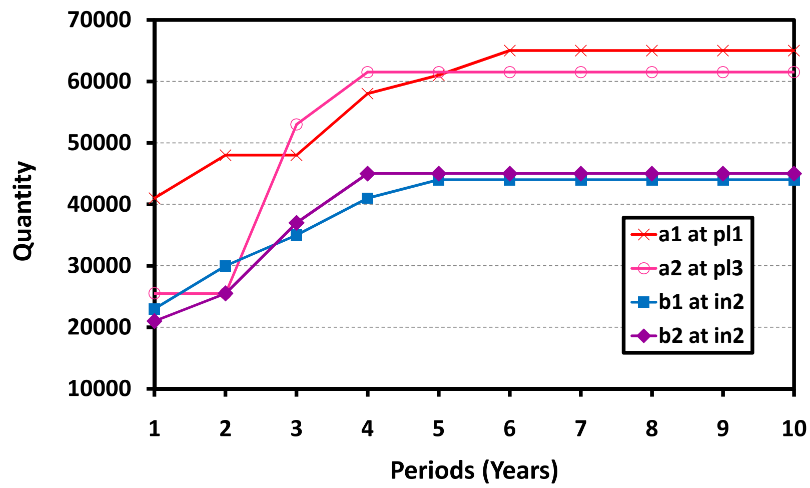
FIGURE 5.11: Relocation (increasing product demands)



(a) for low rates of returns (scenario IL)

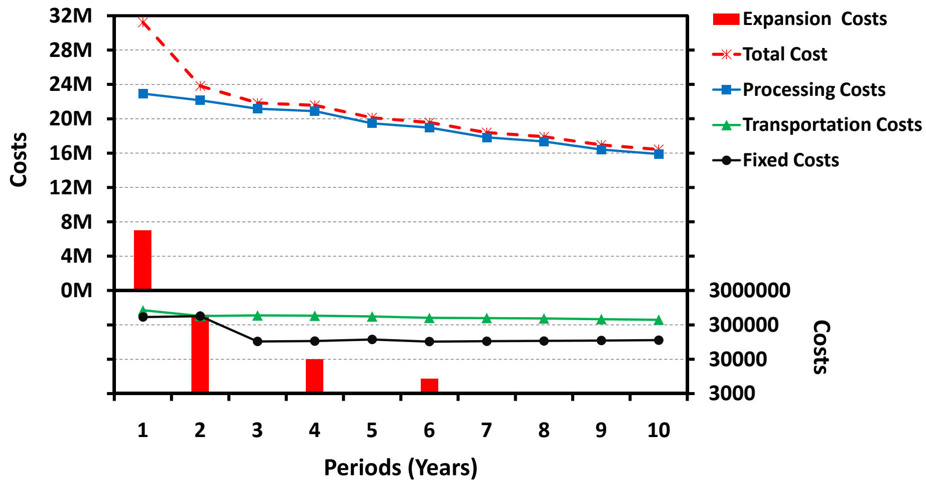


(b) for medium rates of returns (scenario IM)

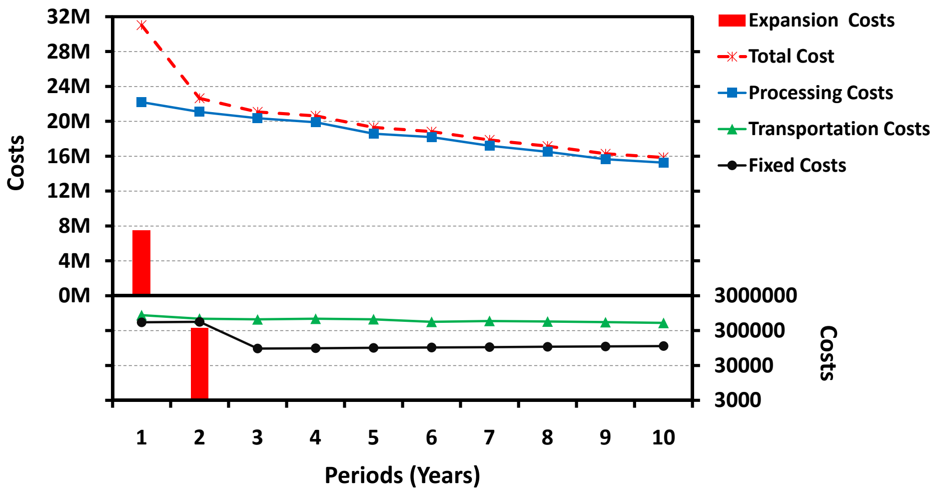


(c) for high rates of returns (scenario IH)

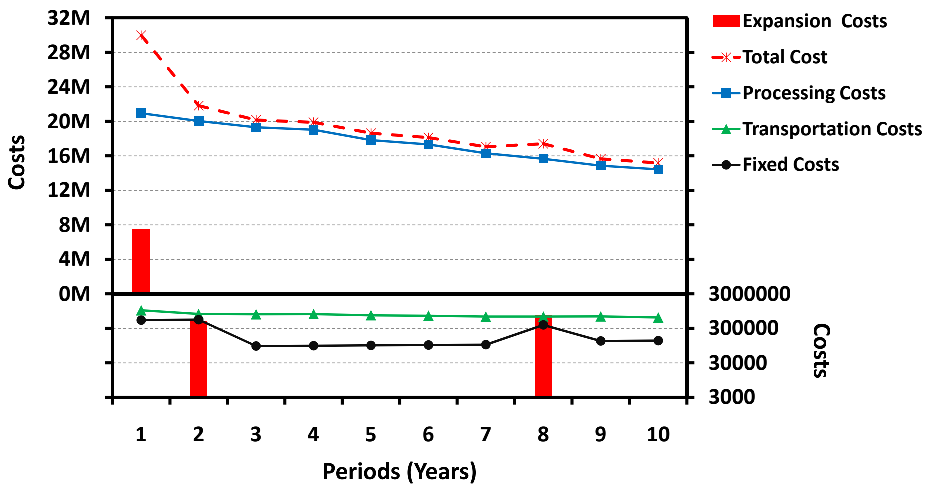
Figure 5.12: Expansion (increasing product demands)



(a) for low rates of returns (scenario DL)

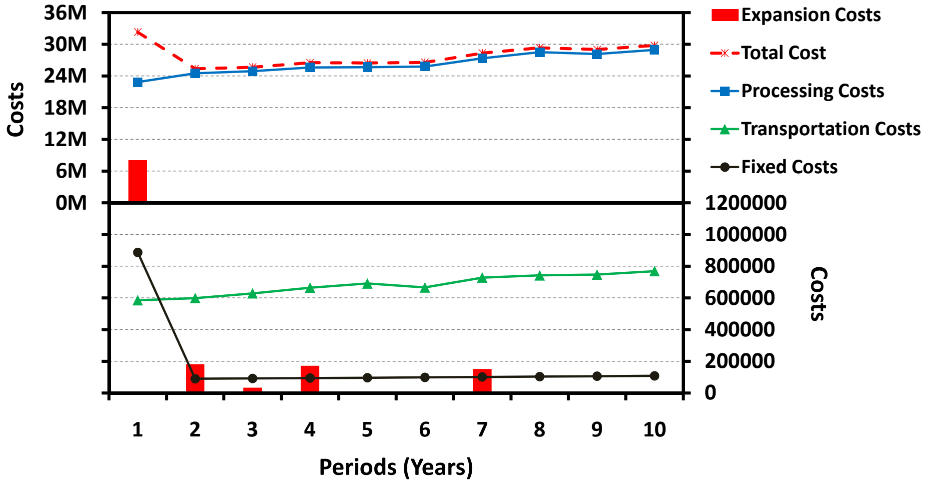


(b) for medium rates of returns (scenario DM)

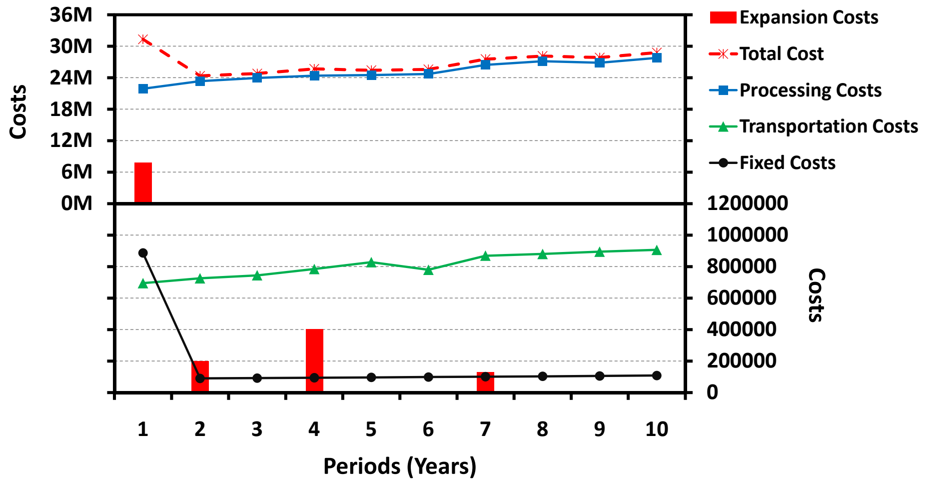


(c) for high rates of returns (scenario DH)

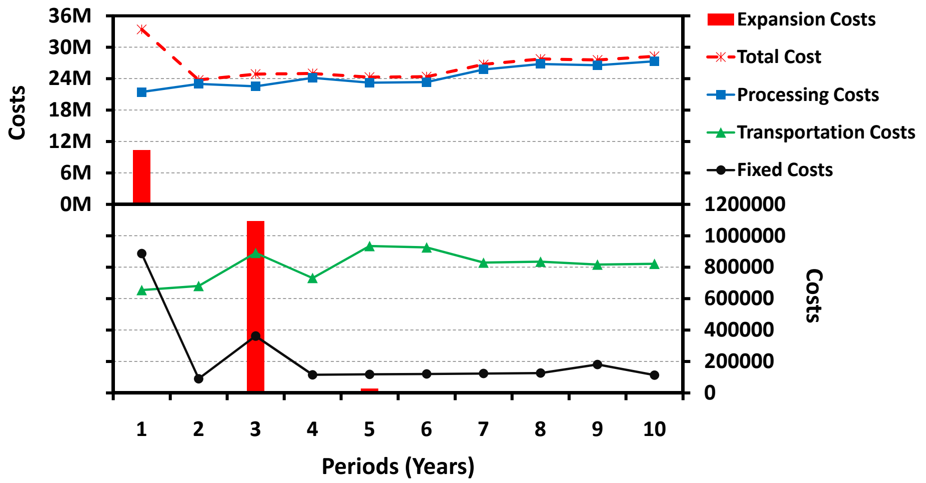
FIGURE 5.13: Total cost versus other costs (decreasing product demands)



(a) for low rates of returns (scenario SL)

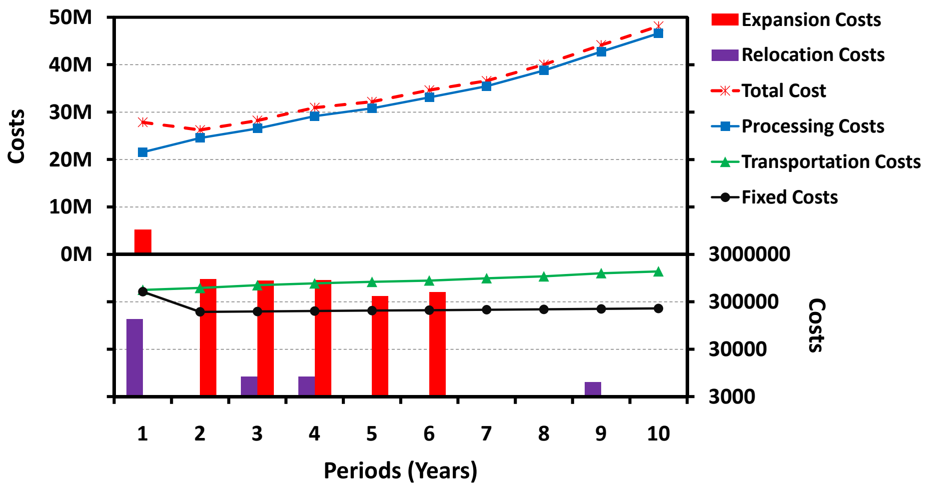


(b) for medium rates of returns (scenario SM)

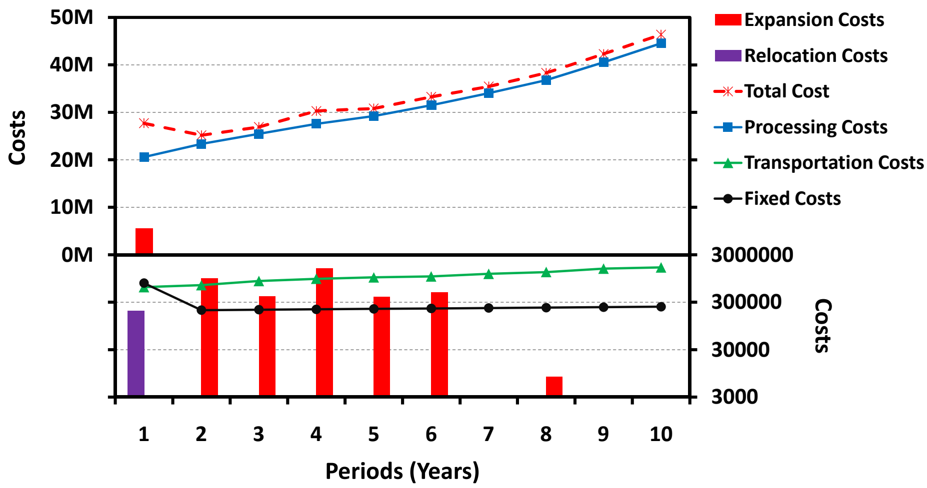


(c) for high rates of returns (scenario SH)

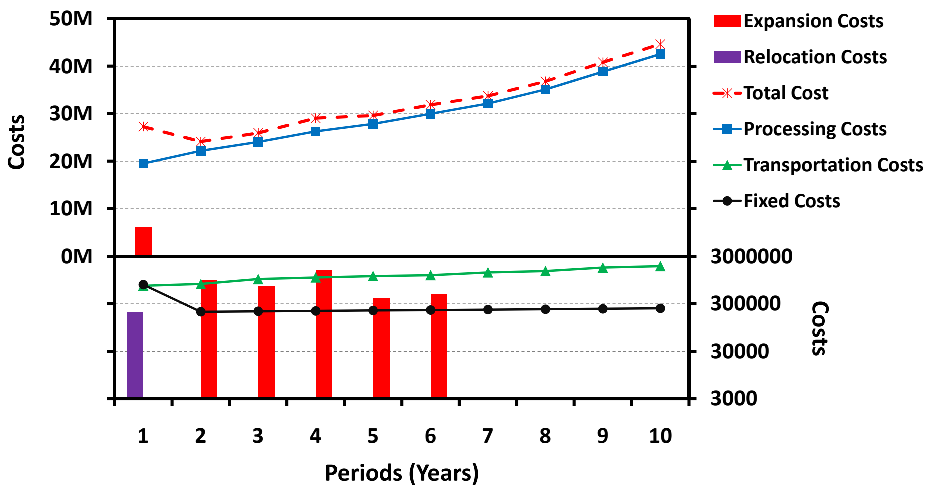
Figure 5.14: Total cost versus other costs (relatively stable product demands)



(a) for low rates of returns (scenario IL)

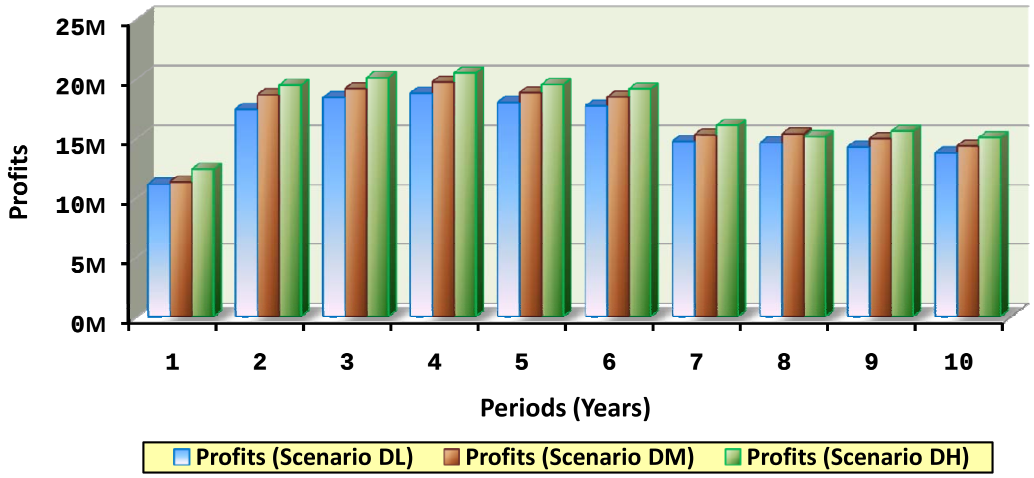


(b) for medium rates of returns (scenario IM)

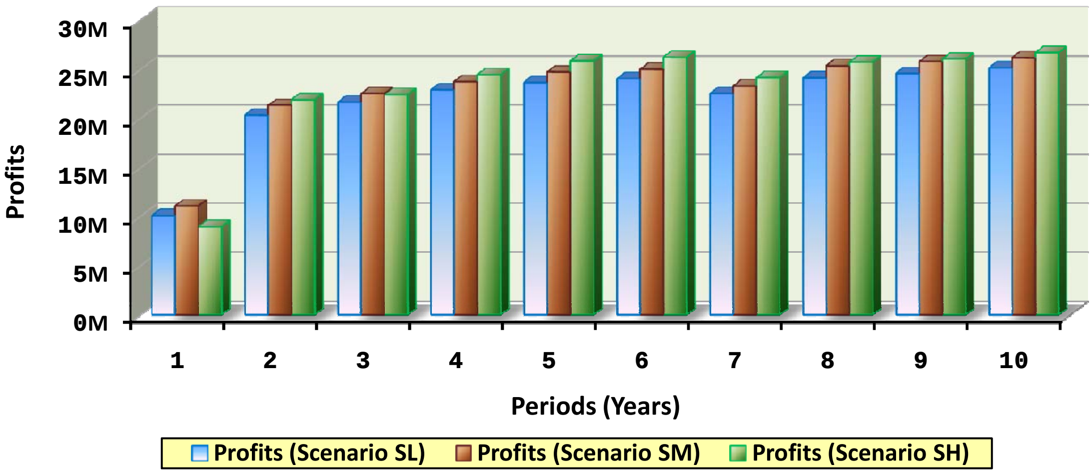


(c) for high rates of returns (scenario IH)

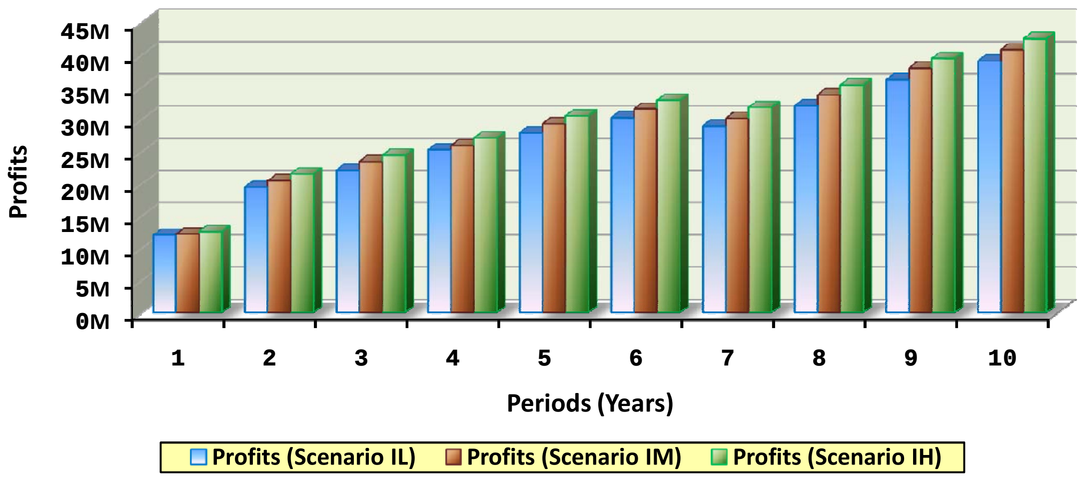
FIGURE 5.15: Total cost versus other costs (increasing product demands)



(a) scenarios for decreasing product demands



(b) scenarios for relatively stable product demands



(c) scenarios for increasing product demands

Figure 5.16: Profits for different rates of returns

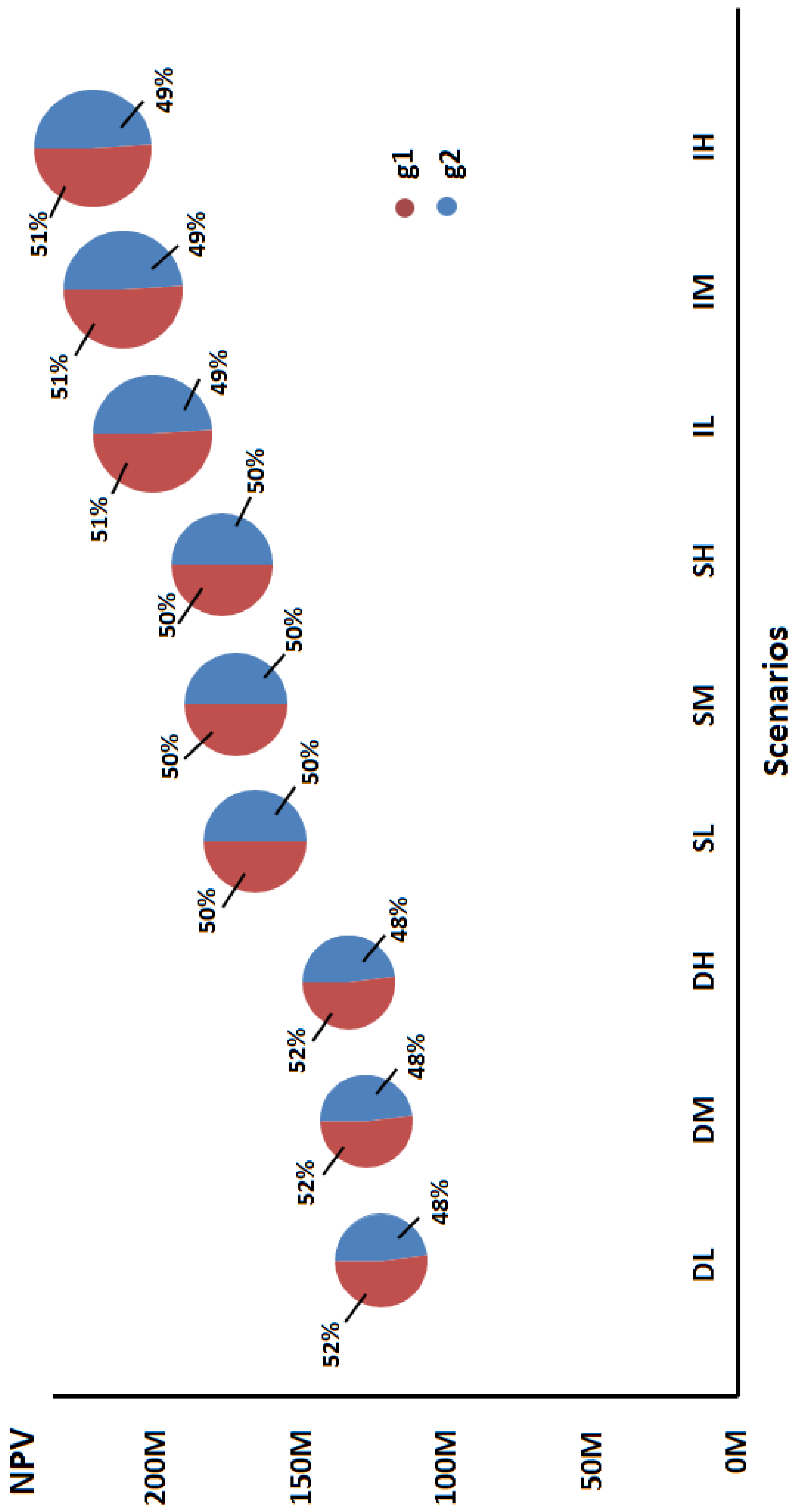


Figure 5.17: NPV for different rates of returns

are, however, much more expensive than transportation costs. It can be noticed from these figures that there are also capacity expansion and/or relocation costs throughout the planning horizon.

Moreover, there are fixed extra costs added during a given 10-year period due to the closing and opening of facilities. The costs of closing and opening facilities with respect to scenarios for decreasing demands can be seen in Figure 5.13. In scenario DL, the costs of closing the disassembly-remanufacturing center a2 at the existing plant site pl2, the costs of closing the distribution center b1 at the existing intermediate site in1 and the costs of opening the new intermediate site in2 for both distribution and collection centers b1 and b2 in the first period, the costs of closing the existing plant site pl2 and its production center a1 in the second period, as well as the costs of closing the existing intermediate site in1 and its collection center b2 in the fifth period are determined as 339,000, 44,3325 and 17,000, respectively. For scenario DM, the costs of closing the disassembly-remanufacturing center a2 at the existing plant site pl2, the costs of closing the existing intermediate site in1 and its distribution and collection center b1 and b2 and the costs of opening the new intermediate site in1 for both distribution and collection centers b1 and b2 in the first period, as well as the costs of closing the existing plant site pl2 and its production center a1 in the second period are found out to be 356,000 and 443,325, respectively. In scenario DH, the variation in fixed costs is the same as scenario DM except the costs increase 249,000 due to the opening of the disassembly-remanufacturing center a2 at the new plant site pl3 in the eighth period.

The costs of closing and opening facilities with respect to scenarios for relatively stable demands can be observed in Figure 5.14. The variation in facility closing and opening costs for scenarios SL and SM are the same. These costs are, the costs of closing the existing plant site pl2 and its production and disassembly-remanufacturing centers a1 and a2, the costs of closing the existing intermediate site in1 and its distribution and collection centers b1 and b2, as well as the costs of opening both distribution and collection centers b1 and b2 at the new intermediate site in2 in the first period (a total of 769,300). In scenario DH, the variation in fixed costs is the same as scenarios

SL and SM except the costs increase 249,000 due to the opening of the disassembly-remanufacturing center a2 at the new plant site pl3 in the third period.

Figure 5.15 depicts the costs of closing and opening facilities with respect to scenarios for increasing demands in addition to the total cost and other included costs. In the scenario IL case, the costs of closing the disassembly-remanufacturing center a2 at the existing plant site pl2, and the costs of opening both distribution and collection centers b1 and b2 at the new intermediate site in2 in the first period are determined as 97,500. The variation in facility closing and opening costs for scenarios IM and IH is the same. These costs are the costs of opening the new plant site pl3 for the disassembly-remanufacturing center a2 and the costs of opening the new intermediate site in2 for both distribution and collection centers b1 and b2 in the first period. The costs are totally equal to 558,000.

Figure 5.16 graphically represents the profits for different scenarios of changing demands and return rates. As expected in Figures 5.16(a)-5.16(c), by increasing the amount of return rates, the profits for each time period increase.

In term of the optimization criterion, Figure 5.17 depicts the optimal net present value (NPV) for all scenario cases. The results show that higher is better for both demands of customers and return rate values, which lead to higher NPV, and thus are more profitable investments in the long term.

5.1.6 Numerical Performance

To analyze the model behavior with the above-mentioned case study, the statistic comparison of the scenarios considered in this study is provided in Table 5.5.

Table 5.5(a) gives the results obtained by setting the gap tolerance to 0.0 and 0.00001. With setting a value for the gap tolerance, the MIP solver is instructed to stop as soon as the proportional difference between the solution found and the best theoretical objective function is guaranteed to be smaller than the specified termination tolerance [77]. Note that the default value of the stopping tolerance for MIPs is 0.10 or 10%, which is quite large. We improve the quality of solutions by adding the statement "<modelname>.optcr = <val>;" and solving for val = 0.01, 0.001, etc., observing how much more work is involved in reaching these tighter tolerances. The optimal solutions for scenarios DL, DM, SL and IL can be found with the gap tolerance 0.0 while the optimal solutions for remaining scenarios can be found with the gap tolerance 0.00001. A very small value near to zero of the gap tolerance setting can be used for the common models, but a small gap tolerance can cause a problem. Consider the proposed model in this chapter. Suppose that there are a huge number of elements in the optimization problem, as well as demand and return volumes from customers that are subject to fluctuations, it does not make sense to spend so much time optimizing the model exactly to optimality. The gap tolerance should be set to a value equal to or higher than the default so that the MIP optimization can stop earlier. The results presented in section 5.1.5.2 are performed at the gap tolerance 0.10 by default. By using the default value of the gap tolerance, the results show that the model performs well under these instances. The CPU times keep their low values for all scenarios. The obtained percent gaps are small and never exceed 3.98% (see Table 5.5(b)).

However, the main drawback of MILP models is their exponential growth when applied to real-world problem instances. Therefore, two questions will be raised in this section: firstly, what are the problems based on realistic situations?, and secondly, how do the models behave with large-scale problem instances?

In the literature, there are several previous models dealing with real-world closed-loop supply chains. For example, Schultmann et al. [113] presented the model that was applied to a closed-loop recycling network problem for spent batteries in Germany. The model of Krikke et al. [68] is another example that dealt with realistic closed-loop supply chains. The authors proposed the model, which was applied to a closed-loop supply chain design problem for refrigerators using real life R&D data. Their case study was carried out by the team of Tokyo University. This team obtained the data from a Large Japanese OEM of consumer electronics.

Scenarios	Objective values	Iterations	CPU (seconds)	Gap (%)
DL	125,886,377.7540	156,374	237.365	0.00
DM	131,6365,782.7263	29,661	31.842	0.00
DH	137,234,465.0898	20,121	23.967	0.00
SL	167,344,599.4398	320,604	612.996	0.00
SM	174,758,252.2295	45,053	45.497	0.00
SH	182,608,869.3515	394,291	471.933	0.00
IL	203,305,843.3214	75,008	124.427	0.00
IM	212,424,925.0588	7,922	11.468	0.00
IH	221,888,539.2514	8,516	21.030	0.00

(a) maximum relative optimality gap (optcr=0.0 or 0.00001)

Scenarios	Objective values	Iterations	CPU (seconds)	Gap (%)
DL	123,098,580.4113	1,659	0.890	2.33
DM	128,624,498.4891	1,617	0.765	2.24
DH	134,087,184.0504	1,572	0.765	2.42
SL	165,917,023.9137	1,744	0.797	0.93
SM	173,541,252.7695	1,646	0.734	0.78
SH	175,714,097.4246	1,469	0.703	3.98
IL	203,250,883.5034	22,471	30.514	0.03
IM	212,360,612.1363	1,943	2.156	0.06
IH	221,815,313.2713	1,840	1.093	0.04

(b) maximum relative optimality gap (optcr=default 0.10 real number)

Table 5.5: Numerical statistics for the example case study

Many problems in the real world are large and complex. In order to further explore the consistency in the model performance when dealing with large instances of the problem, some other cases should be investigated. Salema et al. [109] developed a strategic and tactical model for the simultaneous design of forward and reverse supply chains. The authors analyzed their model behavior with larger problem instances. These instances were randomly generated, and six runs were performed. Each run was performed under different parameters. Their model performs well under considerable large problem instances. However, it does not solve all problem instances.

Due to the nature of MILP, realistically size problems are very time consuming to solve optimally. For larger or very large problem instances. it is hard or impossible to solve with standard optimization software. This problem can be avoid by using heuristic algorithms. Generally, the advantage of heuristic algorithms is their ability to recognize the problem quickly, in some cases even being able to solve it. For instance, Lu and Bostel [76] used a Lagrangian heuristic method to solve a two-level facility location model for the reverse logistics systems that cover remanufacturing activities. The model was tested on the large size data set. They found that the algorithm provides a good performance in terms of computing time. Other techniques should be explored in order to speed up the resolution. These techniques may be decomposition problems, such as the Benders Decomposition. Üster et al. [125] used Benders Decomposition with alternative multiple cuts for a multi-product closed-loop supply chain network design model. The authors provided an effective problem formulation that is amenable to efficient Benders reformulation and an exact solution approach. They also developed an efficient dual solution approach to generate strong Benders cuts in addition to the classical single Benders cut approach. They found that with the use of multiple Benders cuts, as opposed to the classical single Benders cut approach, Benders cuts approach can generate stronger lower bounds and promoted faster convergence.

5.2 Relations of the Proposed Model to the Existing Literature

Since there have been numerous studies on allocation and/or location problems within reverse and closed-loop supply chain contexts, only key models proposed in the literature are discussed here. Tables 5.6 and 5.7 represent an overview of important articles, which are classified into two groups: reverse supply chain models and closed-loop supply chain models. Different mathematical techniques have been used to tackle such problems (for more details on mathematical techniques see the previous papers on these Tables and references therein). We summarize the major findings from the literature below.

Article	Objective Function[a]	Period[b]	Commodity[b]	Echelon[b]	Capacity Constraints[c]	Relocation and/or Expansion[d]
Reverse Supply Chain Models						
[2] Ahluwalia and Nema, 2006	M	M	M	M	C	NO
[6] Alumur et al. 2012	P	M	M	M	C	CE
[17] Barros et al.,1998	C	S	S	M	C	NO
[36] Du and Evans,2008	M	S	M	M	C	NO
[62] Jayaraman et al.,2003	C	S	S	M	C	NO
[78] Mansour and Zarei,2008	C	M	S	M	C	NO
[83] Melachrinousdis et al.,1995	M	M	S	M	C	NO
[94] Mutha and Pokharel,2008	C	S	M	M	C	NO
[117] Spengler et al.,1997	P	S	M	M	C	NO
Closed-Loop Supply Chain Models						
[30] Demirel and Gökçen,2008	C	S	M	M	C	NO
[41] Feischmann et al.,2001	C	S	M	M	U	NO
[61] Jayaraman et al.,1999	C	S	M	M	C	NO
[66] Ko and Evans,2007	C	M	M	M	C	CE
[68] Krikke et al.,2003	M	S	M	M	U	NO
[71] Lee and Dong 2009	C	M	M	M	C	NO
[76] Lu and Bostel,2007	C	S	S	M	U	NO
[80] Marin and Pelegrin,1998	C	S	S	S	U	NO
[107] Sahyouni et al.,2007	C	S	S	M	U	NO
[109] Salema et al.,2009	P	M	M	M	C	NO
[124] Üster et al.,2007	C	S	M	M	U	NO
[130] Wang et al.,2010	C	S	M	M	C	NO
The Proposed Model	NPV	M	M	M	C	CE,CR

[a] C: Cost, P: Profit, M: Multiple, NPV: Net Present Value.
[b] S: Single, M: Multiple.
[c] U: Uncapacitated, C: Capacitated.
[d] CR: Capacity Relocation, CE: Capacity Expansion, NO: No Capacity Relocation and Expansion.

TABLE 5.6: Classification of existing models according to modeling features

Most models found in the reverse supply chain literature focus on maximizing product value recovery at least cost possible. The most commonly used technique to find solutions is mixed-integer programming (MIP). Spengler et al. [117] introduced mixed-integer linear programming (MILP) models for the recycling of industrial by-products in the iron and steel industries. Mutha and Pokharel [94] were among the first authors to explicitly present a general framework for modeling reverse supply chains. They developed a generic MILP model for the design of reverse logistics and remanufacturing using new and old product modules. In addition to the model of Mutha and Pokharel, Alumur et al. [6] afterwards presented a generic MILP model that is flexible to incorporate most of the reverse network structure in practice. Their model allowed for gradually changing in the network structure and in the capacities of the facilities. According to Melachrinoudis et al. [83], and Ahluwalia and Nema [2], multi-objective mixed integer programming (MOMIP) models were established for reverse supply chains. Their models were designed to incorporate conflicting factors: costs and environmental risks. Melachrinousdis et al. developed an effective decision-aid tool for the location of landfills. Ahluwalia and Nema offered a reverse logistics model for selecting an optimum configuration of computer waste management facilities and allocating waste to these facilities. In a subsequent paper, a bi-objective mixed integer programming (BOMIP) model was proposed by Du and Evans [36] for the returns requiring repair service. One objective relates to the overall costs, and the other relates to the total tardiness of cycle time. There have been comparatively few studies on heuristics that can be used to simplify solutions to the problems. More recently by Barros et al. [17], a heuristic procedure for making quick decisions on the recycling of sand from construction waste was presented. Jayaraman et al. [62], and Mansour and Zarei et al. [78] specifically developed heuristic procedures for their models. A model provided by Jayaraman et al. was formulated to tackle very complex reverse distribution problems, which cannot be solved with typical (MIP) tools. Mansour and Zarei et al. conducted an efficient management of the recovery process for end-of-life vehicles (ELVs).

Article	Closing and Opening Facilities	Directional Flow of Facilities[a]	External Suppliers	Bill of Materials	External Subcontractors
Reverse supply chain models					
[2] Ahluwalia and Nema, 2006	✓	UF			
[6] Alumur et al. 2012	✓	UF		✓	✓
[17] Barros et al.,1998		UF			
[36] Du and Evans,2008		UF			
[62] Jayaraman et al.,2003		UF			
[78] Mansour and Zarei,2008	✓	UF			
[83] Melachrinousdis et al.,1995	✓	UF			
[94] Mutha and Pokharel,2008		UF	✓	✓	
[117] Spengler et al.,1997		UF			
Closed-loop supply chain models					
[30] Demirel and Goekcen,2008		UF		✓	
[41] Feischmann et al.,2001		BF			
[61] Jayaraman et al.,1999		UF			
[66] Ko and Evans,2007	✓	UF			
[68] Krikke et al.,2003		UF	✓	✓	
[71] Lee and Dong 2009	✓	HF			
[76] Lu and Bostel,2007		HF			
[80] Marin and Pelegrin,1998		BF			
[107] Sahyouni et al.,2007		HF			
[109] Salema et al.,2009	✓	UF			
[124] Üster et al.,2007		UF			
[130] Wang et al.,2010		UF	✓	✓	
The proposed model	✓	HF	✓	✓	✓

[a] UF: Unidirectional Flow, BF: Bidirectional Flow, HF: Hybrid Uni/Bidirectional Flow.

TABLE 5.7: Additional features of existing models

Closed-loop supply chain models are similar to reverse supply chain models, but concurrently optimize the forward and reverse networks, resulting in increased efficiency and complexity of the system. Both the works of Jayaraman et al. [61] and Fleischmann et al. [41] were the earliest papers proposing generic MILP models for closed-loop supply chains. Jayaraman et al. simultaneously considered distribution/remanufacturing locations, the transshipment, as well as optimal production and storage quantities of remanufactured products and cores. The model of Fleischmann et al. was used to decide whether or not to add a recovery network to an existing production/distribution network. Later on, Demirel and Gökçen [30], and Salema et al. [109] proposed the extensions of generic MILP models. To meet diverse industries' requirements, Demirel and Gökçen reported a case of a remanufacturing system in which both forward and reverse flows and their mutual interactions were taken into account at the same time. Salema et al. dealt with the design of a strategic and tactical model by involving two interconnected time scales. A macro time scale corresponds to strategic decisions while a micro time scale corresponds to tactical decisions. To account for the uncertainty, Lee and Dong et al. [71] developed a two-stage stochastic programming model for reverse logistics network design. A solution approach combining a sample average approximation (SAA) method with a heuristic algorithm was proposed. In the paper by Krikke et al. [68], a single period, MOMIP model was developed for an application to refrigerators. The authors investigated the integration of forward and reverse distribution networks to support multiple product design options and multiple product recovery options. The objectives are to minimize costs, and negative environmental effects of energy and waste management actions. Some papers have described the application of Lagrangian and/or heuristic methods to generate good feasible solutions to the problems. Martin and Pelegrin [80] solved the return plant location problem, using heuristic and exact algorithms based on a Lagrangian decomposition. Each plant can supply the demands and receive the returned products from customers. In Lu and Bostel [76], a Lagrangian heuristic approach was proposed for facility location problems in logistics systems, which covered remanufacturing activities. The formulations of Sahyouni et al. [107] extended the uncapacitated fixed-charge location model by combining forward and reverse distribution activities through the location of bidirectional distribution centers. The authors presented a Lagrangian relaxation-based solution algorithm, which is quick and effective. Several pertinent models have been developed by using more specific techniques. Üster et al. [124] gave an effective formulation of a closed-loop network problem using Benders decomposition. Ko and Evans [66] introduced a genetic algorithm-based heuristic for the dynamic integrated forward and reverse network for third party logistics providers (3PLs). Very recently, Wang et al. [130] adopted a generalized closed-loop logistics model with a spanning-tree based genetic algorithm that allows solving large scale problems within a short time.

It can be seen from both Tables that most of the existing literature proposes closed-loop supply chain models. Some relevant papers introduce models considering only reverse supply chains. Table 5.6 clearly shows that studies of both reverse and closed-loop supply chains mostly refer to multi-echelon cases. Only one previous paper focuses on single-echelon cases. There is also a significant coverage in the literature relating to cost minimization problems. One-third of papers consider a facility location problem with the condition for the closing and opening of facility sites. As shown in Table 5.6, many of the papers deal with single period, rather than multiple periods. Most of the previous models accommodate multiple commodities. Furthermore, a large number of papers present uncapacitated or capacitated models for stand-alone forward and reverse flows (i.e. unidirectional flows) of facilities, while a small number of papers considers the combination of forward and reverse logistics facilities through the location of bidirectional or hybrid uni/bidirectional facilities. Another conclusion from Table 5.7 is that the integration of some key strategic aspects, namely relocation and expansion of facilities, external suppliers and subcontractors, are still scarce in the literature.

Despite the aforementioned models, none of these models consider all the modeling features that we incorporate into the model proposed here for the capacitated facility location problem in closed-loop supply chains: multiple commodities, multiple echelons, multiple periods, closing and opening of facilities, capacity expansion, and hybrid uni/bidirectional flows of facilities. We attempt to fill a gap in the literature. Our approach generalizes and extends the existing models by formulating the model for an even broader perspective, which involves all the features that play a crucial role in helping to shape the optimal structure that fits the closed-loop supply chain strategy.

The other aspects, namely external suppliers, bill of materials, external subcontractors and budget constraints are also included in the model. In particular, we focus on the case of relocating the capacity in addition to the capacity expansion. To evaluate long-term investments, our objective is to maximize the net present value (NPV) for the whole supply chain. The last row of Tables 5.6 and 5.7 is the proposed model in this chapter.

6

Conclusions and Directions of Future Research

In this thesis, we present a set of dynamic (multi-period) models for facility location in closed-loop supply chain design. We first develop a generic MILP model for facility location in the simultaneous design and planning of forward and reverse supply chain networks in Chapter 3. Forward and reverse supply chain networks are comprised of multi-echelon structures, creating a link between plants and customers through distribution or collection centers. The model is demonstrated through an example by using a set of the generated data reflecting fictitious test cases. Three different scenario cases with the low, medium and high rates of returns have been established to compare the performance of these scenarios and to enable better decisions to be made. Hence, a unique tool to understand how the supply chain system behaves under different return rates is given.

The first MILP model in Chapter 4 is presented for integrating forward and reverse logistics activities through the location of bidirectional forward/reverse facilities in addition to dedicated, unidirectional forward and reverse facilities. An example case is conducted for three different network scenarios; forward dominant network, reverse dominant network and neither forward nor reverse dominant network. The second MILP model in Chapter 4 is an extension of the first model in this chapter. The model additionally involves decisions for capacity relocation and expansion of facilities. These models are illustrated by applying it to the case of gradually increasing product demands.

In Chapter 5, we propose a novel and comprehensive MILP model for facility location in strategic long-term closed-loop supply chain planning. The model includes all key features of the facility location problem, namely multi-site processing facilities, multiple periods, multiple products, several location-allocation options, supplier selection and supply chain subcontracting. To the best of our knowledge, it is the first to include several useful features, i.e., hybrid uni/bidirectional flows of facilities, capacity relocation and capacity expansion in a closed-loop supply chain network design problem. A case study with nine different scenarios are considered to illustrate the effects of the changes in volume of demands and returns. These scenarios are decreasing demands/low rates of returns, decreasing demands/medium rates of returns, decreasing demands/high rates of returns, relatively stable demands/low rates of returns, relatively stable demands/medium rates of returns, relatively stable demand/high rates of returns, increasing demands/low rates of returns, increasing demands/medium rates of returns and increasing demands/high rates of returns.

As a main conclusion, it may be stated that manufacturing firms should motivate customers to return their used products to improve their competitive advantage, to become more environmentally friendly responsible and to be able to get more profit. All detailed numerical case studies show that the configuration of both forward and reverse channels has a strong influence on the performance of each other. Facilities should be close to demand and supply points, in case transportation is a large portion of the total cost, while facilities with high processing and/or fixed operating costs require centralized operations. Bidirectional facilities eliminate substantial investment in infrastructure, equipment, and human resources. Only separate forward and reverse facilities might be beneficial in case the transportation and/or (re) manufacturing are a large portion of the total cost. As can be noticed from the results, the increase in both product demands and returns cause the capacity relocation and expansion of facilities to increase. We observe that the NPV maximization is the more appropriate objective for a long-range planning horizon. It can be concluded from the results that the models presented in this thesis provide a great insight into the quantitative aspects of strategic closed-loop supply chain planning.

The proposed model in Chapter 5 can be further improved in respect to a few points. It can be modified to relax the assumption of deterministic demands and returns in the problem and treat them as stochastic. In the case of a realistic large-scale problem, a heuristic procedure should be developed. Lastly, the theme of further research should include multi-objective treatments of closed-loop supply chain network design, which help to achieve environmental impact minimization at a desired economic performance.

A

Appendix A

A.1 Input Data for an Example Problem with Increasing Product Returns

This appendix represents the actual parameter data used for an example problem dealing with three different levels (i.e., low, medium and high) of product return volumes from customers in section 3.3. All the following parameter data on Tables A.1-A.15 together with the data on Tables 3.1 and 3.2 in section 3.3.1 are provided for a generic facility location model for closed-loop supply chains in section 3.2.

A.1.1 Costs

1st yr.	2nd yr.	3rd yr.	4th yr.	5th yr.
15	15.5	16	16.5	17

Table A.1: Cost of purchasing one unit of part/component (CB_t)

Plants	Products	Processing costs in each period (year)				
		1st yr.	2nd yr.	3rd yr.	4th yr.	5th yr.
pl1	p1	200	205	205	210	210
	p2	400	408	416	424	432
pl2	p1	230	235	240	240	240
	p2	400	408	416	424	432
pl3	p1	250	255	260	265	270
	p2	300	308	316	324	332
dl1	p1	11	12	13	14	15
	p2	15	16	17	18	19
dl2	p1	9	10	11	12	13
	p2	21	22	23	24	25

Table A.2: Cost of processing one unit of product ($CP_{j,p,t}$)

Shipping routes	Products	Shipping costs in each period (year)				
		1st yr.	2nd yr.	3rd yr.	4th yr.	5th yr.
pl1 to in1	p1	8	8	8.4	8.4	8.8
	p2	8	8	8.4	8.4	8.8
pl1 to in2	p1	4	4	4.2	4.2	4.4
	p2	4	4	4.2	4.2	4.4
pl2 to in1	p1	8	8	8.4	8.4	8.8
	p2	8	8	8.4	8.4	8.8

Table A.3: Cost of shipping one unit of product ($CT_{l,l',p,t}$)

Shipping routes	Products	Shipping costs in each period (year)				
		1st yr.	2nd yr.	3rd yr.	4th yr.	5th yr.
pl2 to in2	p1	4	4	4.2	4.2	4.4
	p2	4	4	4.2	4.2	4.4
pl3 to in1	p1	8	8	8.4	8.4	8.8
	p2	8	8	8.4	8.4	8.8
pl3 to in2	p1	8	8	8.4	8.4	8.8
	p2	8	8	8.4	8.4	8.8
in1 to cu1	p1	8	8	8.4	8.4	8.8
	p2	8	8	8.4	8.4	8.8
in1 to cu2	p1	8	8	8.4	8.4	8.8
	p2	8	8	8.4	8.4	8.8
in1 to cu3	p1	8	8	8.4	8.4	8.8
	p2	8	8	8.4	8.4	8.8
in2 to cu1	p1	4	4	4.2	4.2	4.4
	p2	4	4	4.2	4.2	4.4
in2 to cu2	p1	4	4	4.2	4.2	4.4
	p2	4	4	4.2	4.2	4.4
in2 to cu3	p1	4	4	4.2	4.2	4.4
	p2	4	4	4.2	4.2	4.4
cu1 to cl1	p1	4	4	4.2	4.2	4.4
	p2	4	4	4.2	4.2	4.4
cu1 to cl2	p1	2	2	2.1	2.1	2.2
	p2	2	2	2.1	2.1	2.2
cu2 to cl1	p1	4	4	4.2	4.2	4.4
	p2	4	4	4.2	4.2	4.4
cu2 to cl2	p1	2	2	2.1	2.1	2.2
	p2	2	2	2.1	2.1	2.2

Table A.3: Cost of shipping one unit of product $\left(CT_{l,l',p,t}\right)$ (continued)

Shipping routes	**Products**	**Shipping costs in each period (year)**				
		1st yr.	**2nd yr.**	**3rd yr.**	**4th yr.**	**5th yr.**
cu3 to cl1	p1	4	4	4.2	4.2	4.4
	p2	4	4	4.2	4.2	4.4
cu3 to cl2	p1	2	2	2.1	2.1	2.2
	p2	2	2	2.1	2.1	2.2
cl1 to dl1	p1	4	4	4.2	4.2	4.4
	p2	4	4	4.2	4.2	4.4
cl1 to dl2	p1	4	4	4.2	4.2	4.4
	p2	4	4	4.2	4.2	4.4
cl2 to dl1	p1	2	2	2.1	2.1	2.2
	p2	2	2	2.1	2.1	2.2
cl2 to dl2	p1	4	4	4.2	4.2	4.4
	p2	4	4	4.2	4.2	4.4

Table A.3: Cost of shipping one unit of product $\left(CT_{l,l',p,t}\right)$ (continued)

1st yr.	**2nd yr.**	**3rd yr.**	**4th yr.**	**5th yr.**
0.1	0.1	0.105	0.105	0.11

Table A.4: Cost of shipping one unit of part/component (CR_t)

Selectable facilities	**Costs of operating selectable facilities in each period (year)**				
	1st yr.	**2nd yr.**	**3rd yr.**	**4th yr.**	**5th yr.**
pl1	50000	51250	52531	53844	55190
pl2	50000	51250	52531	53844	55190
pl3	50000	51250	52531	53844	55190
dl1	15000	15375	15759	16153	16557

Table A.5: Costs of operating selectable facilities $(CF_{o,t})$

Selectable facilities	Costs of operating selectable facilities in each period (year)				
	1st yr.	**2nd yr.**	**3rd yr.**	**4th yr.**	**5th yr.**
dl2	15000	15375	15759	16153	16557
in1	10250	10500	10762	11031	11307
in2	10250	10500	10762	11031	11307
cl1	6150	6457	6618	6784	6954
cl2	6150	6457	6618	6784	6954

Table A.5: Costs of operating selectable facilities ($CF_{o,t}$) (continued)

Existing facilities	Costs of closing existing facilities in each period (year)				
	1st yr.	**2nd yr.**	**3rd yr.**	**4th yr.**	**5th yr.**
pl1	430000	430000	430000	430000	430000
pl2	430000	430000	430000	430000	430000
dl1	70000	70000	70000	70000	70000
in1	30000	30000	30000	30000	30000
cl1	15000	15000	15000	15000	15000

Table A.6: Costs of closing existing facilities ($CC_{e,t}$)

New facilities	Costs of establishing new facilities in each period (year)				
	1st yr.	**2nd yr.**	**3rd yr.**	**4th yr.**	**5th yr.**
pl3	630000	630000	630000	630000	630000
dl2	210000	210000	210000	210000	210000
in2	150000	150000	150000	150000	150000
cl2	85000	85000	85000	85000	85000

Table A.7: Costs of establishing new facilities ($CO_{n,t}$)

Disassembly-remanufacturing plants	Products	Disposal costs in each period (year)				
		1st yr.	2nd yr.	3rd yr.	4th yr.	5th yr.
dl1	p1	1	1.05	1.1	1.15	1.2
	p2	1	1.05	1.1	1.15	1.2
dl2	p1	1	1.05	1.1	1.15	1.2
	p2	1	1.05	1.1	1.15	1.2

Table A.8: Cost of disposing one unit of product ($CD_{b,p,t}$)

A.1.2 Other Parameter Data

Selectable facilities	Maximum allowable capacity
pl1	110000
pl2	90000
pl3	100000
dl1	70000
dl2	80000
in1	120000
in2	140000
cl1	110000
cl2	120000

Table A.9: Maximum allowable capacity at selectable sites (KO_o^{max})

Selectable facilities	Minimum allowable capacity
pl1	500
pl2	500
pl3	500
dl1	100
dl2	100
in1	500
in2	500
cl1	100
cl2	100

Table A.10: Minimum allowable capacity at selectable sites $\left(KO_o^{min}\right)$

Plants	Products	Unit capacity consumption factors
pl1	p1	1
	p2	1.1
pl2	p1	1
	p2	1.1
pl3	p1	1
	p2	1.1
dl1	p1	1
	p2	1.2
dl2	p1	1
	p2	1.2

Table A.11: Unit capacity consumption factors of products processed at plants $(UJ_{j,p})$

Shipping routes	**Products**	**Unit capacity consumption factors**
pl1 to in1	p1	1
	p2	1.1
pl1 to in2	p1	1
	p2	1.1
pl2 to in1	p1	1
	p2	1.1
pl2 to in2	p1	1
	p2	1.1
pl3 to in1	p1	1
	p2	1.1
pl3 to in2	p1	1
	p2	1.1
cu1 to cl1	p1	1
	p2	1.1
cu1 to cl2	p1	1
	p2	1.1
cu2 to cl1	p1	1
	p2	1.1
cu2 to cl2	p1	1
	p2	1.1
cu3 to cl1	p1	1
	p2	1.1
cu3 to cl2	p1	1
	p2	1.1

Table A.12: Unit capacity consumption factors of products shipped to intermediate centers ($UI_{l,i,p}$)

Products	Amount for assembling products
p1	5
p2	8

Table A.13: Amount of parts/components for assembling one unit of product (AM_p)

Products	Amount from disassembling products
p1	5
p2	7

Table A.14: Amount of parts/components from disassembling one unit of product (RM_p)

Products	Fraction of products satisfy specs in each period (year)				
	1st yr.	2nd yr.	3rd yr.	4th yr.	5th yr.
p1	0.7	0.7	0.7	0.7	0.7
p2	0.8	0.8	0.8	0.85	0.8

Table A.15: Fraction of returned products satisfy the quality specifications ($FR_{p,t}$)

A.2 Programming Code for a Generic Facility Location Model for Closed-Loop Supply Chains

This appendix provides the GAMS programming code of a generic facility location model for closed-loop supply chains in section 3.2. The model is coded for an example problem with increasing product returns in section 3.3. The complete model formulated in GAMS is produced as follows[1].

Generic_Model.gms

```
$ontext
This is the formulation of a generic facility location model for closed-loop supply chain
in the file "Generic_Model.gms".
$offtext

$Include Index_sets.gms
$Include Parameters.gms
$Include Decision_variables.gms

Equations
****************************************************
*Objective function*
****************************************************

tcost       'total cost'

****************************************************
*Constraints*
****************************************************
*Forward flow constraints

manufac     'provide required quantities for manufacturing products'
```

[1] See [77, 104] for more details about GAMS programming and optimization.

```
blpdds    'assure the connection between manufacturing process and the
          outbound flows'
flowds    'flow conservation at distribution centers'
demand    'ensure the customer demands are met'

*Reverse flow constraints

ratecus   'predefined return rate of products is used as the returned amount
          from customers'
blcuscl   'balance the returned products transported to collection centers'
blclda    'flow conservation at collection centers'
bldapd    'balance the reusable parts/components at disassembly-remanufacturing
          plants'

*Capacity constraints
**Capacity constraints of plants

maxj      'limit maximum processing capacity at plants'
minj      'limit minimum processing capacity at plants'

**Capacity constraints of intermediate centers

maxi      'limit maximum processing capacity at intermediate centers'
mini      'limit minimum processing capacity at intermediate centers'

*Logical constraints

opere     'if existing facilities are closed, they cannot be reopend'
opern     'if new facilities are opened, they cannot be closed'
;
*________________________________________*
*Objective function*
*________________________________________*
tcost.. obj =e=
```

*Variable purchasing, processing and transportation costs (TOC1)

(**sum**((j,a,t), CP(j,p,t)*x(j,p,t))

+**sum**((l,lp,p,t)$(**ord**(l) ne **ord**(lp)), CT(l,lp,p,t)*y(l,lp,p,t))

+**sum**((b,a,t), CR(t)*q(b,a,t))+**sum**((a,t), CB(t)*z(a,t))

*Fixed costs of operating, closing and establishing Facilities (TOC2)

+**sum**((o,t), CF(o,t)*varphi(o,t))+**sum**(e, CC(e,"1")*(1-varphi(e,"1")))

+**sum**(e,t)$(**ord**(t) ne 1), CC(e,t)*(varphi(e,t-1)-varphi(e,t)))

+**sum**((n,t), CO(n,t)*(varphi(n,t)-varphi(n,t-1)))

*Variable disposal costs (TOC3)

+**sum**((b,p,t), CD((b,p,t)*(1-FR(p,t))*x(b,p,t)))

;

____

Constraints

____

*Forward flow constraints

manufac(a,t).. z(a,t)+**sum**(b, q(b,a,t)) =e= **sum**(p, x(a,p,t)*AM(p));

blpdds(a,p,t).. x(a,p,t) =e= **sum**(d, y(a,d,p,t));

flowds(d,p,t).. **sum**(a, y(a,d,p,t)) =e= **sum**(k, y(d,k,p,t));

demand(k,p,t).. **sum**(d, y(d,k,p,t)) =e= DP(k,p,t);

*Reverse flow constraints

ratecus(k,p,t).. **sum**(d, y(d,k,p,t))*RC(k,p,t) =e= **sum(**c, y(k,c,p,t));

blcuscl(c,p,t).. **sum**(k, y(k,c,p,t)) =e= **sum**(b, y(c,b,p,t));

blclda(b,p,t).. **sum**(c, y(c,b,p,t)) =e= x(b,p,t);

bldapd(b,t).. **sum**(p, x(b,p,t)*FR(p,t)*RM(p)) =e= **sum**(a, q(b,a,t));

*Capacity constraints

**Capacity constraints of plants

maxj(j,t).. **sum**(p, UJ(j,p)*x(j,p,t)) =l= KOmax(j)*varphi(j,t);

```
minj(j,t).. sum(p, UJ(j,p)*x(j,p,t)) =g= KOmin(j)*varphi(j,t);

**Capacity constraints of intermediate centers
maxi(i,t).. sum((l,p), UI(l,i,p)*y(l,i,p,t)) =l= KOmax(i)*varphi(i,t);
mini(i,t).. sum((l,p), UI(l,i,p)*y(l,i,p,t)) =g= KOmin(i)*varphi(i,t);

*Logical constraints
opere(e,t)$(ord(t) ne card(t)).. varphi(e,t) =g= varphi(e,t+1));
opern(n,t)$(ord(t) ne card(t)).. varphi(n,t) =l= varphi(n,t+1));

model flcl /all/;
option limrow=10000;
solve flcl using mip minimizing obj;
display x.l, y.l, z.l, q.l;

$Include Results.gms
```

Index_sets.gms

```
$ontext
The include file "Index_sets.gms" contains index sets of the formulation in the file
"Generic_Model.gms".
$offtext

****************************************************
*Index sets*
****************************************************
Sets

l     'facilities' /pl1, pl2, pl3, dl1, dl2, in1, in2, cl1, cl2, cu1, cu2, cu3/
o(l)  'selectable facilities' /pl1, pl2, pl3, dl1, dl2, in1, in2, cl1, cl2/
e(o)  'existing facilities' /pl1, pl2, , dl1, in1, cl1/
n(o)  'potential sites for establishing new facilities' /pl3, dl2, in2, cl2/
j(o)  'plants' /pl1, pl2, pl3, dl1, dl2/
```

i(o) 'intermediate centers' /in1, in2, cl1, cl2/

a(j) 'production plants' /pl1, pl2, pl3/

b(j) 'disassembly-remanufacturing plants' /dl1, dl2/

d(i) 'distribution centers' /in1, in2/

c(i) 'collection centers' /cl1, cl2/

k(l) 'customer locations' /cu1, cu2, cu3/

p 'product types' /p1, pl2/

t 'periods in the planning horizon' /1*5/

;

alias (lp, l);

Parameters.gms

$ontext

The include file "Parameters.gms" contains parameters of the formulation in the file "Generic_Model.gms".

$offtext

****

Parameters

****

*Costs

Parameter

CB(t) 'variable cost of purchasing one unit of part/component in period t'

```
/ 1   15
  2   15.5
  3   16
  4   16.5
  5   17   /
;
```

Table CP(j,p,t) ’variable cost of processing one unit of product p by plant j in period t’

	1	2	3	4	5
pl1.p1	200	205	205	210	210
pl1.p2	400	408	416	424	432
pl2.p1	230	235	240	240	240
pl2.p2	400	408	416	424	432
pl3.p1	250	255	260	265	270
pl3.p2	300	308	316	324	332
dl1.p1	11	12	13	14	15
dl1.p2	15	16	17	18	19
dl2.p1	9	10	11	12	13
dl2.p2	21	22	23	24	25

;

Table CT(l,lp,p,t) ’variable cost of shipping one unit of product p from facility l to facility lp in period t’

	1	2	3	4	5
pl1.in1.p1	8	8	8.4	8.4	8.8
pl1.in1.p2	8	8	8.4	8.4	8.8
pl1.in2.p1	4	4	4.2	4.2	4.4
pl1.in2.p2	4	4	4.2	4.2	4.4
pl2.in1.p1	8	8	8.4	8.4	8.8
pl2.in1.p2	8	8	8.4	8.4	8.8
pl2.in2.p1	4	4	4.2	4.2	4.4
pl2.in2.p2	4	4	4.2	4.2	4.4
pl3.in1.p1	8	8	8.4	8.4	8.8
pl3.in1.p2	8	8	8.4	8.4	8.8
pl3.in2.p1	8	8	8.4	8.4	8.8
pl3.in2.p2	8	8	8.4	8.4	8.8

in1.cu1.p1	8	8	8.4	8.4	8.8
in1.cu1.p2	8	8	8.4	8.4	8.8
in1.cu2.p1	8	8	8.4	8.4	8.8
in1.cu2.p2	8	8	8.4	8.4	8.8
in1.cu3.p1	8	8	8.4	8.4	8.8
in1.cu3.p2	8	8	8.4	8.4	8.8
in2.cu1.p1	4	4	4.2	4.2	4.4
in2.cu1.p2	4	4	4.2	4.2	4.4
in2.cu2.p1	4	4	4.2	4.2	4.4
in2.cu2.p2	4	4	4.2	4.2	4.4
in2.cu3.p1	4	4	4.2	4.2	4.4
in2.cu3.p2	4	4	4.2	4.2	4.4
cu1.cl1.p1	4	4	4.2	4.2	4.4
cu1.cl1.p2	4	4	4.2	4.2	4.4
cu1.cl2.p1	2	2	2.1	2.1	2.2
cu1.cl2.p2	2	2	2.1	2.1	2.2
cu2.cl1.p1	4	4	4.2	4.2	4.4
cu2.cl1.p2	4	4	4.2	4.2	4.4
cu2.cl2.p1	2	2	2.1	2.1	2.2
cu2.cl2.p2	2	2	2.1	2.1	2.2
cu3.cl1.p1	4	4	4.2	4.2	4.4
cu3.cl1.p2	4	4	4.2	4.2	4.4
cu3.cl2.p1	2	2	2.1	2.1	2.2
cu3.cl2.p2	2	2	2.1	2.1	2.2
cl1.dl1.p1	4	4	4.2	4.2	4.4
cl1.dl1.p2	4	4	4.2	4.2	4.4
cl1.dl2.p1	4	4	4.2	4.2	4.4
cl1.dl2.p2	4	4	4.2	4.2	4.4
cl2.dl1.p1	2	2	2.1	2.1	2.2
cl2.dl1.p2	2	2	2.1	2.1	2.2

```
cl2.dl2.p1     4     4     4.2     4.2     4.4
cl2.dl2.p2     4     4     4.2     4.2     4.4
;
```

Parameter

CR(t) 'variable cost of shipping one unit of part/component from a disassembly-remanufacturing plant in period t'

```
/ 1    0.1
  2    0.1
  3    0.105
  4    0.105
  5    0.11  /
;
```

Table CF(o,t) 'fixed cost of operating selectable facility o in period t'

	1	2	3	4	5
pl1	50000	51250	52531	53844	55190
pl2	50000	51250	52531	53844	55190
pl3	50000	51250	52531	53844	55190
dl1	15000	15375	15759	16153	16557
dl2	15000	15375	15759	16153	16557
in1	10250	10500	10762	11031	11307
in2	10250	10500	10762	11031	11307
cl1	6150	6457	6618	6784	6954
cl2	6150	6457	6618	6784	6954

;

Table CC(e,t) 'fixed cost of closing existing facility e in period t'

	1	2	3	4	5
pl1	430000	430000	430000	430000	430000
pl2	430000	430000	430000	430000	430000
dl1	70000	70000	70000	70000	70000
in1	30000	30000	30000	30000	30000
cl1	15000	15000	15000	15000	15000

;

Table CO(n,t) 'fixed cost of establishing new facility n in period t'

	1	2	3	4	5
pl3	630000	630000	630000	630000	630000
dl2	210000	210000	210000	210000	210000
in2	150000	150000	150000	150000	150000
cl2	85000	85000	85000	85000	85000

;

Table CD(b,p,t) 'variable disposal cost per unit of product p discarded from disassembly-remanufacturing plant b in period t'

	1	2	3	4	5
dl1.p1	1	1.05	1.1	1.15	1.2
dl1.p2	1	1.05	1.1	1.15	1.2
dl2.p1	1	1.05	1.1	1.15	1.2
dl2.p2	1	1.05	1.1	1.15	1.2

;

*Other Parameters

Table DP(k,p,t) 'external demand of product p at customer k in period t'

	1	2	3	4	5
cu1.p1	11000	12000	13000	14000	15000
cu1.p2	10000	12000	12500	13000	14500
cu2.p1	10000	11000	12000	13000	14000
cu2.p2	10000	12000	13000	13500	15000
cu3.p1	12000	13500	14000	14800	16000
cu3.p2	11000	12000	12500	13500	15000

;

Parameter

KOmax(o) 'maximum processing capacity at selectable facility o'

```
/ pl1   110000
  pl2   90000
  pl3   100000
  dl1   100000
  dl2   80000
  in1   120000
  in2   140000
  cl1   110000
  cl2   120000  /
```

KOmin(o) 'minimum processing capacity at selectable facility o'

```
/ pl1   500
  pl2   500
  pl3   500
  dl1   100
  dl2   100
```

in1	500
in2	500
cl1	100
cl2	100 /

;

Table UJ(j,p) 'unit capacity consumption factor of product p processed at plant j'

	p1	p2
pl1	1	1.1
pl2	1	1.1
pl3	1	1.1
dl1	1	1.2
dl2	1	1.2

;

Table UI(l,i,p) 'unit capacity consumption factor of product p shipped from facility l to intermediate center i'

	p1	p2
pl1.in1	1	1.1
pl1.in2	1	1.1
pl2.in1	1	1.1
pl2.in2	1	1.1
pl3.in1	1	1.1
pl3.in2	1	1.1
cu1.cl1	1	1.1
cu1.cl2	1	1.1
cu2.cl1	1	1.1
cu2.cl2	1	1.1
cu3.cl1	1	1.1
cu3.cl2	1	1.1

;

Parameter

AM(p) 'amount of part/component for assembling one unit of product p'

```
/ p1   5
  p2   8    /
```

RM(p) 'amount of part/component obtained from disassembling and remanufacturing one unit of returned product p'

```
/ p1   5
  p2   7    /
;
```

Table RC(k,p,t) 'fraction of product p returned from customer k in period t'

	1	2	3	4	5
cu1.p1	0.2	0.1	0.3	0.2	0.3
cu1.p2	0.1	0.2	0.2	0.3	0.1
cu2.p1	0.2	0.2	0.1	0.2	0.3
cu2.p2	0.2	0.1	0.2	0.2	0.2
cu3.p1	0.1	0.2	0.2	0.3	0.1
cu3.p2	0.2	0.1	0.1	0.2	0.3

;

$ontext

The above table is the data of low rates of returns (scenario L) from Table 3.2(a). See Tables 3.2(b) and 3.2(c) of this thesis for the data of other scenarios.

$offtext

Table FR(p,t) 'fraction of returned product p satisfy the quality specifications in period t'

	1	2	3	4	5
p1	0.7	0.7	0.7	0.7	0.7

p2	0.8	0.8	0.8	0.8	0.8

;

Decision_variables.gms

$ontext
The include file "Decision_variables.gms" contains decision variables of the formulation in the file "Generic_Model.gms".
$offtext

```
**************************************************
*Decision variables*
**************************************************
```

Variables

*Non-negative

x(j,p,t)	'amount of product p processed by plant j in period t'
y(l,lp,p,t)	'amount of product p shipped from facility l to facility lp in period t'
z(a,t)	'amount of part/component purchased from an external supplier to production plant a in period t'
q(b,a,t)	'amount of part/component shipped from disassembly-remanufacturing plant b to production plant a in period t'

*Binary
varphi(o,t) '1 if selectable facility o is operated in period t, 0 otherwise'

*Objective function
obj 'objective function'
;

Positive variables x, y, z, q**;**

Binary variables varphi;

Results.gms

$ontext

The include file "Results.gms" contains additional results from the formulation in the file "Generic_Model.gms" for an illustrative example in section 3.3.2 of this thesis.

$offtext

```
**************************************************
*Results*
**************************************************
```

Parameters

*Fixed costs

cfixe(e,t)	'fixed costs of closing existing facilities in period t'
cfixn(n,t)	'fixed costs of establishing new facilities in period t'
cfixo(t)	'fixed costs of operating selectable facilities in period t'
cfix_total(t)	'total fixed costs in period t'

*Disposal amount

qdisp(b,p,t)	'amount of product p disposed at disassembly-remanufacturing plant b in period t'

*Processing costs

cprod(t)	'production costs in period t'
csup(t)	'purchasing part/component costs in period t'
crem(t)	'disassembly-remanufacturing costs in period t'
cdisp(t)	'disposal costs in period t'
cprocess_total(t)	'total processing costs in period t'

*transportation costs

ctranf(t)	'transportation costs for forward shipments in period t'
ctranr(t)	'transportation costs for reverse shipments in period t'
ctran_total(t)	'total transportation costs in period t'

*total costs

total_cost(t)	'total costs in period t'

;

*Fixed costs

**Fixed costs of closing existing facilities in period t

cfixe(e,"1") = CC(e,"1")*(1-varphi.l(e,"1"));

cfixe(e,t)$(**ord**(t) ne 1) = CC(e,t)*(varphi.l(e,t-1)-varphi.l(e,t));

**Fixed costs of establishing new facilities in period t

fixn(n,t) = CO(n,t)*(varphi.l(n,t)-varhpi.l(n,t-1));

**Fixed costs of operating selectable facilities in period t

cfixo(t) = **sum**(o, CF(o,t)*varphi.l(o,t));

**Total fixed costs in period t

cfix_total("1") = **sum**(o, CF(o,"1")*varphi.l(o,"1"))

+**sum**(e, CC(e,"1")*(1-varphi.l(e,"1")))

+**sum**(n, CO(n,"1")*(varphi.l(n,"1"))) ;

cfix_total(t)$(**ord**(t) ne 1) = **sum**(o, CF(o,t)*varphi.l(o,t))

+**sum**(e, CC(e,t)*(varphi.l(e,t-1)-varphi.l(e,t)))

+**sum**(n, CO(n,t)*(varphi.l(n,t)-varphi.l(n,t-1))) ;

*Amount of product p disposed at disassembly-remanufacturing plant b in period t

qdisp(b,p,t) = (1-FR(p,t))*x.l(b,p,t);

```
*Processing costs

**Production costs in period t
cprod(t) = sum((a,p), CP(a,p,t)*x.l(a,p,t));

**Purchasing part/component costs in period t
csup(t) = sum(a, CB(t)*z.l(a,t));

**Disassembly-remanufacturing costs in period t
crem(t) = sum((b,p), CP(b,p,t)*x.l(b,p,t))+sum((b,a), CR(t)*q.l(b,a,t));

**Disposal costs in period t
cdisp(t) = sum((b,p), CD(b,p,t)*(1-FR(p,t))*x.l(b,p,t));

**Total processing costs in period t
cprocess_total(t) = sum((j,p), CP(j,p,t)*x.l(j,p,t))
+sum(a, CB(t)*z.l(a,t))+sum((b,p), CD(b,p,t)*(1-FR(p,t))*x.l(b,p,t));

*Total transportation costs

**Transportation costs for forward shipment in period t
ctranf(t) = sum((a,d,p), CT(a,d,p,t)*y.l(a,d,p,t))
+sum((d,k,p), CT(d,k,p,t)*y.l(d,k,p,t));

**Transportation costs for reverse shipment in period t
ctranr(t) = sum((k,c,p), CT(k,c,p,t)*y.l(k,c,p,t))+sum((c,b,p), CT(c,b,p,t)*y.l(c,b,p,t))
+sum((b,a), CR(t)*q.l(b,a,t));

**Total transportation costs in period t
tran_total(t) = sum((l,lp,p)$(ord(l) ne ord(lp)), CT(l,lp,p,t)*y.l(l,lp,p,t))+sum((b,a),
CR(t)*q.l(b,a,t));
```

```
*Total cost in period t

total_cost("1") =

**Variable processing, transporting, purchasing costs
sum((b,a), CR("1")*q.l(b,a,"1"))+sum(a, CB("1")*z.l(a,"1"))
+(sum((j,p), CP(j,p,"1")*x.l(j,p,"1"))
+sum((l,lp,p)$(ord(l) ne ord(lp)), CT(l,lp,p,"1")*y.l(l,lp,p,"1"))

**Fixed costs of operating, closing and opening facilities
+sum(o, CF(o,"1")*varphi.l(o,"1"))+sum(e, CC(e,"1")*(1-varphi.l(e,"1")))
+sum(n, CO(n,"1")*(varphi.l(n,"1")))

**Variable disposal costs
+sum((b,p), CD(b,p,"1")*(1-FR(p,"1"))*x.l(b,p,"1")));

total_cost(t)$(ord(t) ne 1) =

**Variable processing, transporting, purchasing costs
sum((b,a), CR(t)*q.l(b,a,t))+sum(a, CB(t)*z.l(a,t))+(sum((j,p), CP(j,p,t)*x.l(j,p,t))
+sum((l,lp,p)$(ord(l) ne ord(lp)), CT(l,lp,p,t)*y.l(l,lp,p,t))

**Fixed costs of operating, closing and opening facilities
+sum(o, CF(o,t)*varphi.l(o,t))+sum(e, CC(e,t)*(varphi.l(e,t-1)-varphi.l(e,t)))
+sum(n, CO(n,t)*(varphi.l(n,t)-varphi.l(n,t-1)))

**Variable disposal costs
+sum((b,p), CD(b,p,t)*(1-FR(p,t))*x.l(b,p,t)));

display cfixe, cfixn, cfixo, cfix_total, qdisp, cprod, csup, crem, cdisp, cprocess_total,
ctranf, ctranr, ctran_total, total_cost;
```

B

Appendix B

B.1 Input Data for an Example Problem to Identify the Locations of Forward, Reverse and Bidirectional Facilities

In this appendix, the actual parameter data used for an example problem under different integrated forward and reverse network scenarios, i.e., a forward dominant network, a reverse dominant network and neither a forward nor a reverse dominant network, in section 4.1.3 are provided. All the following parameter data on Tables B.1-B.4 together with the data on Tables 4.1-4.4 in section 4.1.3.1 are given for a simple facility location model for hybrid uni/bidirectional flows in section 4.1.2.

B.1.1 Costs

Centers at location sites	Costs of closing centers in each period (year)				
	1st yr.	2nd yr.	3rd yr.	4th yr.	5th yr.
a1 at pl1	430000	430000	430000	430000	430000
a1 at pl2	430000	430000	430000	430000	430000
a2 at pl1	70000	70000	70000	70000	70000
a2 at pl2	70000	70000	70000	70000	70000

Table B.1: Costs of closing centers at existing location sites ($CC_{e,c,t}$)

Centers at location sites	Costs of establishing centers in each period (year)				
	1st yr.	2nd yr.	3rd yr.	4th yr.	5th yr.
a1 at pl3	630000	630000	630000	630000	630000
a2 at pl3	210000	210000	210000	210000	210000

Table B.2: Costs of establishing centers at new location sites ($CO_{n,c,t}$)

B.1.2 Other Parameter Data

Centers at location sites	Maximum allowable capacity
a1 at pl1	300000
a1 at pl2	150000
a1 at pl3	300000
a2 at pl1	100000
a2 at pl2	100000
a2 at pl3	100000

Table B.3: Maximum allowable capacity of centers at selectable location sites $\left(KC_{o,c}^{max}\right)$

Centers at location sites	Minimum allowable capacity
a1 at pl1	500
a1 at pl2	500
a1 at pl3	500
a2 at pl1	100
a2 at pl2	100
a2 at pl3	100

Table B.4: Minimum allowable capacity of centers at selectable location sites $\left(KC_{o,c}^{min}\right)$

B.2 Programming Code for a Simple Facility Location Model for Hybrid Uni/Bidirectional Flows

This appendix contains the GAMS programming code of a simple facility location model for hybrid uni/bidirectional flows in section 4.1.2. The model is coded for an example problem to identify the locations of forward, reverse and bidirectional facilities in section 4.1.3.

Bidirectional_Model.gms

```
$ontext
This is the formulation of a simple facility location model for hybrid uni/bidirectional
flows in the file "Bidirectional_Model.gms".
$offtext

$Include Index_sets.gms
$Include Parameters.gms
$Include Decision_variables.gms
```

Equations

```
**************************************************
*Objective function*
**************************************************

tcost      'total cost'

**************************************************
*Constraints*
**************************************************
*Flow constraints

demand     'the demand amount must be met'
ratecus    'guarantee the return amount from demand nodes'


*Capacity constraints
**Capacity constraints of forward supply chain centers

maxf       'limit maximum capacity of forward supply chain centers at selectable
           location sites'
minf       'limit minimum capacity of forward supply chain centers at selectable
           location sites'

**Capacity constraints of reverse supply chain centers

maxr       'limit maximum capacity of reverse supply chain centers at selectable
           location sites'
minr       'limit minimum capacity of reverse supply chain centers at selectable
           location sites'

*Logical constraints

operce     'if centers at existing location sites are closed, they cannot be reopend'
opercn     'if centers at new location sites are opened, they cannot be closed'
;
```

```
*____________________________________*
*Objective function*
*____________________________________*
tcost.. obj =e=
*Variable processing and transportation costs (TOC1)
(sum((l,lp,c,t)$(ord(l) ne ord(lp)), CP(l,lp,t)*x(l,lp,c,t))

*Fixed costs of operating, closing and establishing Facilities (TOC2)
+sum((o,c,t), CF(o,c,t)*delta(o,c,t))+sum((e,c), CC(e,c,"1")*(1-delta(e,c,"1")))
+sum((e,c,t)$(ord(t) ne 1), CC(e,c,t)*(delta(e,c,t-1)-delta(e,c,t)))
+sum((n,c,t), CO(n,c,t)*(delta(n,c,t)-delta(n,c,t-1))))
;
*____________________________________*
*Constraints*
*____________________________________*
*Flow constraints
demand(k,f,t).. sum(o, x(o,k,f,t)) =g= DP(k,t);
ratecus(k,r,t).. RC(k,t) =l= sum(o, x(k,o,r,t));

*Capacity constraints
**Capacity constraints of of forward supply chain centers
maxf(o,f,t).. sum(k, x(o,k,f,t)) =l= KCmax(o,f)*delta(o,f,t);
minf(o,f,t).. sum(k, x(o,k,f,t)) =g= KCmin(o,f)*delta(o,f,t);

**Capacity constraints of of reverse supply chain centers
maxr(o,r,t).. sum(k, x(k,o,r,t))=l=KCmax(o,r)*delta(o,r,t);
minr(o,r,t).. sum(k, x(k,o,r,t)) =g= KCmin(o,r)*delta(o,r,t);

*Logical constraints
operce(e,c,t)$(ord(t) ne card(t)).. delta(e,c,t) =g= delta(e,c,t+1) ;
opercn(n,c,t)$(ord(t) ne card(t)).. delta(n,c,t) =l= delta(n,c,t+1) ;
```

model bifl /all/**;**

option limrow=10000**;**

solve bifl using mip minimizing obj**;**

display x.l**;**

$Include Results.gms

Index_sets.gms

$ontext
The include file "Index_sets.gms" contains index sets of the formulation in the file "Bidirectional_Model.gms".
$offtext

****
Index sets
****

Sets

l	'location sites' /pl1, pl2, pl3, cu1, cu2, cu3/
o(l)	'selectable location sites' /pl1, pl2, pl3/
e(o)	'existing location sites' /pl1, pl2/
n(o)	'potential new location sites' /pl3/
k(l)	'demand nodes' /cu1, cu2, cu3/
c	'center types for supply chain processes' /a1, a2/
f(c)	'the type of forward supply chain centers' /a1/
r(c)	'the type of reverse supply chain centers' /a1/
t	'periods in the planning horizon' /1*5/

;

alias (lp, l)**;**

Parameters.gms

$ontext

The include file ”Parameters.gms” contains parameters of the formulation in the file ”Bidirectional_Model.gms”.

$offtext

****

Parameters

****

*Costs

Table CP(l,lp,t) 'unit variable cost of processing and shipping demand or return from location site l to location site lp in period t'

	1	2	3	4	5
pl1.cu1	200	205	205	210	210
pl1.cu2	250	255	260	265	270
pl1.cu3	250	255	260	265	270
pl2.cu1	250	255	260	265	270
pl2.cu2	220	225	230	230	230
pl2.cu3	250	255	260	265	270
pl3.cu1	230	235	240	240	240
pl3.cu2	200	205	205	210	210
pl3.cu3	200	205	205	210	210
cu1.pl1	11	12	13	14	15
cu1.pl2	21	22	23	24	25
cu1.pl3	8	8	10	10	11
cu2.pl1	11	12	13	14	15
cu2.pl2	15	16	17	18	19
cu2.pl3	8	8	10	10	11
cu3.pl1	11	12	13	14	15

cu3.pl2	15	16	17	18	19
cu3.pl3	8	8	10	10	11

;

$ontext
The above table is the data for scenario F (forward dominant network) from Table 4.3(a). See Tables 4.3(b) and 4.3(c) of this thesis for the data of other scenarios.
$offtext

Table CF(o,c,t) 'fixed cost of operating center c at selectable location site o in period t'

	1	2	3	4	5
pl1.a1	50000	51250	52531	53844	55190
pl2.a1	50000	51250	52531	53844	55190
pl3.a1	50000	51250	52531	53844	55190
pl1.a2	15000	15375	15759	16153	16557
pl2.a2	15000	15375	15759	16153	16557
pl3.a2	15000	15375	15759	16153	16557

;

$ontext
The above table is the data for scenarios F and N (forward and neither forward nor reverse dominant network) from Table 4.4(a). See Table 4.4(b) of this thesis for the data of scenario R.
$offtext

Table CC(e,c,t) 'fixed cost of closing center c at existing location site e in period t'

	1	2	3	4	5
pl1.a1	430000	430000	430000	430000	430000
pl2.a1	430000	430000	430000	430000	430000
pl1.a2	70000	70000	70000	70000	70000

pl2.a2	70000	70000	70000	70000	70000

;

Table CO(n,c,t) 'fixed cost of establishing center c at new location site n in period t'

	1	2	3	4	5
pl3.a1	630000	630000	630000	630000	630000
pl3.a2	210000	210000	210000	210000	210000

;

*Other parameters

Table DP(k,t) 'demand amount at node k in period t'

	1	2	3	4	5
cu1	41000	42000	42500	52000	62000
cu2	40000	41000	42000	52000	62000
cu3	43000	43500	42000	53300	62000

;

Table RC(k,t) 'return amount from node k in period t'

	1	2	3	4	5
cu1	20500	16800	17000	26000	37200
cu2	20000	20500	16800	20800	37200
cu3	17200	21750	21000	31980	24800

;

Parameter

KCmax(o,c) 'maximum allowable capacity of center c at selectable location site o'

```
/ pl1.a1   300000
  pl2.a1   150000
  pl3.a1   300000
  pl1.a2   100000
  pl2.a2   100000
  pl3.a2   100000  /
```

KCmin(o,c) 'minimum allowable capacity of center c at selectable location site o'

```
/ pl1.a1    500
  pl2.a1    500
  pl3.a1    500
  pl1.a2    100
  pl2.a2    100
  pl3.a2    100  /
;
```

Decision_variables.gms

```
$ontext
The include file "Decision_variables.gms" contains decision variables of the formulation
in the file "Bidirectional_Model.gms".
$offtext

***************************************************
*Decision variables*
***************************************************
```

Variables

```
*Non-negative

x(l,lp,c,t)     'amount of demand or return shipped from center c of location site l to
                location site lp in period t'


*Binary
delta(o,c,t)    '1 if center c at selectable location site o is operated in period t,
                0 otherwise'
;
```

*Objective function

obj 'objective function'

;

Positive variable x;

Binary variable delta;

Results.gms

$ontext

The include file "Results.gms" contains additional results from the formulation in the file "Bidirectional_Model.gms.gms" for an illustrative example in section 4.1.3.2 of this thesis.

$offtext

****

Results

****

Parameters

*Fixed costs

cfixec(e,c,t) 'fixed costs of closing centers at existing location sites in period t'

cfixnc(n,c,t) 'fixed costs of establishing centers at new location sites in period t'

cfixoc(c,t) 'fixed costs of operating centers at selectable facilities in period t'

cfix_total(t) 'total fixed costs in period t'

*Processing costs

cprocess_tran(t) 'total processing and transportation costs in period t'

*total costs

total_cost(t) 'total costs in period t'

;

*Fixed costs

**Fixed costs of closing centers at existing location sites in period t

cfixce(e,c,"1")=CC(e,c,"1")*(1-delta.l(e,c,"1"));

cfixce(e,c,t)$(**ord**(t) ne 1)=CC(e,c,t)*(delta.l(e,c,t-1)-delta.l(e,c,t));

**Fixed costs of establishing centers at new location sites in period t

cfixnc(n,c,t)= CO(n,c,t)*(delta.l(n,c,t)-delta.l(n,c,t-1));

**Fixed costs of operating centers at selectable facilities in period t

cfixoc(t)=**sum**((o,c), CF(o,c,t)*delta.l(o,c,t));

**Total fixed costs in period t

cfix_total("1")=**sum**((o,c), CF(o,c,"1")*delta.l(o,c,"1"))

+**sum**((e,c), CC(e,c,"1")*(1-delta.l(e,c,"1")))

+**sum**((n,c), CO(n,c,"1")*(delta.l(n,c,"1")));

cfix_total(t)$(**ord**(t) ne 1) =**sum**((o,c), CF(o,c,t)*delta.l(o,c,t))

+**sum**((e,c), CC(e,c,t)*(delta.l(e,c,t-1)-delta.l(e,c,t)))

+**sum**((n,c), CO(n,c,t)*(delta.l(n,c,t)-delta.l(n,c,t-1)));

*processing and transportation costs

cprocess_tran(t)=**sum**((l,lp,c)$(**ord**(l) ne **ord**(lp)), CP(l,lp,t)*x.l(l,lp,c,t));

*Total cost in period t

total_cost("1") =

**Variable processing and transportation costs

(**sum**((l,lp,c)$(**ord**(l) ne **ord**(lp)), CP(l,lp,1")*x.l(l,lp,c,"1"))

**Fixed costs of operating, closing and opening centers at selectable location sites
+**sum**((o,c), CF(o,c,"1")*delta.l(o,c,"1"))
+**sum**((e,c), CC(e,c,"1")*(1-delta.l(e,c,"1")))
+**sum**((n,c), CO(n,c,"1")*(delta.l(n,c,"1")));

total_cost(t)$(**ord**(t) ne 1) =

**Variable processing and transportation costs
(**sum**((l,lp,c)$(**ord**(l) ne **ord**(lp)), CP(l,lp,t)*x.l(l,lp,c,t))
**Fixed costs of operating, closing and opening centers at selectable location sites
+**sum**((o,c), CF(o,c,t)*delta.l(o,c,t))
+**sum**((e,c), CC(e,c,t)*(delta.l(e,c,t-1)-delta.l(e,c,t)))
+**sum**((n,c), CO(n,c,t)*(delta.l(n,c,t)-delta.l(n,c,t-1))));

display cfixec, cfixnc, cfixoc, cfix_total, cprocess_tran, total_cost;

B.3 Input Data for an Example Problem of the capacity relocation and expansion

Centers at location sites	**Initial capacity**
a1 at pl1	70000
a1 at pl2	50000
a2 at pl1	60000
a2 at pl2	30000

Table B.5: Initial capacity of centers at existing location sites ($KI_{e,c}$)

This appendix gives the actual parameter data used for an example problem of the capacity relocation and expansion in section 4.2.3. All the following parameter data on Tables B.5 and B.6 together with the data on Table 4.1 in section 4.1.3.1 and

Tables 4.5-4.8 in section 4.2.3.1 are provided for a simple relocation/expansion model for hybrid uni/bidirectional flows in section 4.2.2.

Centers at location sites	**Maximum capacity**
a1 at pl1	20000
a1 at pl2	20000
a1 at pl3	100000
a2 at pl1	10000
a2 at pl2	10000
a2 at pl3	80000

Table B.6: Maximum allowable additional capacity of centers at selectable location sites $\left(KA_{o,c}^{max}\right)$

B.4 Programming Code for a Simple Relocation/ Expansion Model for Hybrid Uni/Bidirectional Flows

In this appendix, the GAMS programming code of a simple relocation/expansion model for hybrid uni/bidirectional flows in section 4.2.2 is provided. The model is coded for an example problem of the capacity relocation and expansion in section 4.2.3.

Reloexp_Model.gms

```
$ontext
This is the formulation of a simple relocation/expansion model for hybrid uni/bidirectional flows in the file "Reloexp_Model.gms".
$offtext

$Include Index_sets.gms
```

```
$Include Parameters.gms
$Include Decision_variables.gms

Equations
****************************************************
*Objective function*
****************************************************

tcost       'total cost'

****************************************************
*Constraints*
****************************************************
*Flow constraints

demand      'the demand amount must be met'
ratecus     'guarantee the return amount from demand nodes'

*Capacity constraints
**Capacity relocation and expansion constraints

limexe      'limit capacity for further expansion of centers at existing location sites'
limrlexe    'limit capacity that can be relocated from centers at existing location
            sites'
movce       'ensure the relocated capacity of centers at existing location sites'
expcn       'ensure the expanded capacity of centers at new location sites'

**Capacity constraints of forward supply chain centers

maxef       'limit maximum capacity of forward supply chain centers at existing
            location sites'
maxnf       'limit maximum capacity of forward supply chain centers at new
            location sites'
minf        'limit minimum capacity of forward supply chain centers at selectable
            location sites'
```

**Capacity constraints of reverse supply chain centers

maxer 'limit maximum capacity of reverse supply chain centers at existing location sites'
maxnr 'limit maximum capacity of reverse supply chain centers at new location sites'
minr 'limit minimum capacity of reverse supply chain centers at selectable location sites'

*Logical constraints

operce 'if centers at existing location sites are closed, they cannot be reopend'
opercn 'if centers at new location sites are opened, they cannot be closed'
operexc 'if centers at selectable location sites are expanded, they cannot be closed'

;

____
Objective function
____

tcost.. obj =e=
*Variable processing and transportation costs (TOC1)
(**sum**((l,lp,c,t)$(**ord**(l) ne **ord**(lp)), CP(l,lp,t)*x(l,lp,c,t))

*Fixed costs of operating, closing and establishing Facilities (TOC2)
+**sum**((o,c,t), CF(o,c,t)*delta(o,c,t))+sum((e,c), CC(e,c,"1")*(1-delta(e,c,"1")))
+**sum**((e,c,t)$(**ord**(t) ne 1), CC(e,c,t)*(delta(e,c,t-1)-delta(e,c,t)))
+**sum**((n,c,t), CO(n,c,t)*(delta(n,c,t)-delta(n,c,t-1)))

*Variable costs of capacity relocation and expansion (TOC3)
+**sum**((o,c,t), CVE(o,c,t)*exp(o,c,t))
+**sum**((e,n,c,t), CVR(e,n,c,t)*mov(e,n,c,t)))
;

```
*_______________________________________*
*Constraints*
*_______________________________________*
*Flow constraints
demand(k,f,t).. sum(o, x(o,k,f,t)) =g= DP(k,t);
ratecus(k,r,t).. RC(k,t) =l= sum(o, x(k,o,r,t));

*Capacity constraints
**Capacity relocation and expansion constraints
limexe(e,c).. sum(t, exp(e,c,t)) =l= KAmax(e,c)*rho(e,c);
limrlexe(e,c).. sum((n,t), mov(e,n,c,t)) =l= KI(e,c)*(1-rho(e,c));

movce(e,c,t).. sum((n,tp)$(ord(tp) <= ord(t)), mov(e,n,c,tp))
=l= KI(e,c)*delta(e,c,t);

expcn(n,c,t).. sum(tp$(ord(tp) <= ord(t)), exp(n,c,tp))
+sum((e,tp)$(ord(tp) <= ord(t)), mov(e,n,c,tp)) =l= KAmax(n,c)*delta(n,c,t);

**Capacity constraints of of forward supply chain centers
maxef(e,f,t).. sum(k, x(e,k,f,t)) =l= KI(e,f)*delta(e,f,t)
+sum(tp$(ord(tp) <= ord(t)), exp(e,f,tp))
-sum((n,tp)$(ord(tp) <= ord(t)), mov(e,n,f,tp));

maxnf(n,f,t).. sum(k, x(n,k,f,t)) =l= sum(tp$(ord(tp) <= ord(t)), exp(n,f,tp))
+sum((e,tp)$(ord(tp) <= ord(t)), mov(e,n,f,tp));

minf(o,f,t).. sum(k, x(o,k,f,t))=g=KCmin(o,f)*delta(o,f,t);

**Capacity constraints of of reverse supply chain centers
maxer(e,r,t).. sum(k, x(k,e,r,t)) =l= KI(e,r)*delta(e,r,t)
+sum(tp$(ord(tp) <= ord(t)), exp(e,r,tp))
-sum((n,tp)$(ord(tp) <= ord(t)), mov(e,n,r,tp));
```

maxnr(n,r,t).. **sum**(k, x(k,n,r,t)) =l= **sum**(tp$(**ord**(tp) <= **ord**(t)), exp(n,r,tp))
+**sum**((e,tp)$(**ord**(tp) <= **ord**(t)), mov(e,n,r,tp))**;**

minr(o,r,t).. **sum**(k, x(k,o,r,t)) =g= KCmin(o,r)*delta(o,r,t)**;**

*Logical constraints
operce(e,c,t)$(**ord**(t) ne **card**(t)).. delta(e,c,t) =g= delta(e,c,t+1) ;
opercn(n,c,t)$(**ord**(t) ne **card**(t)).. delta(n,c,t) =l= delta(n,c,t+1) ;
operexc(e,c).. delta(e,c,"5") =g= rho(e,c) ;

model reloexp /all/**;**
option limrow=10000**;**
solve reloexp using mip minimizing obj**;**
display x.l, exp.l, mov.l**;**

$Include Results.gms

Index_sets.gms

$ontext
The include file "Index_sets.gms" contains index sets of the formulation in the file "Reloexp_Model.gms".
$offtext

****
Index sets
****
Sets

l 'location sites' /pl1, pl2, pl3, cu1, cu2, cu3/
o(l) 'selectable location sites' /pl1, pl2, pl3/
e(o) 'existing location sites' /pl1, pl2/
n(o) 'potential new location sites' /pl3/

k(l) 'demand nodes' /cu1, cu2, cu3/

c 'center types for supply chain processes' /a1, a2/

f(c) 'the type of forward supply chain centers' /a1/

r(c) 'the type of reverse supply chain centers' /a1/

t 'periods in the planning horizon' /1*5/

;

alias (lp, l);

alias (tp, t);

Parameters.gms

$ontext

The include file "Parameters.gms" contains parameters of the formulation in the file "Reloexp_Model.gms".

$offtext

```
*****************************************************
*Parameters*
*****************************************************
```

*Costs

Table CP(l,lp,t) 'unit variable cost of processing and shipping demand or return from location site l to location site lp in period t'

	1	2	3	4	5
pl1.cu1	200	205	205	210	210
pl1.cu2	200	205	205	210	210
pl1.cu3	230	235	240	240	240
pl2.cu1	230	235	240	240	240
pl2.cu2	230	235	240	240	240
pl2.cu3	250	255	260	265	270
pl3.cu1	200	205	205	210	210

pl3.cu2	200	205	205	210	210
pl3.cu3	200	205	205	210	210
cu1.pl1	11	12	13	14	15
cu1.pl2	21	22	23	24	25
cu1.pl3	8	8	10	10	11
cu2.pl1	11	12	13	14	15
cu2.pl2	15	16	17	18	19
cu2.pl3	8	8	10	10	11
cu3.pl1	11	12	13	14	15
cu3.pl2	15	16	17	18	19
cu3.pl3	8	8	10	10	11

;

Table CF(o,c,t) 'fixed cost of operating center c at selectable location site o in period t'

	1	2	3	4	5
pl1.a1	50000	51250	52531	53844	55190
pl2.a1	50000	51250	52531	53844	55190
pl3.a1	50000	51250	52531	53844	55190
pl1.a2	15000	15375	15759	16153	16557
pl2.a2	15000	15375	15759	16153	16557
pl3.a2	15000	15375	15759	16153	16557

;

Table CC(e,c,t) 'fixed cost of closing center c at existing location site e in period t'

	1	2	3	4	5
pl1.a1	430000	430000	430000	430000	430000
pl2.a1	430000	430000	430000	430000	430000
pl1.a2	70000	70000	70000	70000	70000
pl2.a2	70000	70000	70000	70000	70000

;

Table CO(n,c,t) 'fixed cost of establishing center c at new location site n in period t'

	1	2	3	4	5
pl3.a1	630000	630000	630000	630000	630000
pl3.a2	210000	210000	210000	210000	210000

;

Table CVE(o,c,t) 'variable cost associated with expanding capacity of center a at selectable location site o in period t'

	1	2	3	4	5
pl1.a1	120	120	120	120	120
pl2.a1	120	120	120	120	120
pl3.a1	120	120	120	120	120
pl1.a2	40	40	40	40	40
pl2.a2	40	40	40	40	40
pl3.a2	40	40	40	40	40

;

Table CVR(e,n,c,t) 'variable cost associated with relocating capacity of center c from existing location site e to new location site n in period t'

	1	2	3	4	5
pl1.pl3.a1	20	20	20	20	20
pl2.pl3.a1	24	24	24	24	24
pl1.pl3.a2	8	8	8	8	8
pl2.pl3.a2	10	10	10	10	10

;

*Other parameters

Table DP(k,t) 'demand amount at node k in period t'

	1	2	3	4	5
cu1	41000	42000	42500	52000	62000

cu2	40000	41000	42000	52000	62000
cu3	43000	43500	42000	53300	62000

;

Table RC(k,t) 'return amount from node k in period t'

	1	2	3	4	5
cu1	20500	16800	17000	21000	25200
cu2	20000	20500	16800	16800	25200
cu3	17200	21750	21000	25980	16800

;

Parameter

KI(e,c) 'initial capacity of center c at existing location site e'

/ pl1.a1 70000
pl2.a1 50000
pl1.a2 60000
pl2.a2 30000 /

KAmax(o,c) 'maximum allowable additional capacity of center c at selectable location site o'

/ pl1.a1 20000
pl2.a1 20000
pl3.a1 100000
pl1.a2 10000
pl2.a2 10000
pl3.a2 80000 /

KCmin(o,c) 'minimum allowable capacity of center c at selectable location site o'

/ pl1.a1 500
pl2.a1 500
pl3.a1 500

```
   pl1.a2      100
   pl2.a2      100
   pl3.a2      100   /
;
```

Decision_variables.gms

$ontext
The include file "Decision_variables.gms" contains decision variables of the formulation in the file "Reloexp_Model.gms".
$offtext

```
**************************************************
*Decision variables*
**************************************************
```

Variables

*Non-negative

x(l,lp,c,t)	'amount of demand or return shipped from center c of location site l to location site lp in period t'
exp(o,c,t)	'amount of capacity expanded at selectable location site o for center c in period t'
mov(e,n,c,t)	'amount of capacity relocated from existing location site e to new location site n for processing at center c in period t'

*Binary

delta(o,c,t)	'1 if center c at selectable location site o is operated in period t, 0 otherwise'
rho(o,c)	'1 if center c is expanded at existing location site e during the planning horizon, 0 otherwise'

*Objective function

obj 'objective function'

;

Positive variables x, exp, mov**;**

Binary variables delta, rho**;**

Results.gms

$ontext

The include file "Results.gms" contains additional results from the formulation in the file "Reloexp_Model.gms.gms" for an illustrative example in section 4.2.3.2 of this thesis.

$offtext

****

Results

****

Parameters

*Fixed costs

cfixec(e,c,t) 'fixed costs of closing centers at existing location sites in period t'

cfixnc(n,c,t) 'fixed costs of establishing centers at new location sites in period t'

cfixoc(c,t) 'fixed costs of operating centers at selectable facilities in period t'

cfix_total(t) 'total fixed costs in period t'

*Processing costs

cprocess_tran(t) 'total processing costs in period t'

;

```
*Capacity relocation and expansion costs
cexp(t)          'capacity expansion costs in period t'
crelo(t)         'capacity relocation costs in period t'

*total costs
total_cost(t)    'total costs in period t'
;

*Fixed costs

**Fixed costs of closing centers at existing location sites in period t
cfixec(e,c,"1")=CC(e,c,"1")*(1-delta.l(e,c,"1"));
cfixec(e,c,t)$(ord(t) ne 1)=CC(e,c,t)*(delta.l(e,c,t-1)-delta.l(e,c,t));

**Fixed costs of establishing centers at new location sites in period t
cfixnc(n,c,t)= CO(n,c,t)*(delta.l(n,c,t)-delta.l(n,c,t-1));

**Fixed costs of operating centers at selectable facilities in period t
cfixoc(t)=sum((o,c), CF(o,c,t)*delta.l(o,c,t));

**Total fixed costs in period t
cfix_total("1")=sum((o,c), CF(o,c,"1")*delta.l(o,c,"1"))
+sum((e,c), CC(e,c,"1")*(1-delta.l(e,c,"1")))
+sum((n,c), CO(n,c,"1")*(delta.l(n,c,"1")));

cfix_total(t)$(ord(t) ne 1) =sum((o,c), CF(o,c,t)*delta.l(o,c,t))
+sum((e,c), CC(e,c,t)*(delta.l(e,c,t-1)-delta.l(e,c,t)))
+sum((n,c), CO(n,c,t)*(delta.l(n,c,t)-delta.l(n,c,t-1)));

*processing and transportation costs
cprocess_tran(t)=sum((l,lp,c)$(ord(l) ne ord(lp)), CP(l,lp,t)*x.l(l,lp,c,t));
```

*Capacity relocation and expansion costs

*Capacity expansion costs

cexp(t)=**sum**((o,c), CVE(o,c,t)*exp.l(o,c,t))**;**

*Capacity relocation costs

crelo(t)=**sum**((e,n,c), CVR(e,n,c,t)*mov.l(e,n,c,t))**;**

*Total cost in period t

total_cost("1") =

**Variable processing and transportation costs

(**sum**((l,lp,c)$(**ord**(l) ne **ord**(lp)), CP(l,lp,"1")*x.l(l,lp,c,"1"))

**Variable costs of capacity relocation and expansion

+**sum**((o,c), CVE(o,c,"1")*exp.l(o,c,"1"))

+**sum**((e,n,c), CVR(e,n,c,"1")*mov.l(e,n,c,"1"))

**Fixed costs of operating, closing and opening centers at selectable location Sites

+**sum**((o,c), CF(o,c,"1")*delta.l(o,c,"1"))+**sum**((e,c), CC(e,c,"1")*(1-delta.l(e,c,"1")))

+**sum**((n,c), CO(n,c,"1")*(delta.l(n,c,"1"))))**;**

total_cost(t)$(**ord**(t) ne 1)) =

**Variable processing and transportation costs

(**sum**((l,lp,c)$(**ord**(l) ne **ord**(lp)), CP(l,lp,t)*x.l(l,lp,c,t))

**Variable costs of capacity relocation and expansion

+**sum**((o,c), CVE(o,c,t)*exp.l(o,c,t))+**sum**((e,n,c), CVR(e,n,c,t)*mov.l(e,n,c,t))

**Fixed costs of operating, closing and opening centers at selectable location Sites

+**sum**((o,c), CF(o,c,t)*delta.l(o,c,t))+**sum**((e,c), CC(e,c,t)*(delta.l(e,c,t-1)-delta.l(e,c,t)))

+**sum**((n,c), CO(n,c,t)*(delta.l(n,c,t)-delta.l(n,c,t-1))))**;**

display cfixec, cfixnc, cfixoc, cfix_total, cprocess_tran, cexp, crelo, total_cost**;**

C

Appendix C

C.1 Input Data for a Case Study on Different Levels of Product Demands and Returns

This appendix represents the actual parameter data used for an example problem dealing with three different changes (i.e., decrease, relatively stable and increase) in product demands and three different levels (i.e., low, medium and high) of product return volumes from customers. All the following parameter data on Tables C.1-C.28 together with the data on Tables 5.3 and 5.4 in section 5.1.5.1 are provided for the formulation of a relocation/expansion model for product recovery system including hybrid uni/bidirectional flows in section 5.1.4.

C.1.1 Capacity of Location Sites

Location sites	**Maximum capacity**
pl1	110000
pl2	90000
pl3	120000
in1	120000
in2	140000

Table C.1: Maximum allowable capacity at selectable location sites (KO_o^{max})

Center at location sites	**Initial capacity**
a1 at pl1	20000
a1 at pl2	40000
a2 at pl1	7000
a2 at pl2	5000
b1 at in1	40000
b2 at in1	21000

Table C.2: Initial capacity of centers at selectable location sites $(KI_{o,c})$

Centers at location sites	**Maximum capacity**
a1 at pl1	110000
a1 at pl2	90000
a1 at pl3	100000
a2 at pl1	132000
a2 at pl2	10800

Table C.3: Maximum allowable capacity of centers at selectable location sites $\left(KC_{o,c}^{max}\right)$

Centers at location sites	Maximum allowable capacity
a2 at pl3	120000
b1 at in1	120000
b1 at in2	140000
b1 at in1	132000
b2 at in2	154000

Table C.3: Maximum allowable capacity of centers at selectable location sites $\left(KC_{o,c}^{max}\right)$ (continued)

Centers at location sites	Minimum allowable capacity
a1 at pl1	2000
a1 at pl2	2000
a1 at pl3	2000
a2 at pl1	1500
a2 at pl2	1500
a2 at pl3	1500
b1 at in1	2000
b1 at in2	2000
b2 at in1	1500
b2 at in2	1500

Table C.4: Minimum allowable capacity of centers at selectable location sites $\left(KC_{o,c}^{min}\right)$

Centers at location sites	Fixed sizes
a1 at pl1	1000
a1 at pl2	1000
a1 at pl3	1000
a2 at pl1	500
a2 at pl2	500
a2 at pl3	500
b1 at in1	1000
b1 at in2	1000
b1 at in1	500
b2 at in2	500

Table C.5: Fixed expanding/relocation sizes for centers at selectable location sites $(KM_{o,c})$

Suppliers	Parts/ coms	Maximum allowable capacity in each period (year)									
		1st yr.	2nd yr.	3rd yr.	4th yr.	5th yr.	6th yr.	7th yr.	8th yr.	9th yr.	10th yr.
su1	m1	220000	220000	220000	220000	220000	220000	220000	220000	220000	220000
	m2	200000	200000	200000	200000	200000	200000	200000	200000	200000	200000
	m3	190000	190000	190000	190000	190000	190000	190000	190000	190000	190000
su2	m1	220000	220000	220000	220000	220000	220000	220000	220000	220000	220000
	m2	200000	200000	200000	200000	200000	200000	200000	200000	200000	200000
	m3	190000	190000	190000	190000	190000	190000	190000	190000	190000	190000
su3	m1	220000	220000	220000	220000	220000	220000	220000	220000	220000	220000
	m2	200000	200000	200000	200000	200000	200000	200000	200000	200000	200000
	m3	190000	190000	190000	190000	190000	190000	190000	190000	190000	190000

Table C.6: Maximum allowable capacity of external suppliers for parts/components $\left(KS^{max}_{s,m,t}\right)$

Subcons	Final products	Maximum allowable capacity in each period (year)									
		1st yr.	2nd yr.	3rd yr.	4th yr.	5th yr.	6th yr.	7th yr.	8th yr.	9th yr.	10th yr.
ou1	g1	120000	120000	120000	120000	120000	120000	120000	120000	120000	120000
	g2	120000	120000	120000	120000	120000	120000	120000	120000	120000	120000

Table C.7: Maximum allowable capacity of disassembly-remanufacturing subcontractors for returned final products $\left(KU_{u,g,t}^{max}\right)$

C.1.2 Selling Prices

Shipping routes	Final products	Price of selling final products in each period (year)									
		1st yr.	2nd yr.	3rd yr.	4th yr.	5th yr.	6th yr.	7th yr.	8th yr.	9th yr.	10th yr.
pl1 to cu1	g1	580	599.50	619.49	639.97	660.97	682.50	604.56	627.17	650.35	674.11
	g2	750	776.25	803.16	830.74	859	877.98	900.68	928.12	959.32	971.31
pl1 to cu2	g1	580	599.50	619.49	639.97	660.97	682.50	604.56	627.17	650.35	674.11
	g2	750	776.25	803.16	830.74	859	877.98	900.68	928.12	959.32	971.31
pl1 to cu3	g1	580	599.50	619.49	639.97	660.97	682.50	604.56	627.17	650.35	674.11
	g2	750	776.25	803.16	830.74	859	877.98	900.68	928.12	959.32	971.31
pl2 to cu1	g1	580	599.50	619.49	639.97	660.97	682.50	604.56	627.17	650.35	674.11
	g2	750	776.25	803.16	830.74	859	877.98	900.68	928.12	959.32	971.31
pl2 to cu2	g1	580	599.50	619.49	639.97	660.97	682.50	604.56	627.17	650.35	674.11
	g2	750	776.25	803.16	830.74	859	877.98	900.68	928.12	959.32	971.31
pl2 to cu3	g1	580	599.50	619.49	639.97	660.97	682.50	604.56	627.17	650.35	674.11
	g2	750	776.25	803.16	830.74	859	877.98	900.68	928.12	959.32	971.31
pl3 to cu1	g1	580	599.50	619.49	639.97	660.97	682.50	604.56	627.17	650.35	674.11
	g2	750	776.25	803.16	830.74	859	877.98	900.68	928.12	959.32	971.31
pl3 to cu2	g1	580	599.50	619.49	639.97	660.97	682.50	604.56	627.17	650.35	674.11
	g2	750	776.25	803.16	830.74	859	877.98	900.68	928.12	959.32	971.31

Table C.8: Price of selling one unit of final product $(SC_{o,k,g,t})$

Shipping routes	Final products	Price of selling final products in each period (year)									
		1st yr.	2nd yr.	3rd yr.	4th yr.	5th yr.	6th yr.	7th yr.	8th yr.	9th yr.	10th yr.
pl3 to cu3	g1	580	599.50	619.49	639.97	660.97	682.50	604.56	627.17	650.35	674.11
	g2	750	776.25	803.16	830.74	859	877.98	900.68	928.12	959.32	971.31
in1 to cu1	g1	580	599.50	619.49	639.97	660.97	682.50	604.56	627.17	650.35	674.11
	g2	750	776.25	803.16	830.74	859	877.98	900.68	928.12	959.32	971.31
in1 to cu2	g1	580	599.50	619.49	639.97	660.97	682.50	604.56	627.17	650.35	674.11
	g2	750	776.25	803.16	830.74	859	877.98	900.68	928.12	959.32	971.31
in1 to cu3	g1	580	599.50	619.49	639.97	660.97	682.50	604.56	627.17	650.35	674.11
	g2	750	776.25	803.16	830.74	859	877.98	900.68	928.12	959.32	971.31
in2 to cu1	g1	580	599.50	619.49	639.97	660.97	682.50	604.56	627.17	650.35	674.11
	g2	750	776.25	803.16	830.74	859	877.98	900.68	928.12	959.32	971.31
in2 to cu2	g1	580	599.50	619.49	639.97	660.97	682.50	604.56	627.17	650.35	674.11
	g2	750	776.25	803.16	830.74	859	877.98	900.68	928.12	959.32	971.31
in2 to cu3	g1	580	599.50	619.49	639.97	660.97	682.50	604.56	627.17	650.35	674.11
	g2	750	776.25	803.16	830.74	859	877.98	900.68	928.12	959.32	971.31

Table C.8: Price of selling one unit of final product ($SC_{o,k,g,t}$) (continued)

C.1.3 Costs

Shipping routes	Parts/ components	Costs of purchasing parts/components in each period (year)									
		1st yr.	2nd yr.	3rd yr.	4th yr.	5th yr.	6th yr.	7th yr.	8th yr.	9th yr.	10th yr.
su1 to pl1	m1	15	15.5	16	16.5	17	17.5	18	18.5	19	19.5
	m2	15	15.5	16	16.5	17	17.5	18	18.5	19	19.5
	m3	15	15.5	16	16.5	17	17.5	18	18.5	19	19.5
su1 to pl2	m1	15	15.5	16	16.5	17	17.5	18	18.5	19	19.5
	m2	15	15.5	16	16.5	17	17.5	18	18.5	19	19.5
	m3	15	15.5	16	16.5	17	17.5	18	18.5	19	19.5

Table C.9: Cost of purchasing one unit of part/component ($CB_{s,j,m,t}$)

Shipping routes	**Parts/ components**	**Costs of purchasing parts/components in each period (year)**									
		1st yr.	**2nd yr.**	**3rd yr.**	**4th yr.**	**5th yr.**	**6th yr.**	**7th yr.**	**8th yr.**	**9th yr.**	**10th yr.**
su1 to pl3	m1	15	15.5	16	16.5	17	17.5	18	18.5	19	19.5
	m2	15	15.5	16	16.5	17	17.5	18	18.5	19	19.5
	m3	15	15.5	16	16.5	17	17.5	18	18.5	19	19.5
su2 to pl1	m1	15	15.5	16	16.5	17	17.5	18	18.5	19	19.5
	m2	15	15.5	16	16.5	17	17.5	18	18.5	19	19.5
	m3	20	21	22	23	24	25	26	27	28	29
su2 to pl2	m1	15	15.5	16	16.5	17	17.5	18	18.5	19	19.5
	m2	15	15.5	16	16.5	17	17.5	18	18.5	19	19.5
	m3	20	21	22	23	24	25	26	27	28	29
su2 to pl3	m1	15	15.5	16	16.5	17	17.5	18	18.5	19	19.5
	m2	15	15.5	16	16.5	17	17.5	18	18.5	19	19.5
	m3	20	21	22	23	24	25	26	27	28	29
su3 to pl1	m1	15	15.5	16	16.5	17	17.5	18	18.5	19	19.5
	m2	15	15.5	16	16.5	17	17.5	18	18.5	19	19.5
	m3	15	15.5	16	16.5	17	17.5	18	18.5	19	19.5
su3 to pl2	m1	15	15.5	16	16.5	17	17.5	18	18.5	19	19.5
	m2	15	15.5	16	16.5	17	17.5	18	18.5	19	19.5
	m3	20	21	22	23	24	25	26	27	28	29
su3 to pl3	m1	15	15.5	16	16.5	17	17.5	18	18.5	19	19.5
	m2	15	15.5	16	16.5	17	17.5	18	18.5	19	19.5
	m3	20	21	22	23	24	25	26	27	28	29

Table C.9: Cost of purchasing one unit of part/component ($CB_{s,j,m,t}$) (continued)

Centers at location sites	**Final products**	**Costs of processing final products in each period (year)**									
		1st yr.	**2nd yr.**	**3rd yr.**	**4th yr.**	**5th yr.**	**6th yr.**	**7th yr.**	**8th yr.**	**9th yr.**	**10th yr.**
a1 at pl1	g1	240	245	245	250	250	255	255	260	265	270
	g2	300	308	316	324	332	340	348	356	364	372
a1 at pl2	g1	250	255	260	265	270	275	280	285	290	295
	g2	400	408	416	424	432	440	448	456	464	472

Table C.10: Cost of processing one unit of final product ($CP_{j,a,g,t}$)

Centers at location sites	Final products	Costs of processing final products in each period (year)									
		1st yr.	2nd yr.	3rd yr.	4th yr.	5th yr.	6th yr.	7th yr.	8th yr.	9th yr.	10th yr.
a1 at pl3	g1	250	255	260	265	270	275	280	285	290	295
	g2	400	408	416	424	432	440	448	456	464	472
a2 at pl1	g1	11	12	13	14	15	16	17	18	19	20
	g2	16	17	18	19	20	21	22	23	24	25
a2 at pl2	g1	13	14	15	16	17	18	19	20	21	22
	g2	21	22	23	24	25	26	27	28	29	30
a2 at pl3	g1	8	8	10	10	11	11	12	13	13	14
	g2	11	12	13	14	15	16	17	18	19	20

Table C.10: Cost of processing one unit of final product ($CP_{j,a,g,t}$) (continued)

Shipping routes	Final products	Costs of subcontracting returned final products in each period (year)									
		1st yr.	2nd yr.	3rd yr.	4th yr.	5th yr.	6th yr.	7th yr.	8th yr.	9th yr.	10th yr.
cu1 to ou1	g1	45	46	47	48	49	50	51	52	53	54
	g2	65	66	67	68	69	70	71	72	73	74
cu2 to ou1	g1	16	17	18	19	20	21	22	23	24	25
	g2	43	44	45	46	47	48	49	50	51	52
cu3 to ou1	g1	40	41	42	43	44	45	46	47	48	49
	g2	60	61	62	63	64	65	66	67	68	69
in1 to ou1	g1	16	17	18	19	20	21	22	23	24	25
	g2	43	44	45	46	47	48	49	50	51	52
in2 to ou1	g1	16	17	18	19	20	21	22	23	24	25
	g2	43	44	45	46	47	48	49	50	51	52

Table C.11: Cost of subcontracting one unit of returned final product ($CS_{l,u,g,t}$)

Shipping routes	Products	Costs of shipping products in each period (year)									
		1st yr.	2nd yr.	3rd yr.	4th yr.	5th yr.	6th yr.	7th yr.	8th yr.	9th yr.	10th yr.
pl1 to in1	g1	8	8	8.4	8.4	8.8	8.8	9.2	9.2	9.6	9.6
	g2	8	8	8.4	8.4	8.8	8.8	9.2	9.2	9.6	9.6
pl1 to in2	g1	4	4	4.2	4.2	4.4	4.4	4.6	4.6	4.8	4.8
	g2	4	4	4.2	4.2	4.4	4.4	4.6	4.6	4.8	4.8
pl1 to cu1	g1	20	20	21	21	22	22	23	23	24	24
	g2	20	20	21	21	22	22	23	23	24	24
pl1 to cu2	g1	20	20	21	21	22	22	23	23	24	24
	g2	20	20	21	21	22	22	23	23	24	24
pl1 to cu3	g1	10	10	10.5	10.5	11	11	11.5	11.5	12	12
	g2	10	10	10.5	10.5	11	11	11.5	11.5	12	12
pl2 to in1	g1	8	8	8.4	8.4	8.8	8.8	9.2	9.2	9.6	9.6
	g2	8	8	8.4	8.4	8.8	8.8	9.2	9.2	9.6	9.6
pl2 to in2	g1	8	8	8.4	8.4	8.8	8.8	9.2	9.2	9.6	9.6
	g2	8	8	8.4	8.4	8.8	8.8	9.2	9.2	9.6	9.6
pl2 to cu1	g1	20	20	21	21	22	22	23	23	24	24
	g2	20	20	21	21	22	22	23	23	24	24
pl2 to cu2	g1	20	20	21	21	22	22	23	23	24	24
	g2	20	20	21	21	22	22	23	23	24	24
pl2 to cu3	g1	20	20	21	21	22	22	23	23	24	24
	g2	20	20	21	21	22	22	23	23	24	24
pl3 to in1	g1	8	8	8.4	8.4	8.8	8.8	9.2	9.2	9.6	9.6
	g2	8	8	8.4	8.4	8.8	8.8	9.2	9.2	9.6	9.6
pl3 to in2	g1	4	4	4.2	4.2	4.4	4.4	4.6	4.6	4.8	4.8
	g2	4	4	4.2	4.2	4.4	4.4	4.6	4.6	4.8	4.8
pl3 to cu1	g1	20	20	21	21	22	22	23	23	24	24
	g2	20	20	21	21	22	22	23	23	24	24
pl3 to cu2	g1	20	20	21	21	22	22	23	23	24	24
	g2	20	20	21	21	22	22	23	23	24	24
pl3 to cu3	g1	10	10	10.5	10.5	11	11	11.5	11.5	12	12
	g2	10	10	10.5	10.5	11	11	11.5	11.5	12	12

Table C.12: Cost of shipping one unit of product $\left(CT_{l,l',p,t}\right)$

Shipping routes	Products	Costs of shipping products in each period (year)									
		1st yr.	2nd yr.	3rd yr.	4th yr.	5th yr.	6th yr.	7th yr.	8th yr.	9th yr.	10th yr.
pl1 to pl1	m1	0.1	0.1	0.105	0.105	0.11	0.11	0.115	0.115	0.12	0.12
	m2	0.1	0.1	0.105	0.105	0.11	0.11	0.115	0.115	0.12	0.12
	m3	0.1	0.1	0.105	0.105	0.11	0.11	0.115	0.115	0.12	0.12
pl1 to pl2	m1	0.5	0.5	0.525	0.525	0.55	0.55	0.75	0.75	1	1
	m2	0.5	0.5	0.525	0.525	0.55	0.55	0.75	0.75	1	1
	m3	0.5	0.5	0.525	0.525	0.55	0.55	0.75	0.75	1	1
pl1 to pl3	m1	0.5	0.5	0.525	0.525	0.55	0.55	0.75	0.75	1	1
	m2	0.5	0.5	0.525	0.525	0.55	0.55	0.75	0.75	1	1
	m3	0.5	0.5	0.525	0.525	0.55	0.55	0.75	0.75	1	1
pl2 to pl1	m1	0.5	0.5	0.525	0.525	0.55	0.55	0.75	0.75	1	1
	m2	0.5	0.5	0.525	0.525	0.55	0.55	0.75	0.75	1	1
	m3	0.5	0.5	0.525	0.525	0.55	0.55	0.75	0.75	1	1
pl2 to pl2	m1	0.1	0.1	0.105	0.105	0.11	0.11	0.115	0.115	0.12	0.12
	m2	0.1	0.1	0.105	0.105	0.11	0.11	0.115	0.115	0.12	0.12
	m3	0.1	0.1	0.105	0.105	0.11	0.11	0.115	0.115	0.12	0.12
pl2 to pl3	m1	0.5	0.5	0.525	0.525	0.55	0.55	0.75	0.75	1	1
	m2	0.5	0.5	0.525	0.525	0.55	0.55	0.75	0.75	1	1
	m3	0.5	0.5	0.525	0.525	0.55	0.55	0.75	0.75	1	1
pl3 to pl1	m1	0.5	0.5	0.525	0.525	0.55	0.55	0.75	0.75	1	1
	m2	0.5	0.5	0.525	0.525	0.55	0.55	0.75	0.75	1	1
	m3	0.5	0.5	0.525	0.525	0.55	0.55	0.75	0.75	1	1
pl3 to pl2	m1	0.5	0.5	0.525	0.525	0.55	0.55	0.75	0.75	1	1
	m2	0.5	0.5	0.525	0.525	0.55	0.55	0.75	0.75	1	1
	m3	0.5	0.5	0.525	0.525	0.55	0.55	0.75	0.75	1	1
pl3 to pl3	m1	0.1	0.1	0.105	0.105	0.11	0.11	0.115	0.115	0.12	0.12
	m2	0.1	0.1	0.105	0.105	0.11	0.11	0.115	0.115	0.12	0.12
	m3	0.1	0.1	0.105	0.105	0.11	0.11	0.115	0.115	0.12	0.12
in1 to cu1	g1	8	8	8.4	8.4	8.8	8.8	9.2	9.2	9.6	9.6
	g2	8	8	8.4	8.4	8.8	8.8	9.2	9.2	9.6	9.6
in1 to cu2	g1	8	8	8.4	8.4	8.8	8.8	9.2	9.2	9.6	9.6
	g2	8	8	8.4	8.4	8.8	8.8	9.2	9.2	9.6	9.6

Table C.12: Cost of shipping one unit of product $\left(CT_{l,l',p,t}\right)$ (continued)

Shipping routes	Products	Costs of shipping products in each period (year)									
		1st yr.	2nd yr.	3rd yr.	4th yr.	5th yr.	6th yr.	7th yr.	8th yr.	9th yr.	10th yr.
in1 to cu3	g1	8	8	8.4	8.4	8.8	8.8	9.2	9.2	9.6	9.6
	g2	8	8	8.4	8.4	8.8	8.8	9.2	9.2	9.6	9.6
in2 to cu1	g1	4	4	4.2	4.2	4.4	4.4	4.6	4.6	4.8	4.8
	g2	4	4	4.2	4.2	4.4	4.4	4.6	4.6	4.8	4.8
in2 to cu2	g1	4	4	4.2	4.2	4.4	4.4	4.6	4.6	4.8	4.8
	g2	4	4	4.2	4.2	4.4	4.4	4.6	4.6	4.8	4.8
in2 to cu3	g1	4	4	4.2	4.2	4.4	4.4	4.6	4.6	4.8	4.8
	g2	4	4	4.2	4.2	4.4	4.4	4.6	4.6	4.8	4.8
in1 to pl1	g1	4	4	4.2	4.2	4.4	4.4	4.6	4.6	4.8	4.8
	g2	4	4	4.2	4.2	4.4	4.4	4.6	4.6	4.8	4.8
in1 to pl2	g1	4	4	4.2	4.2	4.4	4.4	4.6	4.6	4.8	4.8
	g2	4	4	4.2	4.2	4.4	4.4	4.6	4.6	4.8	4.8
in1 to pl3	g1	4	4	4.2	4.2	4.4	4.4	4.6	4.6	4.8	4.8
	g2	4	4	4.2	4.2	4.4	4.4	4.6	4.6	4.8	4.8
in2 to pl1	g1	2	2	2.1	2.1	2.2	2.2	2.3	2.3	2.4	2.4
	g2	2	2	2.1	2.1	2.2	2.2	2.3	2.3	2.4	2.4
in2 to pl2	g1	4	4	4.2	4.2	4.4	4.4	4.6	4.6	4.8	4.8
	g2	4	4	4.2	4.2	4.4	4.4	4.6	4.6	4.8	4.8
in2 to pl3	g1	2	2	2.1	2.1	2.2	2.2	2.3	2.3	2.4	2.4
	g2	2	2	2.1	2.1	2.2	2.2	2.3	2.3	2.4	2.4
cu1 to in1	g1	4	4	4.2	4.2	4.4	4.4	4.6	4.6	4.8	4.8
	g2	4	4	4.2	4.2	4.4	4.4	4.6	4.6	4.8	4.8
cu1 to in2	g1	2	2	2.1	2.1	2.2	2.2	2.3	2.3	2.4	2.4
	g2	2	2	2.1	2.1	2.2	2.2	2.3	2.3	2.4	2.4
cu2 to in1	g1	4	4	4.2	4.2	4.4	4.4	4.6	4.6	4.8	4.8
	g2	4	4	4.2	4.2	4.4	4.4	4.6	4.6	4.8	4.8
cu2 to in2	g1	2	2	2.1	2.1	2.2	2.2	2.3	2.3	2.4	2.4
	g2	2	2	2.1	2.1	2.2	2.2	2.3	2.3	2.4	2.4
cu3 to in1	g1	4	4	4.2	4.2	4.4	4.4	4.6	4.6	4.8	4.8
	g2	4	4	4.2	4.2	4.4	4.4	4.6	4.6	4.8	4.8

Table C.12: Cost of shipping one unit of product $\left(CT_{l,l',p,t}\right)$ (continued)

Shipping routes	Products	Costs of shipping products in each period (year)									
		1st yr.	2nd yr.	3rd yr.	4th yr.	5th yr.	6th yr.	7th yr.	8th yr.	9th yr.	10th yr.
cu3 to in2	g1	2	2	2.1	2.1	2.2	2.2	2.3	2.3	2.4	2.4
	g2	2	2	2.1	2.1	2.2	2.2	2.3	2.3	2.4	2.4
cu1 to pl1	g1	15	15	15.75	15.75	16.5	16.5	17	17	17.5	17.5
	g2	15	15	15.75	15.75	16.5	16.5	17	17	17.5	17.5
cu1 to pl2	g1	15	15	15.75	15.75	16.5	16.5	17	17	17.5	17.5
	g2	15	15	15.75	15.75	16.5	16.5	17	17	17.5	17.5
cu1 to pl3	g1	15	15	15.75	15.75	16.5	16.5	17	17	17.5	17.5
	g2	15	15	15.75	15.75	16.5	16.5	17	17	17.5	17.5
cu2 to pl1	g1	15	15	15.75	15.75	16.5	16.5	17	17	17.5	17.5
	g2	15	15	15.75	15.75	16.5	16.5	17	17	17.5	17.5
cu2 to pl2	g1	15	15	15.75	15.75	16.5	16.5	17	17	17.5	17.5
	g2	15	15	15.75	15.75	16.5	16.5	17	17	17.5	17.5
cu2 to pl3	g1	15	15	15.75	15.75	16.5	16.5	17	17	17.5	17.5
	g2	15	15	15.75	15.75	16.5	16.5	17	17	17.5	17.5
cu3 to pl1	g1	7	7	7.35	7.35	7.7	7.7	8.05	8.05	9	9
	g2	7	7	7.35	7.35	7.7	7.7	8.05	8.05	9	9
cu3 to pl2	g1	15	15	15.75	15.75	16.5	16.5	17	17	17.5	17.5
	g2	15	15	15.75	15.75	16.5	16.5	17	17	17.5	17.5
cu3 to pl3	g1	7	7	7.35	7.35	7.7	7.7	8.05	8.05	9	9
	g2	7	7	7.35	7.35	7.7	7.7	8.05	8.05	9	9
ou1 to pl1	m1	0.25	0.25	0.26	0.26	0.27	0.27	0.28	0.28	0.29	0.29
	m2	0.25	0.25	0.26	0.26	0.27	0.27	0.28	0.28	0.29	0.29
	m3	0.25	0.25	0.26	0.26	0.27	0.27	0.28	0.28	0.29	0.29
ou1 to pl2	m1	0.5	0.5	0.525	0.525	0.55	0.55	0.75	0.75	1	1
	m2	0.5	0.5	0.525	0.525	0.55	0.55	0.75	0.75	1	1
	m3	0.5	0.5	0.525	0.525	0.55	0.55	0.75	0.75	1	1
pl3 to pl3	m1	0.5	0.5	0.525	0.525	0.55	0.55	0.75	0.75	1	1
	m2	0.5	0.5	0.525	0.525	0.55	0.55	0.75	0.75	1	1
	m3	0.5	0.5	0.525	0.525	0.55	0.55	0.75	0.75	1	1

Table C.12: Cost of shipping one unit of product $\left(CT_{l,l',p,t}\right)$ (continued)

Location sites	Costs of operating selectable location sites in each period (year)									
	1st yr.	**2nd yr.**	**3rd yr.**	**4th yr.**	**5th yr.**	**6th yr.**	**7th yr.**	**8th yr.**	**9th yr.**	**10th yr.**
pl1	5000	5000	5000	5000	5000	5000	5000	5000	5000	5000
pl2	5000	5000	5000	5000	5000	5000	5000	5000	5000	5000
pl3	5000	5000	5000	5000	5000	5000	5000	5000	5000	5000
in1	1025	1025	1025	1025	1025	1025	1025	1025	1025	1025
in2	1025	1025	1025	1025	1025	1025	1025	1025	1025	1025

Table C.13: Costs of operating selectable location sites ($CF_{o,t}$)

Location sites	Costs of closing existing location sites in each period (year)									
	1st yr.	**2nd yr.**	**3rd yr.**	**4th yr.**	**5th yr.**	**6th yr.**	**7th yr.**	**8th yr.**	**9th yr.**	**10th yr.**
pl1	13000	13325	12350	13650	13975	14300	14625	14950	15275	15600
pl2	13000	13325	12350	13650	13975	14300	14625	14950	15275	15600
in1	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000

Table C.14: Costs of closing existing location sites ($CC_{e,t}$)

Location sites	Costs of establishing new location sites in each period (year)									
	1st yr.	**2nd yr.**	**3rd yr.**	**4th yr.**	**5th yr.**	**6th yr.**	**7th yr.**	**8th yr.**	**9th yr.**	**10th yr.**
pl3	39000	39000	39000	39000	39000	39000	39000	39000	39000	39000
in2	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000

Table C.15: Costs of establishing new location sites ($CO_{n,t}$)

Centers at location sites	Costs of operating centers at selectable location sites in each period (year)									
	1st yr.	2nd yr.	3rd yr.	4th yr.	5th yr.	6th yr.	7th yr.	8th yr.	9th yr.	10th yr.
a1 at pl1	50000	51250	52531	53844	55190	56570	57984	59434	60920	62443
a1 at pl2	70000	71250	72531	73844	75190	76570	77984	79434	80920	82443
a1 at pl3	50000	51250	52531	53844	55190	56570	57984	59434	60920	62443
a2 at pl1	15000	15375	15759	16153	16557	16971	17395	17830	18276	18732
a2 at pl2	15000	15375	15759	16153	16557	16971	17395	17830	18276	18732
a2 at pl3	15000	15375	15759	16153	16557	16971	17395	17830	18276	18732
b1 at in1	10250	10500	10762	11031	11307	11590	11879	12176	12481	12793
b1 at in2	10250	10500	10762	11031	11307	11590	11879	12176	12481	12793
b2 at in1	6150	6457	6618	6784	6954	7127	7306	7488	7675	7867
b2 at in2	6150	6457	6618	6784	6954	7127	7306	7488	7675	7867

Table C.16: Costs of operating centers at selectable location sites ($CFF_{o,c,t}$)

Centers at location sites	Costs of expanding capacity of centers in each period (year)									
	1st yr.	2nd yr.	3rd yr.	4th yr.	5th yr.	6th yr.	7th yr.	8th yr.	9th yr.	10th yr.
a1 at pl1	120	120	120	120	120	120	120	120	120	120
a1 at pl2	120	120	120	120	120	120	120	120	120	120
a1 at pl3	120	120	120	120	120	120	120	120	120	120
a2 at pl1	40	40	40	40	40	40	40	40	40	40
a2 at pl2	40	40	40	40	40	40	40	40	40	40
a2 at pl3	30	30	30	30	30	30	30	30	30	30
b1 at in1	10	10	10	10	10	10	10	10	10	10
b1 at in2	10	10	10	10	10	10	10	10	10	10
b2 at in1	8	8	8	8	8	8	8	8	10	10
b2 at in2	8	8	8	8	8	8	8	8	10	10

Table C.17: Costs of expanding capacity of centers at selectable location sites ($CVE_{o,c,t}$)

relocating routes	Costs of relocating capacity between location sites in each period (year)									
	1st yr.	**2nd yr.**	**3rd yr.**	**4th yr.**	**5th yr.**	**6th yr.**	**7th yr.**	**8th yr.**	**9th yr.**	**10th yr.**
a1 at pl1 to pl3	20	20	20	20	20	20	20	20	20	20
a1 at pl2 to pl3	24	24	24	24	24	24	24	24	24	24
a2 at pl1 to pl3	8	8	8	8	8	8	8	8	8	8
a2 at pl2 to pl3	10	10	10	10	10	10	10	10	10	10
b1 at in1 to in2	3	3	3	3	3	3	3	3	3	3
b2 at in1 to in2	2	2	2	2	2	2	2	2	2	2

Table C.18: Costs of relocating capacity of centers from existing location sites to new location sites ($CVR_{e,n,c,t}$)

Centers at location sites	Costs of closing centers at existing location sites in each period (year)									
	1st yr.	**2nd yr.**	**3rd yr.**	**4th yr.**	**5th yr.**	**6th yr.**	**7th yr.**	**8th yr.**	**9th yr.**	**10th yr.**
a1 at pl1	430000	430000	430000	430000	430000	430000	430000	430000	430000	430000
a1 at pl2	430000	430000	430000	430000	430000	430000	430000	430000	430000	430000
a2 at pl1	70000	70000	70000	70000	70000	70000	70000	70000	70000	70000
a2 at pl2	70000	70000	70000	70000	70000	70000	70000	70000	70000	70000
b1 at in1	30000	30000	30000	30000	30000	30000	30000	30000	30000	30000
b2 at in1	15000	15000	15000	15000	15000	15000	15000	15000	15000	15000

Table C.19: Costs of closing centers at existing location sites ($CFC_{e,c,t}$)

Centers at location sites	Costs of establishing centers at new location sites in each period (year)									
	1st yr.	**2nd yr.**	**3rd yr.**	**4th yr.**	**5th yr.**	**6th yr.**	**7th yr.**	**8th yr.**	**9th yr.**	**10th yr.**
a1 at pl3	630000	630000	630000	630000	630000	630000	630000	630000	630000	630000
a2 at pl3	210000	210000	210000	210000	210000	210000	210000	210000	210000	210000
b1 at in2	150000	150000	150000	150000	150000	150000	150000	150000	150000	150000
b2 at in2	85000	85000	85000	85000	85000	85000	85000	85000	85000	85000

Table C.20: Costs of establishing centers at new location sites ($CFO_{n,c,t}$)

Centers at plant sites	Final products	Disposal costs at plant sites in each period (year)									
		1st yr.	2nd yr.	3rd yr.	4th yr.	5th yr.	6th yr.	7th yr.	8th yr.	9th yr.	10th yr.
a2 at pl1	g1	1	1.05	1.1	1.15	1.2	1.25	1.3	1.35	1.4	1.45
	g2	1	1.05	1.1	1.15	1.2	1.25	1.3	1.35	1.4	1.45
a2 at pl2	g1	1	1.05	1.1	1.15	1.2	1.25	1.3	1.35	1.4	1.45
	g2	1	1.05	1.1	1.15	1.2	1.25	1.3	1.35	1.4	1.45
a2 at pl3	g1	1	1.05	1.1	1.15	1.2	1.25	1.3	1.35	1.4	1.45
	g2	1	1.05	1.1	1.15	1.2	1.25	1.3	1.35	1.4	1.45

Table C.21: Cost of disposing one unit of returned final product ($CDP_{j,a,g,t}$)

C.1.4 Other Parameter Data

Parts/ components	Final products	Amount for assembling final products
m1	g1	3
	g2	3
m2	g1	2
	g2	3
m3	g2	2

Table C.22: Amount of parts/components for assembling one unit of final product ($AM_{m,g}$)

Parts/ components	Final products	Amount from disassembling final products
m1	g1	3
	g2	3
m2	g1	2
	g2	3
m3	g2	1

Table C.23: Amount of parts/components from disassembling one unit of returned final product ($RM_{m,g}$)

Final Products	Fraction of returned products satisfy specs in each period (year)									
	1st yr.	2nd yr.	3rd yr.	4th yr.	5th yr.	6th yr.	7th yr.	8th yr.	9th yr.	10th yr.
g1	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
g2	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8

Table C.24: Fraction of returned final products satisfy the quality specifications ($FR_{g,t}$)

Centers at location sites	Fraction of centers allowed in location sites
a1 at pl1	1
a1 at pl2	1
a1 at pl3	1
a2 at pl1	0.8
a2 at pl2	0.8
a2 at pl3	0.8

Table C.25: Fraction of centers allowed in selectable location sites ($FC_{o,c}$)

Centers at location sites	Fraction of centers allowed in location sites
b1 at in1	1
b1 at in2	1
b2 at in1	0.9
b2 at in2	0.9

Table C.25: Fraction of centers allowed in selectable location sites ($FC_{o,c}$) (continued)

Centers at plant sites	Final products	Unit capacity consumption factors
a1 at pl1	g1	1
	g2	1.1
a1 at pl2	g1	1
	g2	1.1
a1 at pl3	g1	1
	g2	1.1
a2 at pl1	g1	1
	g2	1.2
a2 at pl2	g1	1
	g2	1.2
a2 at pl3	g1	1
	g2	1.2

Table C.26: Unit capacity consumption factors of final products processed at centers of plant sites ($UJ_{j,a,g}$)

Shipping routes	**Final products**	**Unit capacity consumption factors**
pl1 to b1 at in1	g1	1
	g2	1.1
pl1 to b1 at in2	g1	1
	g2	1.1
pl2 to b1 at in1	g1	1
	g2	1.1
pl2 to b1 at in2	g1	1
	g2	1.1
pl3 to b1 at in1	g1	1
	g2	1.1
pl3 to b1 at in2	g1	1
	g2	1.1
cu1 to b2 at in1	g1	1
	g2	1.1
cu1 to b2 at in2	g1	1
	g2	1.1
cu2 to b2 at in1	g1	1
	g2	1.1
cu2 to b2 at in2	g1	1
	g2	1.1
cu3 to b2 at in1	g1	1
	g2	1.1
cu3 to b2 at in2	g1	1
	g2	1.1

Table C.27: Unit capacity consumption factors of final products shipped to centers at intermediate sites ($UI_{l,i,b,g}$)

Interest rates
0.5

Table C.28: Interest rate for the time value of money (IR)

C.2 Programming Code for a Relocation/ Expansion Model for Product Recovery System Including Hybrid Uni/Bidirectional Flows

In this appendix, the GAMS programming code for the formulation of a relocation/expansion model for product recovery system including hybrid uni/bidirectional flows in section 5.1.4 is given. The model is coded for a case study on different levels of product demands and returns in section 5.1.5.

Proposed_Model.gms

```
$ontext
This is the formulation of a relocation/expansion model for product recovery system
including hybrid uni/bidirectional flows in the file "Proposed_Model.gms".
$offtext

$Include Index_sets.gms
$Include Parameters.gms
$Include Decision_variables.gms
```

Equations

```
**************************************************
*Objective function*
**************************************************

tcost      'total cost in period t'
costp      'variable purchasing, processing, subcontracting and transportation costs
           in period t (TOC_1(t))'
costre     'variable costs of capacity relocation and expansion in period t
           (TOC_2(t))'
costo      'fixed costs of operating facilities in period t (TOC_3(t))'

*fixed costs of closing facilities in period t (TOC_4(t))

costcf     'fixed costs of closing facilities in the first period'
costcl     'fixed costs of closing facilities from the second periods'

coste      'fixed costs of opening facilities in period t (TOC_5(t))'
costd      'variable disposal costs in period t (TOC_6(t))'

*objective function

NPV        'net present value of cash flows'


**************************************************
*Constraints*
**************************************************
*Forward flow constraints

manufac    'provide required quantities for manufacturing products'
blpdds     'assure the connection between manufacturing process and the
```

	outbound flows'
flowds	'flow conservation at distribution centers'
demand	'ensure the customer demands are met'

*Reverse flow constraints

ratecus	'predefined return rate of products is used as the returned amount from customers'
blcuscl	'flow conservation at collection centers'
blclda	'ensure the returned products sent to disassembly-remanufacturing centers'
bldapd	'balance the reusable parts/components at disassembly-remanufacturing centers
subrf	'balance the reusable parts/components at disassembly-remanufacturing subcontractors'

*Capacity constraints

**Capacity relocation and expansion constraints

limexce	'limit capacity for further expansion of centers at existing location sites'
limexe	'limit the full expanded capacity for further expansion at existing location sites'
limrlexe	'limit capacity that can be relocated from centers at existing location sites'
movce	'ensure the relocated capacity of centers at existing location sites'
expcn	'ensure the expanded capacity of centers at new location sites'
expn	'limit the additional capacity at new location sites'
modulexp	'bound the allowable amount of capacity expanded to centers at selectable location sites'
modulmov	'bound the allowable amount of capacity relocated from centers at selectable location sites'

```
**Capacity constraints of plant sites

maxcie    'limit maximum processing capacity of centers at existing intermediate
          sites'
maxcin    'limit maximum processing capacity of centers at new intermediate sites'
minci     'limit minimum processing capacity of centers at intermediate sites'

**Capacity constraints of external suppliers**

supm      'limit maximum capacity of external suppliers'

**Capacity constraint of disassembly-remanufacturing subcontractors**

maxsub    'limit maximum capacity of disassembly-remanufacturing subcontractors'

*Logical constraints

opero     'there is no centers at any selectable location site is operated, if that
          selectable location site is not active'
opere     'if existing location sites are closed, they cannot be reopend'
opern     'if new location sites are opened, they cannot be closed'
operce    'if centers at existing location sites are closed, they cannot be reopend'
opercn    'if centers at new location sites are opened, they cannot be closed'
operexc   'if centers at selectable location sites are expanded, they cannot be
          closed'
;

**++++++++++++++++++++++++++++++++++++++++++++++**
*Total cost*
**++++++++++++++++++++++++++++++++++++++++++++++**

tcost(t).. TOC_total(t) =e= TOC1(t)+TOC2(t)+TOC3(t)+TOC4(t)+TOC5(t)
+TOC6(t);
```

*Variable purchasing, processing, subcontracting and transportation costs (TOC1(t))
costp(t).. TOC1(t) =e= **sum**((s,j,m), CB(s,j,m,t)*z(s,j,m,t))
+**sum**((j,a,g), CP(j,a,g,t)*x(j,a,g,t))+**sum**((l,u,g), CS(l,u,g,t)*q(l,u,g,t))
+**sum**((l,lp,p), CT(l,lp,p,t)*y(l,lp,p,t));

*Variable costs of capacity relocation and expansion (TOC2(t))
costre(t).. TOC2(t) =e= **sum**((o,c), CVE(o,c,t)*exp(o,c,t))
+**sum**((e,n,c), CVR(e,n,c,t)*mov(e,n,c,t));

*Fixed costs of operating facilities (TOC3(t))
costo(t).. TOC3(t) =e= **sum**(o, CF(o,t)*varphi(o,t))
+**sum**((o,c), CFF(o,c,t)*delta(o,c,t));

*Fixed costs of closing facilities (TOC4(t))
costcf("1").. TOC4("1") =e= **sum**(e, CC(e,"1")*(1-varphi(e,"1")))
+**sum**((e,c), CFC(e,c,"1")*(1-delta(e,c,"1")));
costcl(t)$(**ord**(t) ne 1).. TOC4(t) =e= **sum**(e, CC(e,t)*(varphi(e,t-1)-varphi(e,t)))
+**sum**((e,c), CFC(e,c,t)*(delta(e,c,t-1)-delta(e,c,t)));

*Fixed costs of opening facilities (TOC5(t))
coste(t).. TOC5(t) =e= **sum**(n, CO(n,t)*(varphi(n,t)-varphi(n,t-1)))
+**sum**((n,c), CFO(n,c,t)*(delta(n,c,t)-delta(n,c,t-1)));

*Variable disposal costs (TOC6(t))
costd(t).. TOC6(t) =e= **sum**((j,a,g), CDP(j,a,g,t)*(1-FR(g,t))*x(j,a,g,t));

————————————————————
Objective function
————————————————————

NPV.. obj =e=
sum(t, ((**sum**((o,k,g), SC(o,k,g,t)*y(o,k,g,t))-TOC_total(t))/(TVM(t))));

```
*__________________________________*
*Constraints*
*__________________________________*

*Forward flow constraints
manufac(j,a(f),m,t).. sum(s, z(s,j,m,t))+sum(jp, y(jp,j,m,t))+sum(u, y(u,j,m,t))
=e= sum(g, x(j,a,g,t)*AM(m,g));

blpdds(j,a(f),g,t).. x(j,a,g,t) =e= sum(i, y(j,i,g,t))+sum(k, y(j,k,g,t));
flowds(i,g,t).. sum(j, y(j,i,g,t)) =e= sum(k, y(i,k,g,t));
demand(k,g,t).. sum(j, y(j,k,g,t))+sum(i, y(i,k,g,t)) =e= DP(k,g,t);

*Reverse flow constraints
ratecus(k,g,t).. (sum(j, y(j,k,g,t))+sum(i, y(i,k,g,t)))*RC(k,g,t)
=e= sum(i, y(k,i,g,t))+sum(j, y(k,j,g,t))+sum(u, q(k,u,g,t));

blcuscl(i,g,t).. sum(k, y(k,i,g,t)) =e= sum(j, y(i,j,g,t))+sum(u, q(i,u,g,t));
blclda(j,a(r),g,t).. sum(k, y(k,j,g,t))+sum(i, y(i,j,g,t)) =e= x(j,a,g,t);

bldapd(j,a(r),m,t).. sum(g, (FR(g,t)*(x(j,a,g,t)*RM(m,g))))
=e= sum(jp, y(j,jp,m,t));

subrf(u,m,t).. sum(g, (FR(g,t)*(sum(k, q(k,u,g,t))+sum(i, q(i,u,g,t)))*RM(m,g)))
=e= sum(j, y(u,j,m,t));

*Capacity constraints
**Capacity relocation and expansion constraints
limexce(e,c).. sum(t, exp(e,c,t)) =l= (KCmax(e,c)-KI(e,c))*rho(e,c);

limexe(e,t).. sum(c, (FC(e,c)*(sum(tp$(ord(tp) <= ord(t)), exp(e,c,tp))
+KI(e,c)*rho(e,c)))) =l= KOmax(e)*varphi(e,t);

limrlexe(e,c).. sum((n,t), mov(e,n,c,t)) =l= KI(e,c)*(1-rho(e,c));
```

movce(e,c,t).. **sum**((n,tp)$(**ord**(tp) <= **ord**(t)), mov(e,n,c,tp)) =l=
KI(e,c)*delta(e,c,t);

expcn(n,c,t).. **sum**(tp$(**ord**(tp) <= **ord**(t)), exp(n,c,tp))
+**sum**((e,tp)$(**ord**(tp) <= **ord**(t)), mov(e,n,c,tp)) =l= KCmax(n,c)*delta(n,c,t);

expn(n,t).. **sum**(c, (FC(n,c)*(**sum**(tp$(**ord**(tp) <= **ord**(t)), exp(n,c,tp))
+**sum**((e,tp)$(**ord**(tp) <= **ord**(t)), mov(e,n,c,tp))))) =l= KOmax(n)*varphi(n,t);

modulexp(o,c,t).. exp(o,c,t) =e= w(o,c,t)*KM(o,c);
modulmov(e,n,c,t).. mov(e,n,c,t) =e= v(e,n,c,t)*KM(e,c);

**Capacity constraints of plant sites
maxcje(j(e),a,t).. **sum**(g, UJ(j,a,g)*x(j,a,g,t)) =l= KI(j,a)*delta(j,a,t)
+sum(tp$(**ord**(tp) <= **ord**(t)), exp(j,a,tp))
-**sum**((jp(n),tp)$(**ord**(tp) <= **ord**(t)), mov(j,jp,a,tp));

maxcjn(j(n),a,t).. **sum**(g, UJ(j,a,g)*x(j,a,g,t))
=l= **sum**(tp$(**ord**(tp) <= **ord**(t)), exp(j,a,tp))
+**sum**((jp(e),tp)$(**ord**(tp) <= **ord**(t)), mov(jp,j,a,tp));

mincj(j,a,t).. **sum**(g, UJ(j,a,g)*x(j,a,g,t)) =g= KCmin(j,a)*delta(j,a,t);

**Capacity constraints of intermediate sites
maxcie(i(e),b,t).. **sum**((l,g), UI(l,i,b,g)*y(l,i,g,t))=l= KI(i,b)*delta(i,b,t)
+**sum(**tp$(**ord**(tp) <= **ord**(t)), exp(i,b,tp))
-**sum**((ip(n),tp)$(**ord**(tp) <= **ord**(t)), mov(i,ip,b,tp));

maxcin(i(n),b,t).. **sum**((l,g), UI(l,i,b,g)*y(l,i,g,t))
=l= **sum**(tp$(**ord**(tp) <= **ord**(t)), exp(i,b,tp))
+**sum**((ip(e),tp)$(**ord**(tp) <= **ord**(t)), mov(ip,i,b,tp));

minci(i,b,t).. **sum**((l,g), UI(l,i,b,g)*y(l,i,g,t)) =g= KCmin(i,b)*delta(i,b,t);

```
**Capacity constraints of external suppliers
supm(s,m,t).. sum(j, z(s,j,m,t)) =l= KSmax(s,m,t);

**Capacity constraints of disassembly-remanufacturing subcontractors
maxsub(u,g,t).. sum(k, q(k,u,g,t))+sum(i, q(i,u,g,t)) =l= KUmax(u,g,t);

*Logical constraints
opero(o,c,t).. varphi(o,t) =g =delta(o,c,t);
opere(e,t)$(ord(t) ne card(t)).. varphi(e,t) =g= varphi(e,t+1);
opern(n,t)$(ord(t) ne card(t)).. varphi(n,t) =l= varphi(n,t+1);
operce(e,c,t)$(ord(t) ne card(t)).. delta(e,c,t) =g= delta(e,c,t+1);
opercn(n,c,t)$(ord(t) ne card(t)).. delta(n,c,t) =l= delta(n,c,t+1);
operexc(e,c).. delta(e,c,"10") =g= rho(e,c);

*option MIP=cplex;
$ontext
*If Cplex was specified as the default solver during GAMS installation, the above statement is not necessary.
$offtext

*The command below is used for the results in Table 5.5(a).
*option iterlim=1000000;
*option reslim=1000000;

*________________________________________________________________
model dynblcl /all/;
option limrow=100000000;
*________________________________________________________________

*The command below is used for the results in Table 5.5(a).
*dynamic.optcr=0.0;
*or
```

**dynamic.optcr=0.00001;*

scalar DefaultResUsed**;**

solve dynblcl using mip maximizing obj**;**

*To show the time used by solver
DefaultResUsed=dynblcl.resusd**;**
display DefaultResUsed**;**

display x.l, y.l z.l, q.l, w.l, v.l, exp.l, mov.l, TOC_total.l**;**

$Include Results.gms

Index_sets.gms

$ontext
The include file "Index_sets.gms" contains index sets of the formulation in the file "Proposed_Model.gms".
$offtext

****
Index sets
****
Sets

l 'location sites' /pl1, pl2, pl3, in1, in2, su1, su2, su3, cu1, cu2, cu3, ou1/
o(l) 'selectable location sites' /pl1, pl2, pl3, in1, in2/
e(o) 'existing location sites' /pl1, pl2, in1/
n(o) 'potential new location sites' /pl3, in2/
j(o) 'plants sites for production and disassembly-remanufacturing centers' /pl1, pl2, pl3/
i(o) 'intermediate sites for distribution and collection centers' /in1, in2/

s(l) 'locations of external suppliers' /su1, su2, su3/

k(l) 'locations of customers' /cu1, cu2, cu3/

u(l) 'locations of external subcontractors for disassembly-remanufacturing process' /ou1/

c 'center types for supply chain processes' /a1, a2, b1, b2/

f(c) 'center types for forward supply chain processes' /a1, b1/

r(c) 'center types for reverse supply chain processes' /a2, b2/

a(c) 'center types at plant sites' /a1, a2/

b(c) 'center types at intermediate sites' /b1, b2/

p 'product types' /g1, g2, m1, m2, m3/

g(p) 'final products' /g1, g2/

m(p) 'materials/parts' /m1, m2, m3/

t 'periods in the planning horizon' /1*10/

;

alias (lp, l)**;**

alias (op, o)**;**

alias (jp, j)**;**

alias (ip, i)**;**

alias (tp, t)**;**

Parameters.gms

$ontext

The include file "Parameters.gms" contains parameters of the formulation in the file "Proposed_Model.gms".

$offtext

```
**************************************************
*Parameters*
**************************************************

*Capacity of location sites
Parameter
KOmax(o) 'maximum allowable capacity of selectable location site o'

/ pl1   110000
  pl2   90000
  pl3   120000
  in1   120000
  in2   140000  /

KI(o,c) 'initial capacity of center c at selectable location site o'

/  pl1.a1     20000
   pl2.a1     40000
   pl1.a2     7000
   pl2.a2     5000
   in1.b1     40000
   in1.b2     21000    /


KCmax(o,c) 'maximum allowable capacity of center c at selectable location site o'

/  pl1.a1     110000
   pl2.a1     90000
   pl3.a1     100000
   pl1.a2     132000
   pl2.a2     10800
   pl3.a2     120000
   in1.b1     120000
```

```
   in2.b1     140000
   in1.b2     132000
   in2.b2     154000  /


KCmin(o,c) 'minimum allowable capacity of center c at selectable location site o'

/  pl1.a1     2000
   pl2.a1     2000
   pl3.a1     2000
   pl1.a2     1500
   pl2.a2     1500
   pl3.a2     1500
   in1.b1     2000
   in2.b1     2000
   in1.b2     1500
   in2.b2     1500  /


KM(o,c) 'fixed expanding/relocation size for center c at selectable location site o'

/  pl1.a1     1000
   pl2.a1     1000
   pl3.a1     1000
   pl1.a2     500
   pl2.a2     500
   pl3.a2     500
   in1.b1     1000
   in2.b1     1000
   in1.b2     500
   in2.b2     500   /
;
```

Table KSmax(s,m,t) 'maximum available capacity of external supplier s for part/component m in period t'

	1	2	3	4	5
su1.m1	220000	220000	220000	220000	220000
su1.m2	200000	200000	200000	200000	200000
su1.m3	190000	190000	190000	190000	190000
su2.m1	220000	220000	220000	220000	220000
su2.m2	200000	200000	200000	200000	200000
su2.m3	190000	190000	190000	190000	190000
su3.m1	220000	220000	220000	220000	220000
su3.m2	200000	200000	200000	200000	200000
su3.m3	190000	190000	190000	190000	190000

+

	6	7	8	9	10
su1.m1	220000	220000	220000	220000	220000
su1.m2	200000	200000	200000	200000	200000
su1.m3	190000	190000	190000	190000	190000
su2.m1	220000	220000	220000	220000	220000
su2.m2	200000	200000	200000	200000	200000
su2.m3	190000	190000	190000	190000	190000
su3.m1	220000	220000	220000	220000	220000
su3.m2	200000	200000	200000	200000	200000
su3.m3	190000	190000	190000	190000	190000

;

Table KUmax(u,g,t) 'maximum available capacity of the disassembly-remanufacturing subcontractor u for the returned product g in period t'

	1	2	3	4	5
ou1.g1	120000	120000	120000	120000	120000
ou1.g2	120000	120000	120000	120000	120000

```
+
              6        7        8        9        10
ou1.g1        120000   120000   120000   120000   120000
ou1.g2        120000   120000   120000   120000   120000
;
```

*Selling prices

Table SC(o,k,g,t)'variable price of selling one unit of final product g from the selectable location site o to customer k in period t'

	1	2	3	4	5
pl1.cu1.g1	580	599.50	619.49	639.97	660.97
pl1.cu1.g2	750	776.25	803.16	830.74	859
pl1.cu2.g1	580	599.50	619.49	639.97	660.97
pl1.cu2.g2	750	776.25	803.16	830.74	859
pl1.cu3.g1	580	599.50	619.49	639.97	660.97
pl1.cu3.g2	750	776.25	803.16	830.74	859
pl2.cu1.g1	580	599.50	619.49	639.97	660.97
pl2.cu1.g2	750	776.25	803.16	830.74	859
pl2.cu2.g1	580	599.50	619.49	639.97	660.97
pl2.cu2.g2	750	776.25	803.16	830.74	859
pl2.cu3.g1	580	599.50	619.49	639.97	660.97
pl2.cu3.g2	750	776.25	803.16	830.74	859
pl3.cu1.g1	580	599.50	619.49	639.97	660.97
pl3.cu1.g2	750	776.25	803.16	830.74	859
pl3.cu2.g1	580	599.50	619.49	639.97	660.97
pl3.cu2.g2	750	776.25	803.16	830.74	859
pl3.cu3.g1	580	599.50	619.49	639.97	660.97
pl3.cu3.g2	750	776.25	803.16	830.74	859
in1.cu1.g1	580	599.50	619.49	639.97	660.97
in1.cu1.g2	750	776.25	803.16	830.74	859

in1.cu2.g1	580	599.50	619.49	639.97	660.97
in1.cu2.g2	750	776.25	803.16	830.74	859
in1.cu3.g1	580	599.50	619.49	639.97	660.97
in1.cu3.g2	750	776.25	803.16	830.74	859
in2.cu1.g1	580	599.50	619.49	639.97	660.97
in2.cu1.g2	750	776.25	803.16	830.74	859
in2.cu2.g1	580	599.50	619.49	639.97	660.97
in2.cu2.g2	750	776.25	803.16	830.74	859
in2.cu3.g1	580	599.50	619.49	639.97	660.97
in2.cu3.g2	750	776.25	803.16	830.74	859
+					
	6	7	8	9	10
pl1.cu1.g1	682.50	604.56	627.17	650.35	674.11
pl1.cu1.g2	877.98	900.68	928.12	959.32	971.31
pl1.cu2.g1	682.50	604.56	627.17	650.35	674.11
pl1.cu2.g2	877.98	900.68	928.12	959.32	971.31
pl1.cu3.g1	682.50	604.56	627.17	650.35	674.11
pl1.cu3.g2	877.98	900.68	928.12	959.32	971.31
pl2.cu1.g1	682.50	604.56	627.17	650.35	674.11
pl2.cu1.g2	877.98	900.68	928.12	959.32	971.31
pl2.cu2.g1	682.50	604.56	627.17	650.35	674.11
pl2.cu2.g2	877.98	900.68	928.12	959.32	971.31
pl2.cu3.g1	682.50	604.56	627.17	650.35	674.11
pl2.cu3.g2	877.98	900.68	928.12	959.32	971.31
pl3.cu1.g1	682.50	604.56	627.17	650.35	674.11
pl3.cu1.g2	877.98	900.68	928.12	959.32	971.31
pl3.cu2.g1	682.50	604.56	627.17	650.35	674.11
pl3.cu2.g2	877.98	900.68	928.12	959.32	971.31
pl3.cu3.g1	682.50	604.56	627.17	650.35	674.11
pl3.cu3.g2	877.98	900.68	928.12	959.32	971.31

in1.cu1.g1	682.50	604.56	627.17	650.35	674.11
in1.cu1.g2	877.98	900.68	928.12	959.32	971.31
in1.cu2.g1	682.50	604.56	627.17	650.35	674.11
in1.cu2.g2	877.98	900.68	928.12	959.32	971.31
in1.cu3.g1	682.50	604.56	627.17	650.35	674.11
in1.cu3.g2	877.98	900.68	928.12	959.32	971.31
in2.cu1.g1	682.50	604.56	627.17	650.35	674.11
in2.cu1.g2	877.98	900.68	928.12	959.32	971.31
in2.cu2.g1	682.50	604.56	627.17	650.35	674.11
in2.cu2.g2	877.98	900.68	928.12	959.32	971.31
in2.cu3.g1	682.50	604.56	627.17	650.35	674.11
in2.cu3.g2	877.98	900.68	928.12	959.32	971.31

;

*Costs

Table CB(s,j,m,t) 'variable cost of purchasing one unit of part/component m from external supplier s by plant site j in period t'

	1	2	3	4	5
su1.pl1.m1	15	15.5	16	16.5	17
su1.pl1.m2	15	15.5	16	16.5	17
su1.pl1.m3	15	15.5	16	16.5	17
su1.pl2.m1	15	15.5	16	16.5	17
su1.pl2.m2	15	15.5	16	16.5	17
su1.pl2.m3	15	15.5	16	16.5	17
su1.pl3.m1	15	15.5	16	16.5	17
su1.pl3.m2	15	15.5	16	16.5	17
su1.pl3.m3	15	15.5	16	16.5	17
su2.pl1.m1	15	15.5	16	16.5	17
su2.pl1.m2	15	15.5	16	16.5	17
su2.pl1.m3	20	21	22	23	24

su2.pl2.m1	15	15.5	16	16.5	17
su2.pl2.m2	15	15.5	16	16.5	17
su2.pl2.m3	20	21	22	23	24
su2.pl3.m1	15	15.5	16	16.5	17
su2.pl3.m2	15	15.5	16	16.5	17
su2.pl3.m3	20	21	22	23	24
su3.pl1.m1	15	15.5	16	16.5	17
su3.pl1.m2	15	15.5	16	16.5	17
su3.pl1.m3	15	15.5	16	16.5	17
su3.pl2.m1	15	15.5	16	16.5	17
su3.pl2.m2	15	15.5	16	16.5	17
su3.pl2.m3	20	21	22	23	24
su3.pl3.m1	15	15.5	16	16.5	17
su3.pl3.m2	15	15.5	16	16.5	17
su3.pl3.m3	20	21	22	23	24

+

	6	7	8	9	10
su1.pl1.m1	17.5	18	18.5	19	19.5
su1.pl1.m2	17.5	18	18.5	19	19.5
su1.pl1.m3	17.5	18	18.5	19	19.5
su1.pl2.m1	17.5	18	18.5	19	19.5
su1.pl2.m2	17.5	18	18.5	19	19.5
su1.pl2.m3	17.5	18	18.5	19	19.5
su1.pl3.m1	17.5	18	18.5	19	19.5
su1.pl3.m2	17.5	18	18.5	19	19.5
su1.pl3.m3	17.5	18	18.5	19	19.5
su2.pl1.m1	17.5	18	18.5	19	19.5
su2.pl1.m2	17.5	18	18.5	19	19.5
su2.pl1.m3	25	26	27	28	29
su2.pl2.m1	17.5	18	18.5	19	19.5

su2.pl2.m2	17.5	18	18.5	19	19.5
su2.pl2.m3	25	26	27	28	29
su2.pl3.m1	17.5	18	18.5	19	19.5
su2.pl3.m2	17.5	18	18.5	19	19.5
su2.pl3.m3	25	26	27	28	29
su3.pl1.m1	17.5	18	18.5	19	19.5
su3.pl1.m2	17.5	18	18.5	19	19.5
su3.pl1.m3	17.5	18	18.5	28	29
su3.pl2.m1	17.5	18	18.5	19	19.5
su3.pl2.m2	17.5	18	18.5	19	19.5
su3.pl2.m3	25	26	27	28	29
su3.pl3.m1	17.5	18	18.5	19	19.5
su3.pl3.m2	17.5	18	18.5	19	19.5
su3.pl3.m3	25	26	27	28	29

;

Table CP(j,a,g,t) 'variable cost of processing one unit of final product g by center c at selectable location site o in period t'

	1	2	3	4	5
pl1.a1.g1	240	245	245	250	250
pl1.a1.g2	300	308	316	324	332
pl2.a1.g1	250	255	260	265	270
pl2.a1.g2	400	408	416	424	432
pl3.a1.g1	250	255	260	265	270
pl3.a1.g2	400	408	416	424	432
pl1.a2.g1	11	12	13	14	15
pl1.a2.g2	16	17	18	19	20
pl2.a2.g1	13	14	15	16	17
pl2.a2.g2	21	22	23	24	25
pl3.a2.g1	8	8	10	10	11

pl3.a2.g2	11	12	13	14	15
+					
	6	7	8	9	10
pl1.a1.g1	255	255	260	265	270
pl1.a1.g2	340	348	356	364	372
pl2.a1.g1	275	280	285	290	295
pl2.a1.g2	440	448	456	464	472
pl3.a1.g1	275	280	285	290	295
pl3.a1.g2	440	448	456	464	472
pl1.a2.g1	16	17	18	19	20
pl1.a2.g2	21	22	23	24	25
pl2.a2.g1	18	19	20	21	22
pl2.a2.g2	26	27	28	29	30
pl3.a2.g1	11	12	13	13	14
pl3.a2.g2	16	17	18	19	20

;

Table CS(l,u,g,t) 'variable cost of subcontracting one unit of returned final product g from location site l by external subcontractor u in period t'

	1	2	3	4	5
cu1.ou1.g1	45	46	47	48	49
cu1.ou1.g2	65	66	67	68	69
cu2.ou1.g1	16	17	18	19	20
cu2.ou1.g2	43	44	45	46	47
cu3.ou1.g1	40	41	42	43	44
cu3.ou1.g2	60	61	62	63	64
in1.ou1.g1	16	17	18	19	20
in1.ou1.g2	43	44	45	46	47
in2.ou1.g1	16	17	18	19	20
in2.ou1.g2	43	44	45	46	47

+

	6	7	8	9	10
cu1.ou1.g1	50	51	52	53	54
cu1.ou1.g2	70	71	72	73	74
cu2.ou1.g1	21	22	23	24	25
cu2.ou1.g2	48	49	50	51	52
cu3.ou1.g1	45	46	47	48	49
cu3.ou1.g2	65	66	67	68	69
in1.ou1.g1	21	22	23	24	25
in1.ou1.g2	48	49	50	51	52
in2.ou1.g1	21	22	23	24	25
in2.ou1.g2	48	49	50	51	52

;

Table CT(l,lp,p,t) 'variable cost of shipping one unit of product p from location site l to location site lp in period t'

	1	2	3	4	5
pl1.in1.g1	8	8	8.4	8.4	8.8
pl1.in1.g2	8	8	8.4	8.4	8.8
pl1.in2.g1	4	4	4.2	4.2	4.4
pl1.in2.g2	4	4	4.2	4.2	4.4
pl1.cu1.g1	20	20	21	21	22
pl1.cu1.g2	20	20	21	21	22
pl1.cu2.g1	20	20	21	21	22
pl1.cu2.g2	20	20	21	21	22
pl1.cu3.g1	10	10	10.5	10.5	11
pl1.cu3.g2	10	10	10.5	10.5	11
pl2.in1.g1	8	8	8.4	8.4	8.8
pl2.in1.g2	8	8	8.4	8.4	8.8
pl2.in2.g1	8	8	8.4	8.4	8.8

pl2.in2.g2	8	8	8.4	8.4	8.8
pl2.cu1.g1	20	20	21	21	22
pl2.cu1.g2	20	20	21	21	22
pl2.cu2.g1	20	20	21	21	22
pl2.cu2.g2	20	20	21	21	22
pl2.cu3.g1	20	20	21	21	22
pl2.cu3.g2	20	20	21	21	22
pl3.in1.g1	8	8	8.4	8.4	8.8
pl3.in1.g2	8	8	8.4	8.4	8.8
pl3.in2.g1	4	4	4.2	4.2	4.4
pl3.in2.g2	4	4	4.2	4.2	4.4
pl3.cu1.g1	20	20	21	21	22
pl3.cu1.g2	20	20	21	21	22
pl3.cu2.g1	20	20	21	21	22
pl3.cu2.g2	20	20	21	21	22
pl3.cu3.g1	10	10	10.5	10.5	11
pl3.cu3.g2	10	10	10.5	10.5	11
pl1.pl1.m1	0.1	0.1	0.105	0.105	0.11
pl1.pl1.m2	0.1	0.1	0.105	0.105	0.11
pl1.pl1.m3	0.1	0.1	0.105	0.105	0.11
pl1.pl2.m1	0.5	0.5	0.525	0.525	0.55
pl1.pl2.m2	0.5	0.5	0.525	0.525	0.55
pl1.pl2.m3	0.5	0.5	0.525	0.525	0.55
pl1.pl3.m1	0.5	0.5	0.525	0.525	0.55
pl1.pl3.m2	0.5	0.5	0.525	0.525	0.55
pl1.pl3.m3	0.5	0.5	0.525	0.525	0.55
pl2.pl1.m1	0.5	0.5	0.525	0.525	0.55
pl2.pl1.m2	0.5	0.5	0.525	0.525	0.55
pl2.pl1.m3	0.5	0.5	0.525	0.525	0.55
pl2.pl2.m1	0.1	0.1	0.105	0.105	0.11

pl2.pl2.m2	0.1	0.1	0.105	0.105	0.11
pl2.pl2.m3	0.1	0.1	0.105	0.105	0.11
pl2.pl3.m1	0.5	0.5	0.525	0.525	0.55
pl2.pl3.m2	0.5	0.5	0.525	0.525	0.55
pl2.pl3.m3	0.5	0.5	0.525	0.525	0.55
pl3.pl1.m1	0.5	0.5	0.525	0.525	0.55
pl3.pl1.m2	0.5	0.5	0.525	0.525	0.55
pl3.pl1.m3	0.5	0.5	0.525	0.525	0.55
pl3.pl2.m1	0.5	0.5	0.525	0.525	0.55
pl3.pl2.m2	0.5	0.5	0.525	0.525	0.55
pl3.pl2.m3	0.5	0.5	0.525	0.525	0.55
pl3.pl3.m1	0.1	0.1	0.105	0.105	0.11
pl3.pl3.m2	0.1	0.1	0.105	0.105	0.11
pl3.pl3.m3	0.1	0.1	0.105	0.105	0.11
in1.cu1.g1	8	8	8.4	8.4	8.8
in1.cu1.g2	8	8	8.4	8.4	8.8
in1.cu2.g1	8	8	8.4	8.4	8.8
in1.cu2.g2	8	8	8.4	8.4	8.8
in1.cu3.g1	8	8	8.4	8.4	8.8
in1.cu3.g2	8	8	8.4	8.4	8.8
in2.cu1.g1	4	4	4.2	4.2	4.4
in2.cu1.g2	4	4	4.2	4.2	4.4
in2.cu2.g1	4	4	4.2	4.2	4.4
in2.cu2.g2	4	4	4.2	4.2	4.4
in2.cu3.g1	4	4	4.2	4.2	4.4
in2.cu3.g2	4	4	4.2	4.2	4.4
in1.pl1.g1	4	4	4.2	4.2	4.4
in1.pl1.g2	4	4	4.2	4.2	4.4
in1.pl2.g1	4	4	4.2	4.2	4.4
in1.pl2.g2	4	4	4.2	4.2	4.4

in1.pl3.g1	4	4	4.2	4.2	4.4
in1.pl3.g2	4	4	4.2	4.2	4.4
in2.pl1.g1	2	2	2.1	2.1	2.2
in2.pl1.g2	2	2	2.1	2.1	2.2
in2.pl2.g1	4	4	4.2	4.2	4.4
in2.pl2.g2	4	4	4.2	4.2	4.4
in2.pl3.g1	2	2	2.1	2.1	2.2
in2.pl3.g2	2	2	2.1	2.1	2.2
cu1.in1.g1	4	4	4.2	4.2	4.4
cu1.in1.g2	4	4	4.2	4.2	4.4
cu1.in2.g1	2	2	2.1	2.1	2.2
cu1.in2.g2	2	2	2.1	2.1	2.2
cu2.in1.g1	4	4	4.2	4.2	4.4
cu2.in1.g2	4	4	4.2	4.2	4.4
cu2.in2.g1	2	2	2.1	2.1	2.2
cu2.in2.g2	2	2	2.1	2.1	2.2
cu3.in1.g1	4	4	4.2	4.2	4.4
cu3.in1.g2	4	4	4.2	4.2	4.4
cu3.in2.g1	2	2	2.1	2.1	2.2
cu3.in2.g2	2	2	2.1	2.1	2.2
cu1.pl1.g1	15	15	15.75	15.75	16.5
cu1.pl1.g2	15	15	15.75	15.75	16.5
cu1.pl2.g1	15	15	15.75	15.75	16.5
cu1.pl2.g2	15	15	15.75	15.75	16.5
cu1.pl3.g1	15	15	15.75	15.75	16.5
cu1.pl3.g2	15	15	15.75	15.75	16.5
cu2.pl1.g1	15	15	15.75	15.75	16.5
cu2.pl1.g2	15	15	15.75	15.75	16.5
cu2.pl2.g1	15	15	15.75	15.75	16.5
cu2.pl2.g2	15	15	15.75	15.75	16.5

cu2.pl3.g1	15	15	15.75	15.75	16.5
cu2.pl3.g2	15	15	15.75	15.75	16.5
cu3.pl1.g1	7	7	7.35	7.35	7.7
cu3.pl1.g2	7	7	7.35	7.35	7.7
cu3.pl2.g1	15	15	15.75	15.75	16.5
cu3.pl2.g2	15	15	15.75	15.75	16.5
cu3.pl3.g1	7	7	7.35	7.35	7.7
cu3.pl3.g2	7	7	7.35	7.35	7.7
ou1.pl1.m1	0.25	0.25	0.26	0.26	0.27
ou1.pl1.m2	0.25	0.25	0.26	0.26	0.27
ou1.pl1.m3	0.25	0.25	0.26	0.26	0.27
ou1.pl2.m1	0.5	0.5	0.525	0.525	0.55
ou1.pl2.m2	0.5	0.5	0.525	0.525	0.55
ou1.pl2.m3	0.5	0.5	0.525	0.525	0.55
ou1.pl3.m1	0.5	0.5	0.525	0.525	0.55
ou1.pl3.m2	0.5	0.5	0.525	0.525	0.55
ou1.pl3.m3	0.5	0.5	0.525	0.525	0.55
+					
	6	7	8	9	10
pl1.in1.g1	8.8	9.2	9.2	9.6	9.6
pl1.in1.g2	8.8	9.2	9.2	9.6	9.6
pl1.in2.g1	4.4	4.6	4.6	4.8	4.8
pl1.in2.g2	4.4	4.6	4.6	4.8	4.8
pl1.cu1.g1	22	23	23	24	24
pl1.cu1.g2	22	23	23	24	24
pl1.cu2.g1	22	23	23	24	24
pl1.cu2.g2	22	23	23	24	24
pl1.cu3.g1	11	11.5	11.5	12	12
pl1.cu3.g2	11	11.5	11.5	12	12
pl2.in1.g1	8.8	9.2	9.2	9.6	9.6

pl2.in1.g2	8.8	9.2	9.2	9.6	9.6
pl2.in2.g1	8.8	9.2	9.2	9.6	9.6
pl2.in2.g2	8.8	9.2	9.2	9.6	9.6
pl2.cu1.g1	22	23	23	24	24
pl2.cu1.g2	22	23	23	24	24
pl2.cu2.g1	22	23	23	24	24
pl2.cu2.g2	22	23	23	24	24
pl2.cu3.g1	22	23	23	24	24
pl2.cu3.g2	22	23	23	24	24
pl3.in1.g1	8.8	9.2	9.2	9.6	9.6
pl3.in1.g2	8.8	9.2	9.2	9.6	9.6
pl3.in2.g1	4.4	4.6	4.6	4.8	4.8
pl3.in2.g2	4.4	4.6	4.6	4.8	4.8
pl3.cu1.g1	22	23	23	24	24
pl3.cu1.g2	22	23	23	24	24
pl3.cu2.g1	22	23	23	24	24
pl3.cu2.g2	22	23	23	24	24
pl3.cu3.g1	11	11.5	11.5	12	12
pl3.cu3.g2	11	11.5	11.5	12	12
pl1.pl1.m1	0.11	0.115	0.115	0.12	0.12
pl1.pl1.m2	0.11	0.115	0.115	0.12	0.12
pl1.pl1.m3	0.11	0.115	0.115	0.12	0.12
pl1.pl2.m1	0.55	0.75	0.75	1	1
pl1.pl2.m2	0.55	0.75	0.75	1	1
pl1.pl2.m3	0.55	0.75	0.75	1	1
pl1.pl3.m1	0.55	0.75	0.75	1	1
pl1.pl3.m2	0.55	0.75	0.75	1	1
pl1.pl3.m3	0.55	0.75	0.75	1	1
pl2.pl1.m1	0.55	0.75	0.75	1	1
pl2.pl1.m2	0.55	0.75	0.75	1	1

pl2.pl1.m3	0.55	0.75	0.75	1	1
pl2.pl2.m1	0.11	0.115	0.115	0.12	0.12
pl2.pl2.m2	0.11	0.115	0.115	0.12	0.12
pl2.pl2.m3	0.11	0.115	0.115	0.12	0.12
pl2.pl3.m1	0.55	0.75	0.75	1	1
pl2.pl3.m2	0.55	0.75	0.75	1	1
pl2.pl3.m3	0.55	0.75	0.75	1	1
pl3.pl1.m1	0.55	0.75	0.75	1	1
pl3.pl1.m2	0.55	0.75	0.75	1	1
pl3.pl1.m3	0.55	0.75	0.75	1	1
pl3.pl2.m1	0.55	0.75	0.75	1	1
pl3.pl2.m2	0.55	0.75	0.75	1	1
pl3.pl2.m3	0.55	0.75	0.75	1	1
pl3.pl3.m1	0.11	0.115	0.115	0.12	0.12
pl3.pl3.m2	0.11	0.115	0.115	0.12	0.12
pl3.pl3.m3	0.11	0.115	0.115	0.12	0.12
in1.cu1.g1	8.8	9.2	9.2	9.6	9.6
in1.cu1.g2	8.8	9.2	9.2	9.6	9.6
in1.cu2.g1	8.8	9.2	9.2	9.6	9.6
in1.cu2.g2	8.8	9.2	9.2	9.6	9.6
in1.cu3.g1	8.8	9.2	9.2	9.6	9.6
in1.cu3.g2	8.8	9.2	9.2	9.6	9.6
in2.cu1.g1	4.4	4.6	4.6	4.8	4.8
in2.cu1.g2	4.4	4.6	4.6	4.8	4.8
in2.cu2.g1	4.4	4.6	4.6	4.8	4.8
in2.cu2.g2	4.4	4.6	4.6	4.8	4.8
in2.cu3.g1	4.4	4.6	4.6	4.8	4.8
in2.cu3.g2	4.4	4.6	4.6	4.8	4.8
in1.pl1.g1	4.4	4.6	4.6	4.8	4.8
in1.pl1.g2	4.4	4.6	4.6	4.8	4.8

in1.pl2.g1	4.4	4.6	4.6	4.8	4.8
in1.pl2.g2	4.4	4.6	4.6	4.8	4.8
in1.pl3.g1	4.4	4.6	4.6	4.8	4.8
in1.pl3.g2	4.4	4.6	4.6	4.8	4.8
in2.pl1.g1	2.2	2.3	2.3	2.4	2.4
in2.pl1.g2	2.2	2.3	2.3	2.4	2.4
in2.pl2.g1	4.4	4.6	4.6	4.8	4.8
in2.pl2.g2	4.4	4.6	4.6	4.8	4.8
in2.pl3.g1	2.2	2.3	2.3	2.4	2.4
in2.pl3.g2	2.2	2.3	2.3	2.4	2.4
cu1.in1.g1	4.4	4.6	4.6	4.8	4.8
cu1.in1.g2	4.4	4.6	4.6	4.8	4.8
cu1.in2.g1	2.2	2.3	2.3	2.4	2.4
cu1.in2.g2	2.2	2.3	2.3	2.4	2.4
cu2.in1.g1	4.4	4.6	4.6	4.8	4.8
cu2.in1.g2	4.4	4.6	4.6	4.8	4.8
cu2.in2.g1	2.2	2.3	2.3	2.4	2.4
cu2.in2.g2	2.2	2.3	2.3	2.4	2.4
cu3.in1.g1	4.4	4.6	4.6	4.8	4.8
cu3.in1.g2	4.4	4.6	4.6	4.8	4.8
cu3.in2.g1	2.2	2.3	2.3	2.4	2.4
cu3.in2.g2	2.2	2.3	2.3	2.4	2.4
cu1.pl1.g1	16.5	17	17	17.5	17.5
cu1.pl1.g2	16.5	17	17	17.5	17.5
cu1.pl2.g1	16.5	17	17	17.5	17.5
cu1.pl2.g2	16.5	17	17	17.5	17.5
cu1.pl3.g1	16.5	17	17	17.5	17.5
cu1.pl3.g2	16.5	17	17	17.5	17.5
cu2.pl1.g1	16.5	17	17	17.5	17.5
cu2.pl1.g2	16.5	17	17	17.5	17.5

cu2.pl2.g1	16.5	17	17	17.5	17.5
cu2.pl2.g2	16.5	17	17	17.5	17.5
cu2.pl3.g1	16.5	17	17	17.5	17.5
cu2.pl3.g2	16.5	17	17	17.5	17.5
cu3.pl1.g1	7.7	8.05	8.05	9	9
cu3.pl1.g2	7.7	8.05	8.05	9	9
cu3.pl2.g1	16.5	17	17	17.5	17.5
cu3.pl2.g2	16.5	17	17	17.5	17.5
cu3.pl3.g1	7.7	8.05	8.05	9	9
cu3.pl3.g2	7.7	8.05	8.05	9	9
ou1.pl1.m1	0.27	0.28	0.28	0.29	0.29
ou1.pl1.m2	0.27	0.28	0.28	0.29	0.29
ou1.pl1.m3	0.27	0.28	0.28	0.29	0.29
ou1.pl2.m1	0.55	0.75	0.75	1	1
ou1.pl2.m2	0.55	0.75	0.75	1	1
ou1.pl2.m3	0.55	0.75	0.75	1	1
ou1.pl3.m1	0.55	0.75	0.75	1	1
ou1.pl3.m2	0.55	0.75	0.75	1	1
ou1.pl3.m3	0.55	0.75	0.75	1	1

;

Table CF(o,t) 'fixed cost of operating selectable location site o in period t'

	1	2	3	4	5
pl1	5000	5000	5000	5000	5000
pl2	5000	5000	5000	5000	5000
pl3	5000	5000	5000	5000	5000
in1	1025	1025	1025	1025	1025
in2	1025	1025	1025	1025	1025

+

	6	7	8	9	10
pl1	5000	5000	5000	5000	5000
pl2	5000	5000	5000	5000	5000
pl3	5000	5000	5000	5000	5000
in1	1025	1025	1025	1025	1025
in2	1025	1025	1025	1025	1025

;

Table CC(e,t) 'fixed cost of closing existing location site e in period t'

	1	2	3	4	5
pl1	13000	13325	12350	13650	13975
pl2	13000	13325	12350	13650	13975
in1	2000	2000	2000	2000	2000

+

	6	7	8	9	10
pl1	14300	14625	14950	15275	15600
pl2	14300	14625	14950	15275	15600
in1	2000	2000	2000	2000	2000

;

Table CO(n,t) 'fixed cost opening new location site n in period t'

	1	2	3	4	5
pl3	39000	39000	39000	39000	39000
in2	4000	4000	4000	4000	4000

+

	6	7	8	9	10
pl3	39000	39000	39000	39000	39000
in2	4000	4000	4000	4000	4000

;

Table CFF(o,c,t) 'fixed cost of operating center c at selectable location site o in period t'

	1	2	3	4	5
pl1.a1	50000	51250	52531	53844	55190
pl2.a1	70000	71250	72531	73844	75190
pl3.a1	50000	51250	52531	53844	55190
pl1.a2	15000	15375	15759	16153	16557
pl2.a2	15000	15375	15759	16153	16557
pl3.a2	15000	15375	15759	16153	16557
in1.b1	10250	10500	10762	11031	11307
in2.b1	10250	10500	10762	11031	11307
in1.b2	6150	6457	6618	6784	6954
in2.b2	6150	6457	6618	6784	6954

+

	6	7	8	9	10
pl1.a1	56570	57984	59434	60920	62443
pl2.a1	76570	77984	79434	80920	82443
pl3.a1	56570	57984	59434	60920	62443
pl1.a2	16971	17395	17830	18276	18732
pl2.a2	16971	17395	17830	18276	18732
pl3.a2	16971	17395	17830	18276	18732
in1.b1	11590	11879	12176	12481	12793
in2.b1	11590	11879	12176	12481	12793
in1.b2	7127	7306	7488	7675	7867
in2.b2	7127	7306	7488	7675	7867

;

Table CVE(o,c,t) 'variable cost associated with expanding capacity of center c at selectable location site o in period t'

	1	2	3	4	5
pl1.a1	120	120	120	120	120
pl2.a1	120	120	120	120	120
pl3.a1	120	120	120	120	120
pl1.a2	40	40	40	40	40
pl2.a2	40	40	40	40	40
pl3.a2	30	30	20	20	20
in1.b1	10	10	10	10	10
in2.b1	10	10	10	10	10
in1.b2	8	8	8	8	8
in2.b2	8	8	8	8	8

+

	6	7	8	9	10
pl1.a1	120	120	120	120	120
pl2.a1	120	120	120	120	120
pl3.a1	120	120	120	120	120
pl1.a2	40	40	40	40	40
pl2.a2	40	40	40	40	40
pl3.a2	20	20	20	20	20
in1.b1	10	10	10	10	10
in2.b1	10	10	10	10	10
in1.b2	8	8	8	10	10
in2.b2	8	8	8	10	10

;

Table CVR(e,n,c,t) 'variable cost associated with relocating capacity of center c from existing location site e to new location site n in period t'

	1	2	3	4	5
pl1.pl3.a1	20	20	20	20	20
pl2.pl3.a1	24	24	24	24	24
pl1.pl3.a2	8	8	8	8	8
pl2.pl3.a2	10	10	10	10	10
in1.in2.b1	3	3	3	3	3
in1.in2.b2	2	2	2	2	2

+

	6	7	8	9	10
pl1.pl3.a1	20	20	20	20	20
pl2.pl3.a1	24	24	24	24	24
pl1.pl3.a2	8	8	8	8	8
pl2.pl3.a2	10	10	10	10	10
in1.in2.b1	3	3	3	3	3
in1.in2.b2	2	2	2	2	2

;

Table CFC(e,c,t) 'fixed cost of closing center c at existing location site e in period t'

	1	2	3	4	5
pl1.a1	430000	430000	430000	430000	430000
pl2.a1	430000	430000	430000	430000	430000
pl1.a2	70000	70000	70000	70000	70000
pl2.a2	70000	70000	70000	70000	70000
in1.b1	30000	30000	30000	30000	30000
in1.b2	15000	15000	15000	15000	15000

+

	6	7	8	9	10
pl1.a1	430000	430000	430000	430000	430000

pl2.a1	430000	430000	430000	430000	430000
pl1.a2	70000	70000	70000	70000	70000
pl2.a2	70000	70000	70000	70000	70000
in1.b1	30000	30000	30000	30000	30000
in1.b2	15000	15000	15000	15000	15000

;

Table CFO(n,c,t) 'fixed cost of opening center c at new location site n in period t'

	1	2	3	4	5
pl3.a1	630000	630000	630000	630000	630000
pl3.a2	210000	210000	210000	210000	210000
in2.b1	150000	150000	150000	150000	150000
in2.b2	85000	85000	85000	85000	85000

+

	6	7	8	9	10
pl3.a1	630000	630000	630000	630000	630000
pl3.a2	210000	210000	210000	210000	210000
in2.b1	150000	150000	150000	150000	150000
in2.b2	85000	85000	85000	85000	85000

;

Table CDP(j,a,g,t) 'variable disposal cost per unit of returned final product g discarded from center a at plant site j in period t'

	1	2	3	4	5
pl1.a2.g1	1	1.05	1.1	1.15	1.2
pl1.a2.g2	1	1.05	1.1	1.15	1.2
pl2.a2.g1	1	1.05	1.1	1.15	1.2
pl2.a2.g2	1	1.05	1.1	1.15	1.2
pl3.a2.g1	1	1.05	1.1	1.15	1.2
pl3.a2.g2	1	1.05	1.1	1.15	1.2

+

	6	7	8	9	10
pl1.a2.g1	1.25	1.3	1.35	1.4	1.45
pl1.a2.g2	1.25	1.3	1.35	1.4	1.45
pl2.a2.g1	1.25	1.3	1.35	1.4	1.45
pl2.a2.g2	1.25	1.3	1.35	1.4	1.45
pl3.a2.g1	1.25	1.3	1.35	1.4	1.45
pl3.a2.g2	1.25	1.3	1.35	1.4	1.45

;

*Other Parameters

Table DP(k,g,t) 'demand of final product g by customer k in period t'

	1	2	3	4	5
cu1.g1	11000	10000	10000	10000	10000
cu1.g2	10000	10000	9000	9000	7000
cu2.g1	10000	10000	9000	9000	8000
cu2.g2	10000	11000	10500	10000	10000
cu3.g1	12000	10000	9000	9000	8500
cu3.g2	11000	9000	9000	8000	7000

+

	6	7	8	9	10
cu1.g1	10000	10000	9500	9000	8500
cu1.g2	7000	7000	7000	7000	7000
cu2.g1	7500	6500	6500	5500	5500
cu2.g2	9000	8000	7000	6200	5200
cu3.g1	7500	7000	6800	6500	6000
cu3.g2	7000	6000	5600	5100	5000

;

$ontext
The above table is the data for decreasing demand scenarios (scenarios DL, DM and DH) from Table 5.3(a). See Tables 5.3(b) and 5.3(c) of this thesis for the data of other scenarios.
$offtext

Table RC(k,g,t) 'fraction of final product g returned from customer k in period t'

	1	2	3	4	5
cu1.g1	0.2	0.1	0.3	0.2	0.3
cu1.g2	0.1	0.2	0.2	0.3	0.1
cu2.g1	0.2	0.2	0.1	0.2	0.3
cu2.g2	0.2	0.1	0.2	0.2	0.2
cu3.g1	0.1	0.2	0.2	0.3	0.1
cu3.g2	0.2	0.1	0.1	0.2	0.3

\+

	6	7	8	9	10
cu1.g1	0.2	0.1	0.2	0.3	0.2
cu1.g2	0.2	0.3	0.2	0.3	0.2
cu2.g1	0.1	0.2	0.3	0.2	0.3
cu2.g2	0.2	0.3	0.2	0.1	0.2
cu3.g1	0.3	0.2	0.1	0.2	0.3
cu3.g2	0.3	0.2	0.3	0.3	0.2

;

$ontext
The above table is the data of low rates of returns (for scenarios DL, SL and IL) from Table 5.4(a). See Tables 5.4(b) and 5.4(c) of this thesis for the data of other scenarios.
$offtext

Table AM(m,g) 'amount of part/component m for assembling one unit of final product g'

	g1	g2
m1	3	3
m2	2	3
m3		2

;

Table RM(m,g) 'amount of part/component m obtained from disassembling and re-manufacturing one unit of returned final product g'

	g1	g2
m1	3	3
m2	2	3
m3		1

;

Table FR(g,t) 'fraction of returned final product g satisfying the quality specifications in period t'

	1	2	3	4	5
g1	0.7	0.7	0.7	0.7	0.7
g2	0.8	0.8	0.8	0.8	0.8

+

	6	7	8	9	10
g1	0.7	0.7	0.7	0.7	0.7
g2	0.8	0.8	0.8	0.8	0.8

;

Parameter FC(o,c) 'fraction of capacity of center c allowed in selectable location site o'

/ pl1.a1 1

pl2.a1	1	
pl3.a1	1	
pl1.a2	0.8	
pl2.a2	0.8	
pl3.a2	0.8	
in1.b1	1	
in2.b1	1	
in1.b2	0.9	
in2.b2	0.9	/

;

Table UJ(j,a,g) 'unit capacity consumption factor of final product g processed at center a of plant site j in period t'

	g1	g2
pl1.a1	1	1.1
pl2.a1	1	1.1
pl3.a1	1	1.1
pl1.a2	1	1.2
pl2.a2	1	1.2
pl3.a2	1	1.2

;

Table UI(l,i,b,g) 'unit capacity consumption factor of final product g shipped from location site l to center b at intermediate site i in period t'

	g1	g2
pl1.in1.b1	1	1.1
pl1.in2.b1	1	1.1
pl2.in1.b1	1	1.1
pl2.in2.b1	1	1.1
pl3.in1.b1	1	1.1

```
pl3.in2.b1  1        1.1
cu1.in1.b2  1        1.1
cu1.in2.b2  1        1.1
cu2.in1.b2  1        1.1
cu2.in2.b2  1        1.1
cu3.in1.b2  1        1.1
cu3.in2.b2  1        1.1
;

Scalar IR 'interest rate for the time value of money' /0.05/;

*Time value of money
Parameter TVM(t) 'time value of money';

Parameter TT(t)

/ 1    1
  2    2
  3    3
  4    4
  5    5
  6    6
  7    7
  8    8
  9    9
  10   10   /
;

TVM(t)=(1+IR)**TT(t);
```

Decision_variables.gms

$ontext

The include file "Decision_variables.gms" contains decision variables of the formulation in the file "Proposed_Model.gms".

$offtext

```
**************************************************
*Decision variables*
**************************************************
```

Variables

*Non-negative integer

x(j,a,g,t)	'amount of final product g processed by center a at plant site j in period t'
y(l,lp,p,t)	'amount of product p shipped from location site l to location site lp in period t'
z(s,j,m,t)	'amount of part/component m purchased from external supplier s by plant site j in period t'
q(l,u,g,t)	'amount of returned final product g subcontracted from location site l by external subcontractor u in period t'
w(o,c,t)	'number of fixed sizes for expanding center c at selectable location site o in period t'
v (e,n,c,t)	'number of fixed sizes for relocating from existing location site e to new location site n for center c in period t'
exp(o,c,t)	'total amount of the capacity expanded for center c at selectable location site o in period t'
mov(o,op,c,t)	'total amount of the capacity relocated from selectable location site o to selectable location site op for center c in period t'

```
*Binary
varphi(o,t)     'if selectable location site o is operated in period t, 0 otherwise'
delta(o,c,t)    '1 if center c is operated at selectable location site o in period t,
                0 otherwise'
rho(e,c)        '1 if center c is expanded at existing location site e during the planning
                horizon, 0 otherwise'

*Costs
TOC_total(t) 'total cost in period t'
TOC1(t)         'variable purchasing, processing, subcontracting an transportation
                costs in period t'
TOC2(t)         'variable costs of capacity relocation and expansion in period t'
TOC3(t)         'fixed costs of operating facilities in period t'
TOC4(t)         'fixed costs of closing facilities in period t'
TOC5(t)         'fixed costs of opening facilities in period t'
TOC6(t)         'variable disposal costs in period t'

*Objective function
obj             'objective function'
;
```

Integer variables x, y, z, q, w, v, exp, mov;

Binary variables varphi, delta, rho;

```
x.up(j,a,g,t)=10000000000;
y.up(l,lp,p,t)=10000000000;
z.up(s,j,m,t)=10000000000;
q.up(l,u,g,t)=10000000000;
w.up(o,c,t)=100000000;
v.up(e,n,c,t)=100000000;
```

exp.up(o,c,t)=10000000000;

mov.up(o,op,c,t)=1000000000;

Results.gms

$ontext

The include file "Results.gms" contains additional results from the formulation in the file "Proposed_Model.gms" for an illustrative example in section 5.1.5.2 of this thesis.

$offtext

****

Results

****

Parameters

*Fixed costs

cfixe(e,t)	'fixed costs of closing existing location sites in period t'
cfixec(e,c,t)	'fixed costs of closing centers at existing location sites in period t'
cfixn(n,t)	'fixed costs of establishing new location sites in period t'
cfixnc(n,c,t)	'fixed costs of establishing centers at new location sites in period t'
cfixo(t)	'fixed costs of operating selectable facilities in period t'
cfixoc(c,t)	'fixed costs of operating centers at selectable facilities in period t'
cfix_total(t)	'total fixed costs in period t'

*Processing costs

cprocess_total(t)	'total processing costs in period t'

*Transportation costs

ctran_total(t)	'total transportation costs in period t'

```
*Capacity relocation and expansion costs
cexp(t)            'capacity expansion costs in period t'
crelo(t)           'capacity relocation costs in period t'
;

*Fixed costs

**Fixed costs of closing existing location sites in period t
cfixe(e,"1") = CC(e,"1")*(1-varphi.l(e,"1");
cfixe(e,t)$(ord(t) ne 1) = CC(e,t)*(varphi.l(e,t-1)-varphi.l(e,t));

**Fixed costs of closing centers at existing location sites in period t
cfixec(e,c,"1")=CFC(e,c,"1")*(1-delta.l(e,c,"1"));
cfixec(e,c,t)$(ord(t) ne 1)=CFC(e,c,t)*(delta.l(e,c,t-1)-delta.l(e,c,t));

**Fixed costs of establishing new location sites in period t
cfixn(n,t) = CO(n,t)*(varphi.l(n,t)-varhpi.l(n,t-1));

**Fixed costs of establishing centers at new location sites in period t
cfixnc(n,c,t)= CFO(n,c,t)*(delta.l(n,c,t)-delta.l(n,c,t-1));

**Fixed costs of operating selectable facilities in period t
cfixo(t) = sum(o, CF(o,t)*varphi.l(o,t));

**Fixed costs of operating centers at selectable facilities in period t
cfixoc(t)=sum((o,c), CFF(o,c,t)*delta.l(o,c,t));

**Total fixed costs in period t
cfix_total("1") = sum(o, CF(o,"1")*varphi.l(o,"1"))
+sum(e, CC(e,"1")*(1-varphi.l(e,"1")))
+sum(n, CO(n,"1")*(varphi.l(n,"1")))
+sum((o,c), CFF(o,c,"1")*delta.l(o,c,"1"))
+sum((e,c), CFC(e,c,"1")*(1-delta.l(e,c,"1")))
```

```
+sum((n,c), CFO(n,c,"1")*(delta.l(n,c,"1")));

cfix_total(t)$(ord(t) ne 1) = sum(o, CF(o,t)*varphi.l(o,t))
+sum(e, CC(e,t)*(varphi.l(e,t-1)-varphi.l(e,t)))
+sum(n, CO(n,t)*(varphi.l(n,t)-varphi.l(n,t-1)))
+sum((o,c), CFF(o,c,t)*delta.l(o,c,t))
+sum((e,c), CFC(e,c,t)*(delta.l(e,c,t-1)-delta.l(e,c,t)))
+sum((n,c), CFO(n,c,t)*(delta.l(n,c,t)-delta.l(n,c,t-1)));

*Processing costs

**Total processing costs in period t
cprocess_total(t)=sum((j,a,g), CP(j,a,g,t)*x.l(j,a,g,t))
+sum((s,j,m), CB(s,j,m,t)*z.l(s,j,m,t))
+sum((l,u,g), CS(l,u,g,t)*q.l(l,u,g,t))
+sum((j,a,g), CDP(j,a,g,t)*(1-FR(g,t))*x.l(j,a,g,t));

*Total transportation costs

**Total transportation costs in period t
ctran_total(t)=sum((l,lp,p), CT(l,lp,p,t)*y.l(l,lp,p,t));

*Capacity relocation and expansion costs

**Capacity expansion costs
cexp(t)=sum((o,c), CVE(o,c,t)*exp.l(o,c,t));

**Capacity relocation costs
crelo(t)=sum((e,n,c), CVR(e,n,c,t)*mov.l(e,n,c,t));

display cfixe, cfixec, cfixn, cfixnc, cfixo, cfixoc, cfix_total, cprocess_total, ctran_total,
cexp, crelo;
```

List of Figures

List of Tables

References

[1] E. Aghezzaf. Capacity planning and warehouse location in supply chains with uncertain demands. *Journal of Operation Research Society*, 56(4):453–462, 2005. 28, 31, 32, 34, 104, 105

[2] P. K. Ahluwalia and A. K. Nema. Multi-objective reverse logistics model for integrated computer waste management. *Waste Managment and Research*, 24(3):514–527, 2006. 65, 163, 164, 165

[3] C. H. Aikens. Facility location models for distribution planning. *European Journal of Operational Research*, 22:263–279, 1985. 17

[4] M. Albareda-Sambola, E. Fernández, Y. Hinojosa, and J. Puerto. The multi-period incremental service facility location problem. *Computers & Operation Research*, 36(5):71356–1375, 2009. 28, 31, 32, 34

[5] M. Alizadeh. *Facility Location in Supply Chain.* In R. Z. Farahani and M. Hekmatfar (eds.), *Facility Location: Concepts, Models, Algorithms and Case Studies, Contributions to Management Science, Chapter 20.* Physica Verlag Heidelberg, 2009. 15

[6] S. A. Alumur, S. Nickel, F. S. da Gama, and V. Verter. Multi-period reverse logistics network design. *European Journal of Operational Research*, 220(1):67–78, 2012. 28, 31, 32, 34, 65, 104, 105, 163, 164, 165

All references are followed by their citation page numbers

[7] D. Ambrosino and M. G. Scutellà. Distribution network design: New problems and related models. *European Journal of Operation Research*, 165(3):610–624, 2005. 28, 31, 32, 34

[8] S. H. Amin and G. Zhang. A proposed mathematical model for closed-loop network configuration based on product life cycle. *Int J Adv Manuf Technol*, 58(5-8):791–801, 2012. 65

[9] A. Antunes and D. Peeters. A dynamic optimization model for school network planning. *Socio-Economic Planning Sciences*, 34(2):101–120, 2000. 28, 31, 32, 34, 104, 105

[10] A. Antunes and D. Peeters. On solving complex multi-period location models using simulated annealing. *European Journal of Operational Research*, 130(1):190–201, 2001. 28, 31, 32, 34, 104, 105

[11] A. B. Arabani and R. Z. Farahani. Dynamic facility location: An overview of classifications, models, solutions and applications. *Under review*. 8, 9, 26, 90

[12] A. B. Arabani and R. Z. Farahani. Facility location dynamics: An overview of classifications and applications. *Computers & Industrial Engineering*, 62(1):408–420, 2012. 26

[13] N. Aras, D. Aksen, and A. G. Tanuğur. Locating collection centers for incentive-dependent returns under a pick-up policy with capacitated vehicles. *European Journal of Operational Research*, 191(3):1223–1240, 2008. 65

[14] T. Assavapokee and W. Wongthatsanekorn. Reverse production system infrastructure design for electronic products in the state of texas. *Computers & Industrial Engineering*, 62(1):129–140, 2012. 28, 31, 32, 34, 65

[15] M. L. Balinski. Integer programming: Methods, uses, computation. *Management Science*, 15(3):253–313, 1965. 103

[16] R. H. Ballou. Dynamic warehouse location analysis. *Journal of Marketing Research*, 5(3):271–276, 1968. 10

[17] A. I. Barros, R. Dekker, and V. Scholten. A two-level network for recycling sand: a case study. *European Journal of Operational Research*, 110(2):199–214, 1998. 65, 163, 164, 165

[18] B. M. Beamon and C. Fernandes. Supply-chain network configuration for product recovery. *Production Planning & Control*, 15(3):270–281, 2004. 65

[19] C. Canel and B. M. Khumawala. Multi-period international facilities location: An algorithm and application. *International Journal of Production Economics*, 35(7):1891–1910, 1997. 28, 31, 32, 34

[20] C. Canel, B. M. Khumawala, J. Law, and A. Loh. An algorithm for the capacitated, multi-commodity, multi-period facility location problem. *Computer & Operation Research*, 28(5):411–427, 2001. 20, 22, 28, 31, 32, 34

[21] C. Canel, B. M. Khumawala, J. Law, and A. Loh. International facilities location: A heuristic procedure for the dynamic uncapacitated problem. *International Journal of Production Research*, 39(17):3975–400, 2001. 28, 31, 32, 34

[22] A. R. Clarke, Q. Zhang, J. K. Gershenson, and J. W. Sutherland. Selection of remanufacturing facility locations to minimize cost and environment impact. In *Proceedings of 15th CIRP International Conference on Life Cycle Engineering*, pages 229–234, Sydney, Australia, March 2008. 40, 79

[23] R. Cruz-Rivera and J. Ertel. Reverse logistics network design for the collection of end-of-life vehicles in mexico. *Production, Manufacturing and Logistics*, 196(3):930–939, 2009. 65

[24] J. Current, M. Daskin, and D. Schilling. *Discrete Network Location Models*. In Z. Drezner and H. W. Hamacher (eds.), *Facility location applications and theory, Chapter 3*. Springer-Verlag, pages 81-108, 2001. 13, 16

[25] J. R. Current. The design of a hierarchical transportation network with transshipment facilities. *Transportation Science*, 22(4):270–277, 1988. 9

[26] F. Daneshzand and R. Shoeleh. *Multifacility Location Problem.* In R. Z. Farahani and M. Hekmatfar (eds.), *Facility Location: Concepts, Models, Algorithms and Case Studies, Constributions to Management Science, Chapter 4.* Springer-Verlag, pages 69-92, 2009. 25

[27] K. Das and A. H. Chowdhury. Designing a reverse logistics network for optimal collection, recovery and quality-based product-mix planning. *Int. J. Production Economics*, 135(1):209–221, 2012. 65

[28] L. Q. Dat, D. T. T. Linh, S. Chou, and V. F. Yu. Optimizing reverse logistic costs for recycling end-of-life electrical and electronic products. *Expert Systems with Applications*, 39(7):6380–6387, 2012. 65

[29] M. P. De Brito and R. Dekker. *A Framework for Reverse Logistics.* In R. Dekker and M. Fleischmann and K. Inderfurth and L. N. Van Wassenhove (eds.), *Reverse Logistics: Quantitative Models for Closed-Loop Supply Chains, Chapter 1, Part I.* Springer, Berlin, pages 3-27, 2004. 38

[30] N. O. Demirel and H. Gökçen. A mixed integer programming model for remanufacturing in reverse logistics environment. *Int Adv Manuf Technol*, 39:1197–1206, 2008. 44, 65, 163, 165, 166

[31] J. Dias, M. E. Captivo, and J. Clímaco. Capacitated dynamic location problems with opening, closure and reopening of facilities. *IMA Journal of Management Mathematics*, 17(4):317–348, 2006. 28, 31, 32, 34

[32] J. Dias, M. E. Captivo, and J. Clímaco. Efficient primal-dual heuristic for a dynamic location problem. *Computer & Operation Research*, 34(6):1800–1823, 2007. 28, 31, 32, 34

[33] J. Dias, M. E. Captivo, and J. Clímaco. A memetic algorithm for multi-objective

dynamic location problems. *Journal of Global Optimization*, 42(2):221–253, 2008. 28, 31, 32, 34

[34] Z. Drezner. Dynamic facility location: The progressive p-median problem. *Location Science*, 13(1):1–7, 1995. 28, 30, 31, 32, 34

[35] Z. Drezner and H. W. Hamacher. *Facility location applications and theory*. Springer Verlag Berlin, 2002. 9

[36] F. Du and G. W. Evans. A bi-objective reverse logistics network analysis for post-sale service. *Computer & Operation Research*, 35(8):2617–2634, 2008. 65, 163, 164, 165

[37] G. Easwaran and H. Üster. Tabu search and benders decomposition approaches for a capacitated closed-loop supply chain network design problem. *Transportation Science*, 43(3):301–320, 2009. 65

[38] G. Easwaran and H. Üster. A closed-loop supply chain network design problem with integrated forward and reverse channel decisions. *IIE Transactions*, 42(11):779–792, 2010. 65

[39] H. A. Eiselt and C.-L. Sandblom. *Decision Analysis, Location Models, and Scheduling Problems*. In H. A. Eiselt and V. Marianov (eds.), *Uncapacitated and Capacitated Facility Location Problems, Chapter 2*. Springer-Verlag, pages 169-208, 2004. 13, 16

[40] M. El-Sayed, N. Afia, and A. El-Kharbotly. A stochastic model for forward-reverse logistics network design under risk. *Computer & Industrial Engineering*, 58(3):423–431, 2010. 65

[41] M. Fleischmann, P. Beullens, J. M. Bloemhof-Ruwaard, and L. N. V. Wassenhove. The impact of product recovery on logistics network design. *Production and Operations Management*, 10(2):497–508, 2001. 65, 163, 165

[42] M. Fleischmann, H. R. Krikke, R. Dekker, and S. D. P. Flapper. A characterisation of logistics networks for product recovery. *Omega*, 28(6):653–666, 2000. 38, 39

[43] B. Flieschmann, S. Ferber, and P. Henrich. Strategic planning of BMWs global production network. *Interfaces*, 36(3):194–208, 2006. 28, 31, 32, 34, 104, 105

[44] C. O. Fong and V. Srinivasan. The multiregion dynamic capacity expansion problem, parts i and ii. *Operations Research*, 29(4):787–816, 1981. 104, 105

[45] C. O. Fong and V. Srinivasan. The multiregion dynamic capacity expansion problem, an improved heuristic. *Management Science*, 32(9):1140–1152, 1986. 104, 105

[46] M. C. Fonseca and A. García-Sánchez. A stochastic bi-objective location model for strategic reverse logistics. *TOP*, 18(1):158–184, 2010. 65

[47] P. Georgiadis, D. Vlachos, and G. Tagaras. The impact of product lifecycle on capacity planning of closed-loop supply chains with remanufacturing. *Production and Operation Management Society*, 15(4):514–527, 2006. 69

[48] K. R. Gue. A dynamic distribution model for combat logistics. *Computer & Operation Research*, 30(3):367–381, 2003. 28, 30, 31, 32, 34

[49] V. D. R. Guide and L. N. V. Wassenhove. The evolution of closed-loop supply chain research. *Operation Researchs*, 57(1):10–18, 2009. 3

[50] S. L. Hakimi. Optimum locations of switching centers and absolute centers and medians of a graph. *Operational Research*, 12(3):450–459, 1964. 13, 14

[51] S. L. Hakimi. Optimum locations of switching centers in a communications network and some related graph-theoretic problems. *Operational Research*, 13(3):462–475, 1965. 13, 14

[52] H. W. Hamacher and S. Nickel. Classification of location models. *Location Science*, 6(1-4):229–242, 1998. 9

[53] R. Hammami, Y. Frein, and A. B. H. Alouane. A strategic-tactical model for the supply chain design in the delocalization context: Mathematical formulation and a case study. *International Journal of Production Economics*, 122(1):351–365, 2009. 28, 31, 32, 34, 104, 105

[54] S. S. Heragu. *Facilities Design*. iUniverse, second edition, 2006. 12

[55] Y. Hinojosa, J. Kalcsics, S. Nickel, J. Puerto, and S. Velten. Dynamic supply chain design with inventory. *Computer & Operation Research*, 36(2):373–392, 2008. 28, 31, 32, 34

[56] Y. Hinojosa, J. Puerto, and F. R. Fernández. A multiperiod two-echelon multi-commodity capacitated plant location problem. *European Journal of Operational Research*, 123(2):271–291, 2000. 28, 31, 32, 34

[57] W. Ho, C. K. M. Lee, and G. T. S. Ho. Optimization of the facility location-allocation problem in a customer-driven supply chain. *Oper Manag Res*, 1(1):69–79, 2008. 1

[58] J. N. Hooker, R. S. Garfinkel, and C. K. Chen. Finite dominating sets for network location problems. *Operation Researchs*, 39(1):100–118, 1991. 14

[59] A. Hugo and E. N. Pistikopoulos. Environmentally conscious long-range planning and design of supply chain networks. *Journal of Operation Research Society*, 13(15):1471–1491, 2005. 28, 31, 32, 34, 104, 105

[60] S. K. Jacobsen. *Discrete Location Theory*. Series in Discrete Mathematics and Optimization, In P. B. Mirchandani and R. L. Francis (eds.), *Multiperiod Capacitated Location Models, Chapter 4*. Wiley-Interscience, pages 173-207, 1990. 19

[61] V. Jayaraman, V. G. Jr, and R. Srivastava. A closed-loop logistics model for remanufacturing. *The Journal of Operational Research Society*, 50(5):497–508, 1999. 65, 163, 165

[62] V. Jayaraman, R. A. Patterson, and E. Rolland. The design of reverse distribution networks: models and solution procedures. *European Journal of Operational Research*, 150(1):128–149, 2003. 65, 163, 164, 165

[63] A. A. Kamil, A. Mustafa, and K. Ibrahim. Stochastic optimization for portfolio selection problem with mean absolute negative deviation measure. *Journal of Mathematics and Statistics*, 5(4):379–386,, 2009. 25

[64] S. S. Kara and S. Onut. A stochastic optimization approach for paper recycling reverse logistics network design under uncertainty. *Int. J. Environ. Sci. Tech.*, 7(4):717–730, 2010. 65

[65] A. Klose and A. Drexel. Facility location models for distribution system design. *European Journal of Operational Research*, 162(1):4–29, 2004. 10, 16

[66] H. J. Ko and G. W. Evans. A genetic algorithm-based heuristic for the dynamic integrated forward/reverse logistics network for 3PLs. *Computer & Operation Research*, 34(2):346–366, 2007. 28, 31, 32, 34, 65, 104, 105, 163, 165, 167

[67] H. Krikke. Impact of closed-loop network configurations on carbon footprints: A case study in copier. *Resources, Conservation and Recycling*, 55(12):1196–1205, 2011. 65

[68] H. Krikke, J. Bloemhof-Ruwaard, and L. N. V. Wassenhove. Concurrent product and closed-loop supply chain design with an application to refrigerators. *Production and Operations Management*, 41(16):3689–3719, 2003. 65, 160, 163, 165, 166

[69] H. R. Krikke, C. P. Pappis, G. T. Tsoulfas, and J. Bloemhof-Ruwaard. Design principles for closed loop supply chains: Optimizing economic, logistic and environmental performance. *ERIM Report Series Research in Management*, 62, 2001. 2

[70] A. Kumar and P. Malegeant. Strategic alliance in a closed-loop supply chain,

a case of manufacturer and eco-non-profit organization. *Technovation*, 26:1127–1135, 2006. 39

[71] D. Lee and M. Dong. Dynamic network design for reverse logistics operations under uncertainty. *transportation Research Part E*, 45(1):61–71, 2009. 2, 28, 31, 32, 34, 65, 66, 104, 163, 165, 166

[72] S. B. Lee and H. Luss. Multifacility-type capacity expansion planning: Algorithms and complexities. *Operations Research*, 35(2):249–253, 1987. 104, 105

[73] K. Lieckens and N. Vandaele. Reverse logistics network design with stochastic lead times. *Computers & Operations Research*, 34(2):395–416, 2007. 65

[74] O. Listeş. A generic stochastic model for supply-and-return network design. *Computer & Operation Research*, 34(2):417–442, 2007. 65

[75] O. Listeş and R. Dekker. A stochastic approach to a case study for product recovery network design. *European Journal of Operational Research*, 160(1):268–287, 2005. 65

[76] Z. Lu and N. Bostel. A facility location model for logistics systems including reverse flows: The case of remanufacturing activities. *Computer & Operation Research*, 34(2):299–323, 2007. 65, 103, 104, 162, 163, 165, 166

[77] B. A. MacCarl, A. Meeraus, P. van der Eiik, M. Bussieck, S. Dirkse, P. Steacy, and F. Nelissen. *McCarl GAMS User Guide*. GAMS Development Corporation, 2002. `http://www.gams.com/dd/docs/bigdocs/gams2002/mccarlgamsuserguide.pdf`. 159, 182

[78] S. Mansour and M. Zarei. A multi-period reverse logistics optimization model for end-of-life vehicles recovery based on EU directive. *International Journal of Integrated Manufacturing*, 21(7):764–777, 2008. 28, 31, 32, 34, 65, 163, 164, 165

[79] R. Manzini and E. Gebennini. Optimizaiton models for the dynamic facility location and allocation problem. *International Journal of Production Research*, 46(8):2061–2086, 2008. 28, 31, 32, 34

[80] A. Marín and B. Pelegrín. The return plant location problem: Modelling and resolution. *European Journal of Operational Research*, 104(2):375–392, 1998. 65, 163, 165, 166

[81] E. Melachrinoudis, A. Messac, and H. Min. Consolidating a warehouse network: A physical programming approach. *International Journal of Production Economics*, 97(1):1–17, 2005. 104, 105

[82] E. Melachrinoudis and H. Min. The dynamic relocation and phase-out of a hybrid, two-echelon plant/warehousing facility: A multiple objective approach. *European Journal of Operational Research*, 123(2):1–5, 2000. 28, 31, 32, 34, 104, 105

[83] E. Melachrinousdis, H. Min, and X. Wu. A multiobjective model for the dynamic location of landfills. *Location Science*, 3(3):143–166, 1995. 65, 66, 163, 164, 165

[84] M. T. Melo, S. Nickel, and F. S. da Gama. Dynamic multi-commodity capacitated facility location: a mathematical modeling framework for strategic supply chain planning. *Computer & Operation Research*, 33(1):181–208, 2006. 22, 29, 31, 32, 34, 44, 72, 90, 93, 104, 105

[85] M. T. Melo, S. Nickel, and F. S. da Gama. Facility location and supply chain management - A review. *European Journal of operation Research*, 196(2):401–412, 2008. 26

[86] M. T. Melo, S. Nickel, and F. S. da Gama. An efficient heuristic approach for a multi-period logistics network redesign problem. *TOP*, pages 1–29, 2012. 29, 31, 32, 34, 104, 105

[87] M. T. Melo, S. Nickel, and F. S. da Gama. A tabu search heuristic for redesigning a multi-echelon supply chain network over a planning horizon. *International Journal of Production Economics*, 136(1):218–230, 2012. 29, 31, 32, 34, 104, 105

[88] H. Min, C. Ko, and H. J. Ko. The spatial and temporal consolidation of returned products in a closed-loop supply chain network. *Computer & Industrial Engineering*, 51(2):309–320, 2006. 29, 31, 32, 34

[89] H. Min, C. S. Ko, and H. J. Ko. The spatial and temporal consolidation of returned products in a closed-loop supply chain network. *Computers & Industrial Engineering*, 51(2):309–320, 2006. 65, 66

[90] H. Min and H. Ko. The dynamic design of a reverse logistics network from the perspective of third-party logistics service providers. *International Journal of Production Economics*, 113(1):176–192, 2008. 29, 31, 32, 34, 65, 104, 105

[91] H. Min, H. J. Ko, and C. S. Ko. A genetic algorithm approach to developing the multi-echelon reverse logistics network for product returns. *Omega*, 34(1):56–69, 2006. 65

[92] H. Min and E. Melachrinoudis. The relocation of a hybrid manufacturing/distribution facility from supply chain perspectives: a case study. *Omega, Int. J. Mgmt. Sci.*, 27(1):75–85, 1999. 7

[93] N. Mladenović, M. Labbé, and P. Hannsen. Solving the p-center problem with tabu search and variable neighborhood search. *Network*, 42(1):48–64, 2003. 13

[94] A. Mutha and S. Pokharel. Strategic network design for reverse logistics and remanufacturing using new and old product modules. *Computer and Industrial Engineering*, 56(1):334–346, 2009. 65, 163, 164, 165

[95] P. K. Naraharisetti, I. A. Karimi, and R. Srinivasan. Supply chain redesign through optimal asset management and capital budgeting. *Computers and Chemical Engineering*, 32(12):3153–3169, 2008. 29, 30, 31, 32, 34, 104, 105

[96] P. K. Naraharisetti, I. A. Karimi, and R. Srinivasan. Supply chain redesign and new process introduction in multipurpose plants. *Chemical Engineering Science*, 65(8):2596–2607, 2010. 29, 30, 31, 32, 34, 104, 105

[97] S. H. Owen and M. S.Daskin. Strategic facility location: A review. *European Journal of Operational Research*, 111(3):423–447, 1998. 9, 25

[98] R. K. Pati, P. Vrat, and P. Kumar. A goal programming model for paper recycling system. *Omega*, 36(3):405–417, 2008. 65, 66

[99] M. S. Pishvaee, M. Rabbani, and S. A. Torabi. A robust optimization approach to closed-loop supply chain network design under uncertainty. *Applied Mathematical Modelling*, 35(2):637–649, 2011. 65

[100] F. Plastria. *Facility Location, A Survey of Applications and Methods.* In Z. Drezner (ed.), *Continuous location problems.* Sprinker-Verlag Newyork, 1995. 10

[101] J. Reese. Methods for solving the p-median problem: An annotated bibliography. *Mathematics Faculty Research,* Paper 28, 2005. 13

[102] C. Ren and J. Ye. Improved particle swarm optimization algorithm for reverse logistics network design. *Energy Procedia*, 13(3):4591–4600, 2011. 65

[103] G. M. Roodman and L. B. Schwarz. Optimal and heuristic facility phase-out strategies. *AIIE Transactions*, 7(2):177–184, 1975. 17

[104] R. E. Rosenthal. *GAMS—A User Guide.* GAMS Development Corporation, 2010. `http://www.gams.com/dd/docs/bigdocs/GAMSUsersGuide.pdf`. 182

[105] T. J. V. Roy and D. Erlenkitter. A dual-based procedure for dynamic facility location. *Management Science*, 28(10):1091–1105, 1982. 17

[106] E. H. Sabri and B. M. Beamon. A multi-objective approach to simultaneous strategic and operational planning in supply chain design. *Omega*, 28(5):581–598, 2000. 26

[107] K. Sahyouni, R. C. Savaskan, and M. S. Daskin. A facility location model for bidirectional flows. *Transportation Science*, 41(4):484–499, 2007. 65, 68, 69, 72, 103, 104, 163, 165, 166

[108] M. I. G. Salema, A. P. Barbosa-Povoa, and A. Q. Novais. An optimization model for the design of a capacitated multi-product reverse logistics network with uncertainty. *European Journal of Operational Research*, 179(3):1063–1077, 2007. 65

[109] M. I. G. Salema, A. P. Barbosa-Povoa, and A. Q. Novais. A strategic and tactical model for closed-loop supply chains. *OR Spectrum*, 31(3):573–599, 2009. 29, 31, 32, 34, 65, 161, 163, 165, 166

[110] M. I. G. Salema, A. P. Barbosa-Povoa, and A. Q. Novais. Simultaneous design and planning of supply chains with reverse flows: A generic modelling framework. *European Journal of Operational Research*, 203(2):336–349, 2010. 29, 31, 32, 34, 65

[111] P. Sasikumar, G. Kannan, and A. N. Haq. A multi-echelon reverse logistics network design for product recovery-a case of truck tire remanufacturing. *Int J Adv Manuf Technol*, 49(9-12):1223–1234, 2010. 65

[112] R. C. Savaskan, S. Bhattacharya, and L. van Wassenhove. Closed-loop supply chain models with product remanufacturing. *Managment Science*, 50(2):239–252, 2004. 65, 66

[113] F. Schultmann, B. Engels, and O. Rentz. Closed-loop supply chains for spent batteries. *Interfaces*, 33(6):57–71, 2003. 65, 104, 105, 160

[114] A. J. Scott. Dynamic location-allocation systems: Some basic planning strategies. *Environment and Planning*, 3(1):73–82, 1971. 17

[115] L. V. Snyder. *Supply chain robustness and reliability: models and algorithms*. Ph. D. Dissertation, Department of Industrial Engineering and Management Sciences, Northwestern University, 2003. 25

[116] J. T. Soto. *Dynamic and robust capacitated facility location in time varying demand environments*. Ph. D. Dissertation, Department of Industrial and System Engineering, Texas A&M University, 2009. 7

[117] T. Spengler, H. Puechert, T. Penkuhn, and O. Rentz. Environmental integrated production and recycling management. *European Journal of Operational Research*, 97(2):308–326, 1997. 65, 163, 164, 165

[118] S. K. Srivastava. Network design for reverse logistics. *Omega*, 36(4):535–548, 2008. 29, 31, 32, 34, 65, 104, 105

[119] D. R. Sule. *Logistics of facility location and allocation*. Industrial Engineering: A Series of Reference Books and Textbooks. Marcel Dekker, Inc., 2001. 8, 13

[120] P. N. Thanh, N. Bostel, and O. Péton. A dynamic model for facility location in the design of complex supply chains. *International Journal of Production Economics*, 113(2):678–693, 2008. 29, 31, 32, 34, 104, 105

[121] J. E. Torres-Soto and H. Üster. Dynamic-demand capacitated facility location problems with and without relocation. *European Journal of Production Research*, 49(13):3979–4005, 2011. 29, 31, 32, 34

[122] J. J. Troncoso and R. A. Garrido. Forestry production and logistics planning: an analysis using mixed-integer programming. *Journal of Operation Research Society*, 7(4):525–633, 2005. 29, 31, 32, 34, 104, 105

[123] N. L. Ulstein, M. Christiansen, and R. Grønhaug. Elkem uses optimization in redesigning its supply chain. *Interfaces*, 536(4):314–325, 2006. 29, 31, 32, 34, 104, 105

[124] H. Üster, G. Easwaran, E. Akcali, and S. Cetinkaya. Benders decomposition with alternative multiple cuts for a multi-product closed-loop supply chain network design model. *Naval Research Logistics*, 54, 2007. 2, 163, 165, 166

[125] H. Üster, G. Easwaran, E. Akçali, and S. Çetinkaya. Benders decomposition with alternative multiple cuts for a multi-product closed-loop supply chain network design model. *Computer & Operation Research*, 54(8):890–907, 2007. 65, 162

[126] B. Vahdani, J. Razmi, and R. Tavakkoli-Moghaddam. Fuzzy possibilistic modeling for closed loop recycling collection networks. *Environ Model Assess*, pages 1–15, 2012. 65

[127] V. Verter. *Foundations of Location Analysis.* International Series in Operations Research & Management. In H. A. Eiselt and V. Marianov (eds.), *Uncapacitated and Capacitated Facility Location Problems, Chapter 2*. Springer, 155:25-37, first edition, 2011. 15

[128] D. Vila, A. Martel, and R. Beauregard. Designing logistics networks in divergent process industries: A methodology and its application to the lumber industry. *International Journal of Production Economics*, 102(2):358–378, 2006. 104, 105

[129] J. K. Visich, S. Li, and B. M. Khumawala. Enhancing product recovery value in closed-loop supply chains with RFID. *Journal of Managerial Issues*, 19(3):436–452, 2007. 38, 39

[130] H.-F. Wang and H.-W. Hsu. A closed-loop logistic model with a spanning-tree based genetic algorithm. *Computer & Operation Research*, 37(2):376–389, 2010. 65, 163, 165, 167

[131] A. Warszawski. Multi-dimensional location problems. *Operational Research Quarterly*, 24(2):165–179, 1973. 16

[132] A. Weber. *Über den Standort der Industrien.* 1. Teil: Reine Theorie des Standorts. Verlag J.C.B. Mohr, Tübingen, 1909. 10

[133] G. O. Wesolowsky. Dynamic facility location. *Manage Science*, 19(11):1241–1248, 1973. 2, 10, 11

[134] O. G. Wesolowsky and W. G. Truscott. The multiperiod location-allocation problem with relocation of facilities. *Management Science*, 22(1):57–65, 1975. 14

[135] M. H. F. Zarandi, A. H. Sisakht, and S. Davari. Design of a closed-loop supply chain (clsc) model using an interactive fuzzy goal programming. *Int J Adv Manuf Technol*, 56(5):809–821, 2011. 65

[136] G. Zhou, Z. Cao, J. Cao, and Z. Meng. A genetic algorithm approach on reverse logistics optimization for product return distribution network. *Lecture Notes in Computer Science*, 3801/2005:267–272, 2005. 65