공학석사학위논문

The Physical Internet: Estimation and Allocation of Cost Savings from Collaborations

피지컬 인터넷: 협업으로 얻는 비용 절감 추정과 배분

2021 년 08 월

서울대학교 대학원
산업공학과

김 민 지

The Physical Internet: Estimation and Allocation of Cost Savings from Collaborations

피지컬 인터넷: 협업으로 얻는 비용 절감 추정과 배분

지도교수 문 일 경

이 논문을 공학석사 학위논문으로 제출함

2021 년 06 월

서울대학교 대학원

산업공학과

김 민 지

김민지의 공학석사 학위논문을 인준함

2021 년 06 월

위 원 장 이 경 식

부위원장 문 일 경

위 원 박 건 수

Abstract

The Physical Internet: Estimation and Allocation of Cost Savings from Collaborations

Min Ji Kim

Department of Industrial Engineering

The Graduate School

Seoul National University

The physical internet (PI) is a state-of-the-art open global supply chain network that is gaining attention from both participants and researchers of supply chains. The PI uses standardized containers to dispatch shipments through an interconnected network within a supply chain, where information, storage facilities, and transportation methods are shared participants of the physical internet. The network aims to save costs, handle volatile demand and information, and be socially and environmentally responsible. Up until now, however, almost all studies concerning the PI have focused primarily on its conceptual development and the advantages of putting it into practical, widespread use. Studies that consider realistic constraints of its use, such as empty runs of transportation, limited capacity of resources, or an equitable allocation of the cost savings obtained from its implementation are limited. While in general the PI can offer greater efficiency and sustainability compared to the traditional supply chain network, in certain situations some users of it experience loss through its use because of the inherent setup it presents of sharing capacitated resources. Therefore, compensating companies that experience loss when joining a PI is essential in building a solid network. In this thesis, in order to address the minimization of a total cost problem in the production-inventory-distribution decision of a PI, we first propose a mixed-integer linear programming (MILP) model formulation that takes into account capacitated factory and warehouse capacity, the penalty sustained by empty runs of transportation, and the maximum delivery distance of freight runs. Next, we use the model to compare the costs incurred by individual players when they do not participate in the PI and the costs of collaboration in the PI in which players do participate. After comparing the costs saved by participating in the PI, we then allocated the cost savings among independent supply chains, allotting them through three different allocation methods, including the Shapley value method, which is a cooperative game theory solution method.

Keywords: Physical Internet, Collaboration, Cost savings allocation, Cooperative game theory, Shapley value
Student Number: 2019-29485

Contents

List of Tables

List of Figures

Chapter 1

Introduction

The current way that physical objects are supplied, stored, and moved through the supply chain system is not sustainable on many levels [1]. To give a few examples, when loaded cargo trucks depart from their destinations, official statistics report that in South Korea, approximately only 80 percent of them are fully loaded, and only 60 percent of them are fully loaded in the United States. Additionally, trucks moving without any freight, a phenomenon usually referred to as "empty running," account for 40 percent of total cargo truck transport in South Korea and 20 percent of total cargo truck transport in the United States [1, 2]. Moreover, in South Korea, 18.4 percent of truckers are reported to have been involved in traffic accidents, and their rate of occupational accidents is three times higher than the average rate of total occupational accidents for workers in other industries in South Korea [3]. Conventional logistics systems, such as the hub-and-spoke system and centralization, allow freight to move to one or a few large distribution centers covering a wide range of areas before reaching a final destination, which inevitably increases unnecessary freight transportation over long distances [4]. Even if packages are to travel within close proximity, they must first be transported to a hub before reaching their destination. Widespread change in customer purchasing behavior also is a factor that has made the conventional supply chain system unsustainable. A recent increase in e-commerce has helped customers buy products at any time of day or night, making order intervals irregular and hard to predict. Furthermore, orders are generally made in small amounts rather than in bulk, resulting in multiple delivery points. Customers can find substitutes for their desired products easily through the internet, making factors besides price and quality, such as speed of delivery, an essential aspect that companies must now consider in order to attract customers [5]. Irregular and unpredictable orders, multiple delivery points, and tight delivery schedules also have increased last-mile delivery costs. To reduce last-mile delivery costs, which account from between 13 percent to 75 percent of the total supply chain costs [6], warehouses near delivery points are preferred over warehouses at distant locations. However, investing in a large number of warehouses in urban or suburban areas is costly and inefficient from a business perspective. Usually, obtaining storage facilities near high-demand density areas is costly, while obtaining storage facilities near low-demand density areas decreases return on investment (ROI). Using low fill-rate freight transportation and having excessive warehouses is not sustainable economically or environmentally. A new form of a supply chain logistics system, the physical internet, has appeared as a solution for a more sustainable supply chain network.

The physical internet (PI) is an emerging paradigm for a sustainable supply chain network. The concept of this contemporary network was inspired by the digital internet. The physical internet applies the open sharing characteristic of the digital internet to the physical domain, thus the term “physical internet.” While traditionally one or a few numbers of firms used resources such as transportation or warehouses independently, with the physical internet, all the participants can freely use the existing resources, regardless of who owns them. In other words, by freely sharing existing resources with all participants, the physical internet builds a dense supply chain that can drive its full efficiency.

In the PI, participants use modularized and standard containers to dispatch freight to shared consolidation and storage facilities, referred to as π-hubs in the PI system, by using shared transportation methods. As a result of being shipped in modularized standard containers, referred to as π-containers, freight can easily be interlocked with each other or broken down for better handling while in transit. The use of π-containers helps save time and costs in the supply chain because the containers are designed to be handled easily. Sharing resources among participants helps the physical internet utilize its resources to maximum potential. Through the PI, participants gain cost savings, achieve efficient supply chain logistics, and reduce CO_2 emissions. The PI enables sustainability by achieving an open logistics system in storage, transportation, and business productivity.

Numerous scholars and supply chain industry participants have studied this paradigm-breaking concept. However, existing studies primarily have focused on developing a framework for the PI or advantages of its use. Studies about allocating cost savings among participants of the PI are limited.

Independent companies considering joining the PI will not be interested in how many expenses the integrated supply chain can save. They will be interested instead in how costs can be reduced if they join a PI network. If no rules are set prior to collaborating in a PI, a participant must pay the usage costs of resources, regardless of who uses those resources. Because resources are limited by nature, sharing limited resources can result in a collaboration failure if independent parties act upon their benefits regardless of the other players’ losses. It will always be cheaper for a company to use others’ resources instead of their own, even though it is more expensive within an overall framework to do so. Therefore, to encourage companies to participate in the PI system, it is important to first estimate the total cost savings that collaboration in the PI might achieve, and then to allocate the saved costs among participants in a fair and credible way.

Constraints such as warehouse capacity, maximum delivery distance, and empty running of trucks should be considered when estimating the cost of collaboration in a PI. Warehouse capacity can be an essential factor because some warehouses are preferred over others. In general, warehouses near cities with high-demand density will likely suffer from a lack of storage capacity, while warehouses near rural areas where customer demands are low will not be able to fully utilize their storage facilities. As a result, supply chain participants with warehouses near high-demand areas have a low incentive to join the PI.

Moreover, the maximum delivery distance of freight and the empty running of trucks should not be neglected factors when estimating the cost of the PI. These two factors are important when considering sustainability of the network, and increasing the sustainability of the supply chain is the core reason why the physical internet has been developed. Setting a maximum delivery distance of freight transportation ensures that truckers have better utility. Numerous traffic accidents involving truckers are caused by long-distance driving and fatigue. By setting a maximum delivery distance, not only is the sustainability of a supply chain improved, but also preventable expenses can be reduced, such as insurance costs.

In addition, the empty running of trucks has become a big issue in the modern supply chain network and represents a logistics system’s inefficiency. The PI can reduce empty running by consolidating shipments through sharing warehouses and transportation methods. However, empty truck penalty costs are often omitted in PI papers that deal with quantitative optimization modeling.

In addition to the need for a comprehensive consideration of several key characteristics of the PI, a thorough cost calculation of the whole process of the supply chain is needed. A supply chain consists of various factors, and only optimizing one function without regard to others will not necessarily achieve optimal total cost savings of a supply chain. Coordinating production planning, inventory management, and transportation schedules can yield a higher efficiency rate. Various studies have dealt with production-inventory-distribution problems in light of achieving full efficiency. However, such a comprehensive combination has not yet been fully studied alongside the PI.

After estimating the cost savings of the PI with various factors, as mentioned above, the allocation of cost savings should be considered. A rational decision-maker will take into account whether the marginal benefit of an action is greater than the marginal cost. Therefore, when joining a PI system is even slightly more beneficial than sticking with the previous supply chain, a rational decision-maker will join the PI. At the same time, companies try to make as much profit as possible. Thus, when allocating cost savings, each company tries its best to gain as much as possible.

There are many solution methods to allocating cost savings. The most common method followed in real life is to undertake a negotiation. However, as more participants join the PI, this method becomes time-consuming and costly. Setting simple rules, such as having each participant pay for his or her own resources, or having participants share cost savings proportional to the number of resources used, is also a factor to consider. However, in this problem, the cost savings achieved by joining the PI system can be due to numerous factors, such as sharing transportation capacity, designing better delivery routes, lowering last-mile costs, and allowing for a more flexible production schedule. One change in a part of a supply chain creates a chain reaction throughout the entire supply chain. Simply sharing cost savings proportional to the inventory or the freight amount does not always result in a fair distribution of the benefit obtained by the consolidation of shipments because of the chain effect of the network [7]. A better alternative to allocating cost savings is needed, and cooperative game theory with transferable utilities is generally applied to solve this type of problem.

In this thesis, we will concentrate on the aspects already summarized. First, we will propose a mixed-integer linear programming (MILP) model formulation that captures capacitated factory and warehouse throughput and an empty running penalty of transportation. This will address the minimization of the total cost problem in the production-inventory-distribution decision in the PI. Next, we will examine the cost savings of individual players when they do not participate in the PI and the cost savings of players within the PI setting. After comparing the costs saved by agents who participate in the PI, we will then allocate the cost savings among independent supply chains, allotting them through three different allocation methods, including the Shapley value method, one of the most prominent methods of solution application in cooperative game theory.

The remainder of this thesis is organized as follows. In Chapter 2, a literature review of concepts will be presented and the difference between the PI and the conventional supply chain will be summarized. In Chapter 3, an optimization model developed for the PI while considering constraints such as capacity constraints, empty running, warehouse shutdowns, and maximum delivery distance will be proposed through the MILP model. In Chapter 4, estimation of the cost savings in the PI will be analyzed through numerical examples. In Chapter 5, we will discuss methods to allocate cost savings using the estimated cost arrived at in Chapter 4. This chapter will also show the shortcomings of not having a rule in place beforehand and in allocating the cost savings proportional to customers' demands. Additionally, Chapter 5 introduces the Shapley value. To finish the thesis, we offer concluding remarks in Chapter 6.

Chapter 2

Literature Review

This thesis explores themes closely related to the physical internet and the cost savings allocation problem.

2.1. The Physical Internet

The term "physical internet" was first mentioned in an article in The Economist [8]. However, it wasn't until Montreuil [1] presented and described the phrase "physical internet" that the paradigm-breaking concept gained wide attention from supply chain participants and scholars. The paper described the global challenges of a conventional supply chain within the framework of environmental, economic, and social sustainability. Using the metaphor of the digital internet and its transmission of data, the paper proposed a detailed conceptual framework of the PI and its potential for gaining environmental, economic, and social sustainability.

As mentioned earlier, π-containers and π-hubs are two of the main factors in the physical internet. Concept designs and explorations of π-containers and π-hubs have been studied to build a solid base for the framework. Scholars [9-11] have studied effective ways to standardize π-containers. These studies have focused on sizing the π-container, as well as on its design, its loading and unloading processes, and its composition and subsequent breakdown. Concept design for π-hubs was studied by Meller et al. [12]. The paper presented components of facilities' designs and their functional designs. Ballot et al. [13] researched open hub network design for the PI. The study used a bio-inspired evolutionary algorithm to design an open hub PI system. The paper showed efficiency of this system by applying it to the large-scale case of food distribution in France.

Promising effects of applying the PI system have been conducted as well by comparing the network to other existing networks. Sohrabi et al. [14] compared private supply networks, shared supply webs, and open supply webs using simple optimization-based assessments to examine potential gains from implementing the PI-enabled open supply web. Fazili et al. [15] compared the PI to the conventional system and the hybrid logistics system in the routing optimism framework by using the eastern Canada road network. The paper evaluated driving time, the number of loading and unloading instances, and cost performance.

Over time, research criteria have become more detailed, focusing on specific contexts relevant to the PI system. Pan et al. [16] studied the PI's effects from an inventory management perspective. The paper concluded that the PI system reduces the inventory level while maintaining the service level simultaneously by using a simulation approach. Yao [17] applied the PI system to online shopping, and Kong et al. [18] proposed a timely operational scheduling solution for perishable goods in auction logistics centers. Crainic et al. and Mohamed et al. [19, 20] applied the concept of PI hubs to city logistics and presented a framework for designing an effective, sustainable system. Venkatadri et al. [21] analyzed characteristics of the PI logistics network and used it to propose a P2P optimal dispatch MILP that captures the characteristics of the PI. Caballini et al. [22] defined and modeled the network of road transportation to minimize total transportation costs, utilize truck capacity to its fullest extent, and minimize empty return trips. Ji et al. [23] proposed a MILP formulation that combines production, inventory, and distribution problems in the PI. By conducting extensive computational experiments, the researchers showed that small-scale enterprises could significantly benefit from using the PI system.

Many existing studies of conventional supply chains have similar features to studies of the PI. Yang et al. [24] compared the following five related research categories to the PI: lateral trans-shipment, multiple source supplier options, inventory routing problems combining vehicle routing and inventory control problems, integrated location-inventory models, and vendor-managed inventory. The paper identifies the difference between the PI and lateral trans-shipment in that the network in the PI is fully connected among various users and the source of replenishment is dynamically selected. For multi-sourcing options, unlike with the PI, storage points on the same echelon of the supply chain are independent, and products do not move freely between these storage points. The difference between inventory routing problems and the PI is that the PI uses modularized and standard π-containers while sharing available transportation. And unlike with inventory routing problems, the PI addresses stock rebalancing among different companies. Additionally, location-inventory models assume location decisions are made at the beginning of the planning horizon and barely consider horizontal collaborations among different companies. In contrast, the PI can change the facility it uses dynamically during the time horizon, and collaboration among different networks is the main component of the PI. Lastly, the PI-enabled vendor-managed inventory models differ from the classic vendor-managed inventory models in that vendors can use storage capacity dynamically and rebalance stock among distribution centers freely, if needed.

The PI has a similar characteristic with the dynamic supply chain design in that it considers collaboration among different companies by sharing resources and information. In a dynamic supply chain, a company no longer operates a static supply chain. It either utilizes existing capabilities to their fullest extent by opening and closing warehouses or it collaborates with other companies and shares their resources. The difference, however, is that studies concerning dynamic supply chain design barely consider horizontal trans-shipment among the same supply chain echelon.

2.2. Cost Savings Allocation Problem

The PI is formed according to different companies' efforts to collaborate, and an essential aspect of collaboration among agents with different interests depends on deciding how to allocate the cost savings that have been obtained from such an alliance. Recently, an increasing number of papers concerning the cost allocation problem have been published, and they are well organized by a review paper on the cost allocation problem [25, 26].

Allocating cost savings is complex, especially when collaborating with different agents through the entire supply chain. Simply allocating costs proportional to a certain resource that participants use may be an easy way to solve this problem. However, such allocation is neither fair nor satisfactory, because it does not capture a given company's total contribution to the overall alliance [25]. Because of this, cooperative game theories are used to provide a theoretically grounded solution method to allocate cost savings.

Game theory is a field of mathematical models used to study the strategic interaction among independent decision-makers [27]. And cooperative games are what result when the decision-makers of the game make externally enforced binding commitments to follow the rules and find it beneficial to cooperate with others [28]. Therefore, in cooperative games, the joint actions of groups are analyzed and the main goal is to fairly distribute the outcome to each player according to their contribution [29]. This concept is the crux of our thesis.

Many solution concepts are used in cooperative game theory, and in this thesis, we make use of the Shapley value. The Shapley value is one of the most commonly used cooperative game solution methods, which has properties that can be applied successfully in transferable utility games [30] and that can make the cost allocation fair for players in various situations [31]. The properties are Null player property (i.e., when a player does not contribute to the coalition, their rewards are zero), Symmetry property (i.e., symmetric players make the same contribution to any coalition, and therefore obtain the same amount of rewards), and Additivity property (i.e., if a coalition can be divided into two different parts, what a player can obtain in a combined coalition is equal to the sum of what the player can obtain through two different parts of the coalition: $\psi_i(v+w) = \psi_i(v) +\psi_i(w)$) [32].

The Shapley value has been applied to many different collaborations by previous researchers. In infrastructure cost games, setting an aircraft landing fee in a shared airport has been evaluated [33]. Railway access tariff allocation has been estimated [34], and application of the Shapley value for revenue distribution between internet service providers has been studied [35]. These are just a few of the studies on this topic.

Chapter 3

Model Formulation

In this chapter, a mixed-integer linear program is presented to calculate the total cost of the production-inventory-distribution problem in the PI. This calculation of the total cost of the network is essential for cost savings allocation that will later be presented, because no matter how fair an allocation method is, it is no use if we estimate the cost savings incorrectly. There are several studies that calculate the cost of operating a physical internet. The differences between our model and previous models are presented in Table 3.1. The main agent of the model is the supply chain itself. We deal with a production-inventory-distribution problem and assume that a firm will handle all the processes in the supply chain, such as the production of an item, its wholesale, and its retail. Therefore, in estimating the cost when companies operate independently using our suggested model, we've set the main agent as the firm that handles the supply chain. Similarly, when estimating the cost of the physical internet using our suggested model, we've set the main agent as the collaborative supply chain that handles every process, from production to retailing. By setting the main agent as a collaborative supply chain, we can more easily find a global optimum. This method is quite common in papers on the physical internet and in studies on other types of supply chain coordination, such as in studies of revenue sharing and buyback contracts.

In our model, we will consider maximum delivery distance and empty running return costs, which are essential factors to consider in the physical internet. Also, to make the model more realistic, we consider warehouse capacity and warehouse shutdowns as well.

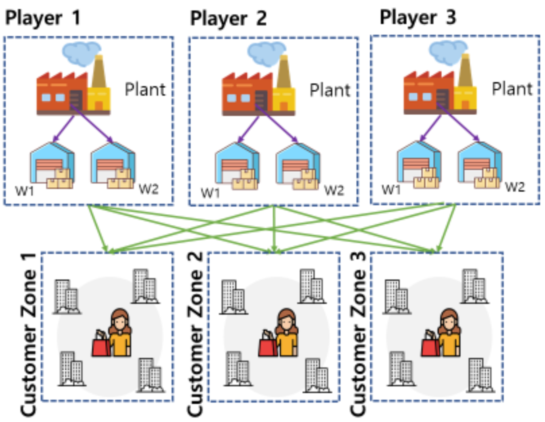
Table 3.1: Physical internet papers using quantitative models

	Methodology	**Warehouse capacity**	**Maximum delivery distance**	**Empty return**	**Production cost**	**Inventory cost**	**Transportation cost**	**Warehouse shut down**
Pan et al. (2015)	Inventory control algorithm with (Q,r) policy	X	X	X	X	O	O	X
Venkatadri et al. (2016)	MILP model	O	O	X	X	O	O	X
Fazil et al. (2017)	Disaggregate the model into three sub-problems and solve sequentially	O	O	O	X	X	O	X
Yang et al. (2017)	Non-linear simulation-based optimization model	X	X	X	X	O	O	X
Caballini et al. (2017)	MILP model	X	X	X	X	O	O	X
Ji et al. (2019)	MILP model	O	X	X	O	O	O	X
This study	MILP model	O	O	O	O	O	O	O

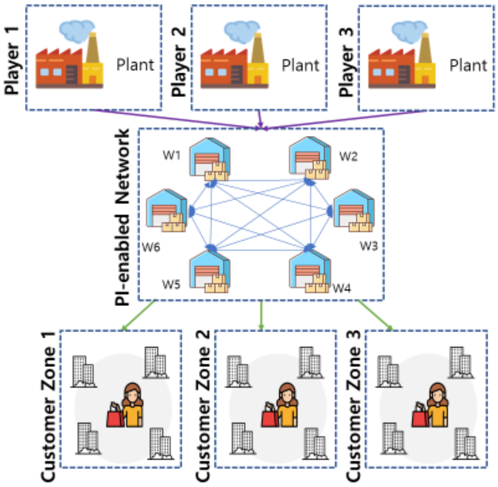
3.1. Problem Definition

In this thesis, the production-inventory-distribution problem in the PI that we consider deals with multiple players, each with multiple products made in a production facility. Additionally in this thesis, multiple warehouses serve as PI hubs, and players share multiple customer zones.

Figure 3.1 provides a general sketch of the problem setups in which companies independently run a supply chain and in which they collaborate in the PI system. When players do not collaborate with other players, they each run an independent supply chain, as depicted in Figure 3.1 (a). Figure 3.1 (b) depicts when companies collaborate in sharing capacitated warehouses, which will serve as π-hubs in the PI system.



(a) Independent supply chain network when players do not collaborate in the PI system



(b) Supply chain network when 3 players collaborate in the PI system

Figure 3.1: General representation of supply chain network

Each player manufactures multiple items that they sell. In this thesis, we assumed that a player's items are not in competition with items of other players. Therefore, even when players collaborate in a PI system and share advantages of utilizing warehouses close to customer zones, no player has to worry about losing its market share to other players.

Items are produced in manufacturing plants and can be stored at either the plant itself or in warehouses. Capacity constraints are considered in both plants and warehouses. Therefore, one cannot store items past the capacity of the given facility. The maintenance cost of a warehouse is considered as well. If operating a warehouse is more expensive than shutting it down, one can choose not to utilize the warehouse. Once a warehouse has been slated for shutdown, it will not be utilized until the end of the planning period.

Items can be delivered directly from the plant or from one of the warehouses to satisfy the demand of customer zones. The transportation flow of an item is depicted in a simple notational concept in Figure 3.2.

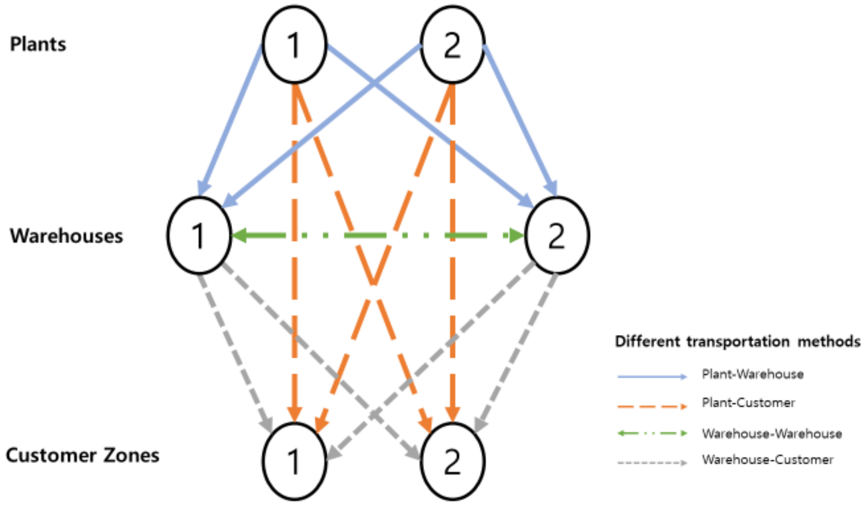


Figure 3.2: Freight transportation flows

As shown in Figure 3.2, transportation methods vary according to the starting point and ending point of freight transportation. Conveying items from a plant to a warehouse uses transportation methods that have a relatively large capacity with a smaller cost per mile, while shipping to customer zones utilizes delivery trucks with smaller capacities and higher costs per mile, because of the difference in work intensity of the last mile of delivery. Additionally, empty running penalty costs are considered in this thesis. However, in this model, we will only use the warehouse-to-warehouse route to calculate empty running penalty costs. In other routes, such as plant-warehouse, plant-customer, and warehouse-customer routes, freight transportation flow does not move back to the starting node, even though the truck itself does. Thus, we assumed that the empty running penalty cost of transportation is already included in the dispatch cost of such routes.

In the PI, a trucker's well-being is an important consideration that is taken into account by reducing long-distance deliveries. Maximum delivery distance is predetermined before the calculation of the model, and the shape of the network is set. Also in this thesis, to simplify the situation, customers are grouped by the proximity of their distance within a customer zone. Furthermore, demand patterns for a given item might differ according to the customer zone.

3.2. Assumptions

The assumptions applied to production-inventory-delivery cost minimization in the MILP formulation are as follows:

(1) Demands are deterministic.

(2) All demands are met. There will be no backorders or lost sales.

(3) Items can be stored at both plants and warehouses.

(4) Items can be delivered directly from a manufacturing plant or from a warehouse.

(5) Inventory capacity constraints are considered in plants and warehouses.

(6) Item holding costs are charged for each unit item per unit time and they vary depending on the type of facility and item.

(7) Maintenance cost of a warehouse is considered. If maintenance cost is more expensive than additional costs incurred by shutting down a warehouse, a company will shut down the warehouse.

(8) Once a warehouse has been slated for shutdown, it cannot be utilized within the planning period.

(9) Source of replenishment is dynamic. This means that when replenishing items at a warehouse, trans-shipment is the typical strategy used for refilling stock, rather than a lateral means of support for regular replenishment orders.

(10) Maximum length of a delivery distance is predetermined.

(11) When items are delivered to another facility, they can be moved again at the start of the next unit time.

(12) Transportation costs, which can either be a dispatch cost or an empty return penalty cost, are proportional to the delivery distance.

(13) The costs of loading and unloading items are not considered in this thesis.

(14) Dispatch costs, which vary depending on the type of transportation method used, are incurred regardless of the capacity utilization rate. If even only one item is loaded on departing cargo trucks and trailers, a dispatch cost will be incurred.

(15) If a transportation method is dispatched it can only visit one location and has to return to the point of origin.

(16) When returning trucks do not have any items loaded, an empty return penalty cost will be incurred. However, other than with the warehouse-to-warehouse route, the empty return penalty cost is included in the dispatch cost. Therefore, empty running penalty costs will be considered only in the warehouse-to-warehouse route.

(17) An empty return penalty cost per distance is less than or equal to the dispatch cost per distance of the same type of freight transportation method.

(18) Transportation methods used to move freight have different capacities, dispatch costs, and empty return penalty costs, depending on the node of origin and the destination node.

3.3. Notations and Formulations

Sets and Indices

I : Set of items, denoted by indices i

P : Set of manufacturing plants, denoted by indices j

W : Set of warehouses, denoted by indices j and k

CZ : Set of customer zones, denoted by indices k

T : Set of time periods, denoted by indices t

V : Set of freight transportation vehicle types, denoted by indices v

Parameters

M : Large number

D_{ik}^{t} : Demand of item i at location $k \in CZ$ at time t

S_i : Fixed setup cost of item i

O_j : Maintenance cost of warehouse j per unit period of time

P_i : Unit production cost of item i

C_j : Capacity constraint of location j

h_{ij} : Unit holding cost of item i at location $j \in (P \cup W)$

U_v : Load capacity of freight transportation of vehicle type v

L_{max} : Maximum possible transportation distance

l_{jk} : Geographic distance between location j and k

d_v : Dispatch cost of dispatching vehicle type v per unit distance

e_v : Empty running penalty cost of vehicle type v per unit distance

Decision variables

x_{ijk}^{t} : Number of items i delivered from location j to location k at time t

y_{ij}^{t} : 1 if item i is manufactured at location $j \in P$ at time t

q_{ij}^{t} : Number of items i produced at manufacturing plant $j \in P$ at time t

z_j^t : 1 if warehouse j is operating at time t, 0 if warehouse j is shut down at time t

F_{jkv}^{t}	: Number of vehicles with items loaded that depart from location j to location k by using vehicle type v at time t
I_{ij}^{t}	: Inventory level of item i at location $j \in (P \cup W)$ at time t
Δ_{jkv}^{t}	: Number of unmatched trips from location j to location k using vehicle type v at time t
Δ_{jkv}^{t+}	: Positive component of free variable Δ_{jkv}^{t}
Δ_{jkv}^{t-}	: Negative component of free variable Δ_{jkv}^{t}

Minimize

$$\sum_{i}\sum_{j\in P}\sum_{t}(S_i y_{ij}^{t} + P_i q_{ij}^{t}) + \sum_{i}\sum_{j\in(P\cup W)}\sum_{t} h_{ij} I_{ij}^{t} + \sum_{j\in W}\sum_{t} O_j z_j^{t} + \sum_{j}\sum_{k}\sum_{v}\sum_{t} l_{jk} d_v F_{jkv}^{t} + \sum_{j}\sum_{k}\sum_{v}\sum_{t} l_{jk} e_v \, \Delta_{jkv}^{t+} \quad (1)$$

subject to

$$q_{ij}^{t} \le y_{ij}^{t} M \qquad \forall i, j \in P, \forall t \qquad (2)$$

$$I_{ij}^{t} = I_{ij}^{(t-1)} + q_{ij}^{t} - \sum_{k} x_{ijk}^{t} \qquad \forall i, j \in P, \forall t \qquad (3)$$

$$I_{ij}^{t} = I_{ij}^{(t-1)} + \sum_{k}(x_{ikj}^{t} - x_{ijk}^{t}) \qquad \forall i, j \in W, \forall t \qquad (4)$$

$$\sum_{i}\sum_{j} x_{ijk}^{t} \le z_k^{t} M \qquad k \in W, \forall t \qquad (5)$$

$$\sum_{i}\sum_{k} x_{ijk}^{t} \le z_j^{t} M \qquad j \in W, t \in T \backslash \{0\} \qquad (6)$$

$$z_j^{t-1} \le z_j^{t} \qquad j \in W, t \in T \backslash \{0\} \qquad (7)$$

$$\sum_{i} I_{ij}^{t} \le C_j \qquad j \in (P \cup W), \forall t \qquad (8)$$

$$\sum_{k} x_{ijk}^{t} \leq I_{ij}^{(t-1)} \qquad \forall i, j \in W, \forall t \qquad (9)$$

$$\sum_{i} x_{ijk}^{t} \leq \sum_{v} U_v F_{jkv}^{t} \qquad \forall j, \forall k, \forall t \qquad (10)$$

$$D_{ik}^{t} = \sum_{j} x_{ijk}^{t} \qquad \forall i, k \in CZ, \forall t \qquad (11)$$

$$\Delta_{jkv}^{t} = F_{kjv}^{t} - F_{jkv}^{t} \qquad \forall j, \forall k, \forall v, \forall t \qquad (12)$$

$$\Delta_{jkv}^{t} = \Delta_{jkv}^{t+} - \Delta_{jkv}^{t-} \qquad \forall j, \forall k, \forall v, \forall t \qquad (13)$$

$$(L_{max}^{v} - l_{jk}) x_{ijk}^{t} \geq 0 \qquad \forall i, j \in (P \cup W), \forall k, \forall t \qquad (14)$$

$$x_{ijk}^{t} \geq 0 \qquad \forall i, \forall j, \forall k, \forall t \qquad (15)$$

$$x_{ijk}^{t} = 0 \qquad \forall i, j \in CZ, \forall k, \forall t \qquad (16)$$

$$x_{ijk}^{t} = 0 \qquad \forall i, \forall j, k \in P, \forall t \qquad (17)$$

$$D_{ik}^{t} \geq 0 \qquad \forall i, k \in CZ, \forall t \qquad (18)$$

$$I_{ij}^{t} \geq 0 \qquad \forall i, j \in (P \cup W), \forall t \qquad (19)$$

$$I_{ij}^{t} = 0 \qquad \forall i,\ j \in (P \cup W),\ t = 0, T \tag{20}$$

$$F_{jkv}^{t} \in \mathbb{Z} \qquad \forall j, \forall k, \forall v, \forall t \tag{21}$$

$$\Delta_{jkv}^{t}\ free\ variable,\ \ \Delta_{jkv}^{t+} \geq 0,\ \ \Delta_{jkv}^{t-} \geq 0 \qquad \forall j, \forall k, \forall v, \forall t \tag{22}$$

The objective function (1) minimizes the total cost of producing, stocking, moving, and delivering items. The first term in (1) is the production setup cost and the variable production cost, and the second term is the inventory cost of plants and warehouses. The third term is the maintenance cost of a warehouse, incurred when a warehouse is in operation. The fourth term is the freight vehicle dispatch cost, and the fifth term is the empty running return penalty cost. Constraint (2) ensures that when no items are manufactured, no number of items will be recognized. Constraint (3) is for inventory balance at a manufacturing plant. Constraint (4) is for inventory balance at a warehouse. Constraint (5) ensures that items can enter a warehouse only when the warehouse is in operation. Likewise, constraint (6) ensures that only when a warehouse is still in operation can item transportation flow depart from the warehouse. Constraint (7) ensures that if a warehouse is shut down at any given point, it will not be utilized again within the remaining period of time. Constraint (8) indicates that a capacity constraint is in place on stocking goods in plants and warehouses. Constraint (9) ensures that the number of products that depart from a warehouse does not exceed the inventory level of the last time period. This is because we previously assumed that after items arrive at a warehouse, they can be moved again at the start of the next unit of time. For manufacturing plants, this constraint is not needed because we assumed that there is no lead time in producing items. Therefore, items can be sent immediately without any delay. Constraint (10) limits the amount of load dispatched between locations based on the number of dispatched vehicles. Constraint (11) guarantees that all demands are met by equalizing them with the number of items delivered at time, t. Constraints (12), (13), and (22) are accommodated from a cost minimization model of Lozano et al. [36]. Constraint (12) computes the number of unmatched trips of loaded freight transportation. Using constraints (13) and (22), we can compute the number of empty running freight trips. Constraint (14) indicates that if the distance of transportation between two nodes is longer than the predetermined maximum delivery length, no item can be transported through the aforementioned route. Constraint (15) indicates that the amount of product delivered should always have a positive value. Constraints (16) and (17) restrict the transportation flow of an item. Constraint (16) shows that an item flow cannot originate from a customer zone, and constraint (17) shows that items cannot go back to the manufacturing plant. Constraints (18)–(22) define the domain and nature of the variables.

Chapter 4

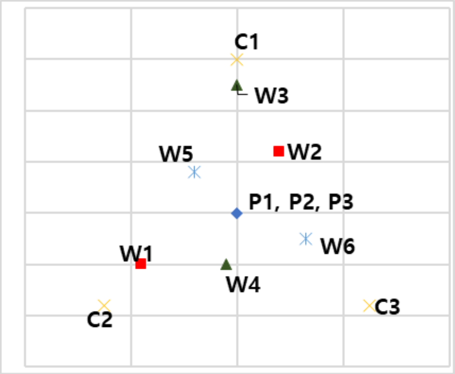
Numerical Analysis of the MILP Model

In this chapter, a numerical analysis has been carried out to estimate the cost savings of the PI system. To validate the performance of consolidation in the PI, the results obtained from consolidations will be compared to those of individual supply chain networks.

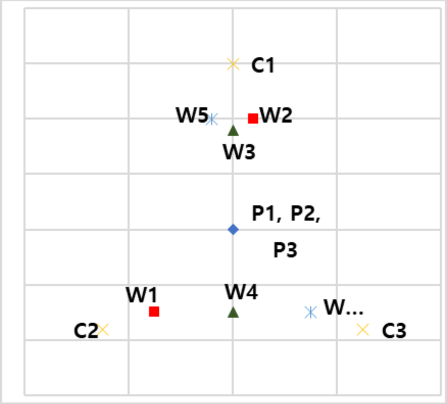
4.1. Experimental Design

We consider three independent supply chains, each with two warehouses and a manufacturing plant selling two items to three shared customer zones. Because the cost savings achieved through the collaborations can differ depending on the location of the warehouse, we consider three different types of warehouse locations within individual supply chains.

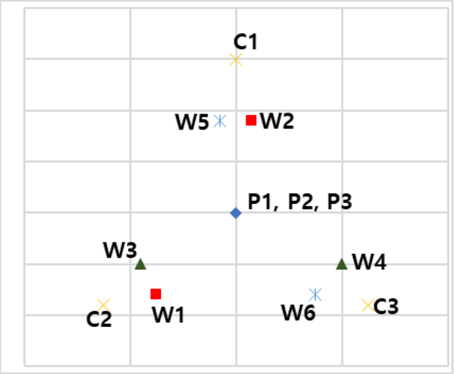
We chose three types of warehouse locations of a supply chain as follows. First, we looked at supply chains with warehouses that could cover all customer zones, even before joining the PI. Second, we looked at supply chains that each had one warehouse that was as close to the same customer zone as was the case in the other two supply chains. Third, we looked at supply chains with warehouses that were each close to a specific customer zone, making one customer zone unreachable from both warehouses.



(a) Type 1: Supply chains with warehouse combination that cover all customer zones



(b) Type 2: Supply chains all with a warehouse near one region (C1)



(c) Type 3: Supply chains with warehouses that each neglects a specific region

Figure 4.1: A pictorial description of different types of warehouse locations

For easier understanding, Figure 4.1 provides a pictorial explanation for each type of warehouse location collaboration. “P” represents a manufacturing plant, “W” represents a warehouse, and “C” represents a customer zone. W1 and W2 belong to P1, W3 and W4 belong to P2, and W5 and W6 belong to P3.

The exact coordinates of facilities and customer zones used in this numerical analysis are presented in Table 4.1.

Table 4.1: Coordinates of facilities in supply chains

Warehouse type	Player	Title (x-coordinate , y-coordinate)
Type 1	Player 1	W1 (-180 , 100) , W2 (80 , 120)
(Cover all)	Player 2	W3 (0 , 250) , W4 (-20 , -100)
	Player 3	W5 (-80 , 80) , W6 (130 , -50)
Type 2	Player 1	W1 (-150 , -150) , W2 (40 , 200)
(Focus on C1)	Player 2	W3 (0 , 180) , W4 (0 , -150)
	Player 3	W5 (-40 , 200) , W6 (150 , -150)
Type 3	Player 1	W1 (-150 , -160) , W2 (30 , 180)
(Neglect one	Player 2	W3 (-180 , -100) , W4 (200 , -100)
customer zone)	Player 3	W5 (-30 , 180) , W6 (150 , -160)
Other coordinates of locations that are constant through all three types of warehouse locations;		
Manufacturing plant	Player 1	P1 (0 , 0)
	Player 2	P2 (0 , 0)
	Player 3	P3 (0 , 0)
Customer zones	3 Customer zones	C1 (0 , 300) , C2 (-250 , -150) , C3 (250 , -150)

Table 4.2: Three different demand patterns

Demand Pattern	Customer Zone	Demand for each item, Normal distribution **(μ, σ)**
Pattern 1	C1	A1, A2, A3, A4, A5, A6 : N(200,40)
(Similar)	C2	A1, A2, A3, A4, A5, A6 : N(200,40)
	C3	A1, A2, A3, A4, A5, A6 : N(200,40)
Pattern 2	C1	A1, A2, A3, A4, A5, A6 : N(400,80)
(High at C1)	C2	A1, A2, A3, A4, A5, A6 : N(200,40)
	C3	A1, A2, A3, A4, A5, A6 : N(200,40)
Pattern 3	C1	A1, A3: N(400,80) A2, A4, A5, A6 : N(200,40)
(Various)	C2	A2, A5: N(400,80) A1, A3, A4, A6 : N(200,40)
	C3	A4, A6: N(400,80) A1, A2, A3, A5 : N(200,40)

In each supply chain collaboration, we set the planning horizon at six periods. Demand patterns that we considered in this thesis are listed in Table 4.2. A1 and A2 represent items that player 1 handles, while A3 and A4 are the items of player 2, and A5 and A6 are the items of player 3. Each demand follows the normal distribution suggested in Table 4.2. If the data of a demand worked out to be below zero, we adjusted the data to zero. Other values of parameters chosen to calculate the cost of suggested supply chains are shown in Table 4.3.

Table 4.3: Other parameter values

Name	Parameter	Values
Fixed setup costs	$\boldsymbol{S_i}$	U (5000 , 10000)
Unit production cost	$\boldsymbol{P_i}$	U (5 , 10)
Maintenance cost of a warehouse	$\boldsymbol{O_j}$	3000
Inventory capacity of facility (P, W)	$\boldsymbol{C_j}$	500 , 1000
Unit holding cost of items (P, W)	$\boldsymbol{h_{ij}}$	U (0.25 , 0.5) , U(0.4 , 0.8)
Maximum delivery distance	$\boldsymbol{L_{max}}$	400
Load capacity of vehicle (P-W, P-C, W-W, W-C)	$\boldsymbol{U_v}$	1000 , 50 , 500 , 50
Dispatch cost (P-W, P-C, W-W, W-C)	$\boldsymbol{d_v}$	4 , 6 , 1.2 , 2
Empty running penalty cost	$\boldsymbol{e_v}$	0.96

For each warehouse type and demand pattern, we randomly generated five instances by using the demand distributions in Table 4.2 and averaged them to achieve general results. All experimental tests were coded in a Python-based commercial solver, a Gurobi solver, version 9.1.1. To solve the problem within a reasonable time, the MIP gap was set to 0.5 percent. The MIP gap in the Gurobi solver is given by $\frac{|Z_P - Z_D|}{|Z_D|}$. $\boldsymbol{Z_P}$ is the primal objective bound, and $\boldsymbol{Z_D}$ is the dual optimization bound.

4.2. Results Analysis

Tables 4.4, 4.5, and 4.6 show how different operational cost factors changed after the collaboration, as compared to the sum of the costs of operating individual supply chains. The performance ratio is calculated by the following mathematical expression, $\frac{\mathit{Total\ Cost}_{collaboration} - \mathit{Total\ Cost}_{Individuals}}{\mathit{Total\ Cost}_{Individuals}}$.

Table 4.4: Type 1 performance ratios of cost factors in the collaboration vs. independent networks

Type 1		Demand Pattern	
Parameter value	Pattern 1	Pattern 2	Pattern 3
Total cost	-12.64%	-10.95%	-15.39%
Production cost	-4.07%	-0.79%	-1.43%
Holding cost	9.73%	7.77%	11.15%
Maintenance cost	-9.52%	-2.38%	-2.38%
Total transport cost	-27.78%	-28.05%	-36.12%

Table 4.5: Type 2 performance ratios of cost factors in the collaboration vs. independent networks

Type 2		Demand Pattern	
Parameter value	Pattern 1	Pattern 2	Pattern 3
Total cost	-25.89%	-19.76%	-24.30%
Production cost	-10.76%	-0.93%	-5.78%
Holding cost	29.21%	9.66%	20.45%
Maintenance cost	-5.71%	0.00%	-3.33%
Total transport cost	-51.68%	-47.65%	-46.75%

Table 4.6: Type 3 performance ratios of cost factors in the collaboration vs. independent networks

Type 3		Demand Pattern	
Parameter value	Pattern 1	Pattern 2	Pattern 3
Total cost	-32.82%	-24.68%	-30.65%
Production cost	-13.55%	-6.94%	-3.62%
Holding cost	45.86%	18.48%	26.15%
Maintenance cost	-1.90%	-0.48%	0.00%
Total transport cost	-63.94%	-46.62%	-64.02%

Depending on the warehouse locations and demand patterns, the performance ratio of the total cost in the PI is from 12.64 percent to 32.82 percent. This means that through collaboration in the PI, the total cost is always reduced compared to the sum of independent supply chains. This is because, in our model, we did not consider items in competition or warehouse congestion costs. Simply put, adding new players to the network cannot make the situation worse. It will always reduce the total cost of the network compared to summing the total cost of independent supply chains because it means that there are more options to choose from for players.

Figure 4.2 shows that when comparing the total costs of type 1, 2, and 3 warehouse locations, type 3 collaboration shows the highest reduction in the total cost, followed by type 2 and then type 1. This is because collaboration among supply chains with warehouse locations that focused on a specific customer zone can obtain the biggest effect when joining a PI. Before the collaboration, type 3 supply chains each had a region that required a costly last-mile delivery because one customer zone was unreachable from a warehouse. Through collaboration, all customer zones are reachable from the warehouse; thus, transportation costs can be reduced. Supply chains with warehouse combinations that can cover all customer regions gain the least cost savings from joining a PI. The reason for this is that the last-mile delivery distance after collaboration through the physical internet does not vary significantly from that from before the collaboration. Therefore, the reduction in transportation costs in this setup is relatively low compared to the transportation costs in the setups with the other two types of warehouse locations.

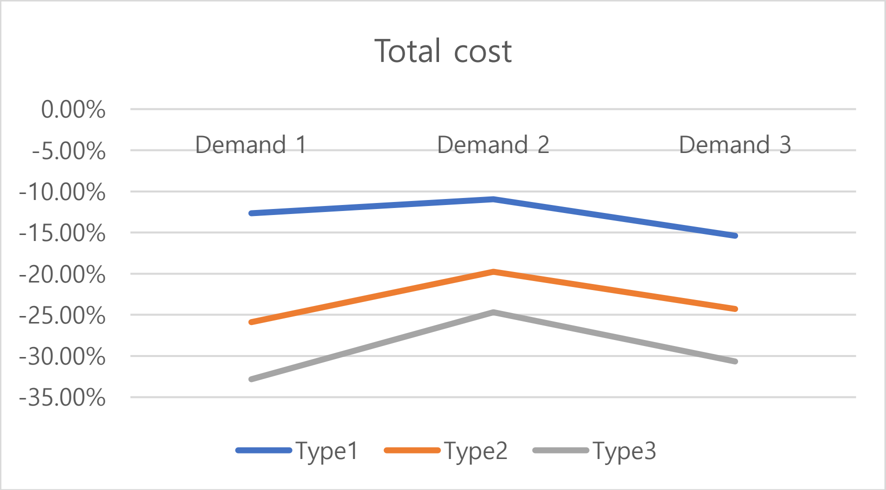


Figure 4.2: Performance ratio of the total cost

Tables 4.4, 4.5, and 4.6 all show that operational costs are lower when independent supply chains collaborate in the PI compared to when they act independently, with the exception of holding costs. The reason for this is that through collaboration one can better utilize warehouse capacity, causing the inventory holding costs to increase. The reason type 1 warehouse locations have the lowest increase in holding costs is because type 1 warehouse locations have similar last-mile delivery distances after collaboration and thus have less incentive to maintain multiple warehouses with similar characteristics. Because warehouse shutdowns increase after collaboration in the physical internet, the amount of cost increase in inventory holding costs is relatively lower in type 1 collaboration. For the same reason, in type 3 collaboration, in which supply chains with warehouses focused especially on certain customer zones collaborate, there is less incentive to shut down a warehouse, resulting in the biggest increase in inventory holding costs. This tendency is depicted in Figure 4.3. Figure 4.3 shows the performance ratio of inventory holding costs and maintenance costs.

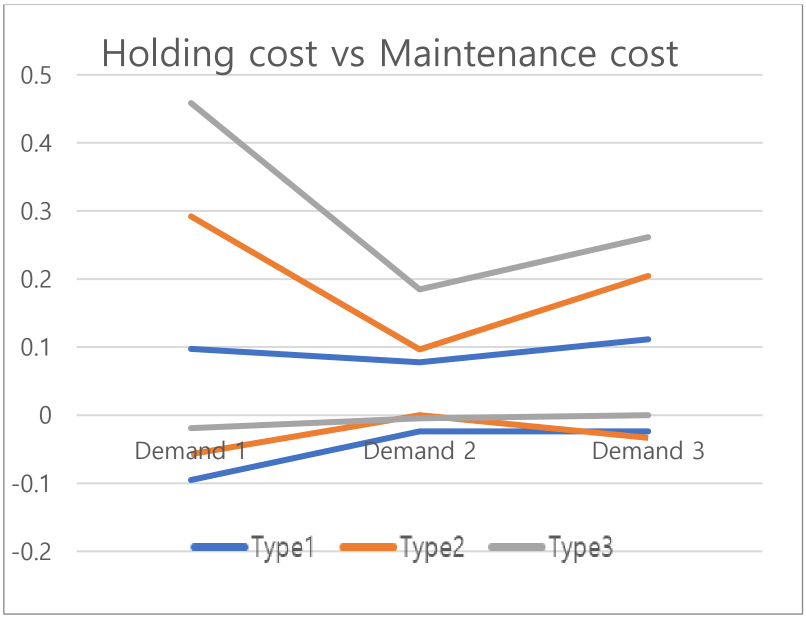


Figure 4.3: Performance ratio of inventory holding cost and maintenance cost

4.3. Cost Parameter Sensitivity Analysis

We conducted a sensitivity analysis of cost parameters to see the effect of parameters on the PI. Data from type 1 collaboration with demand pattern 1 was used as a basis for the sensitivity analysis.

Figure 4.4 presents the effect of maximum delivery distance on the total cost of the PI.

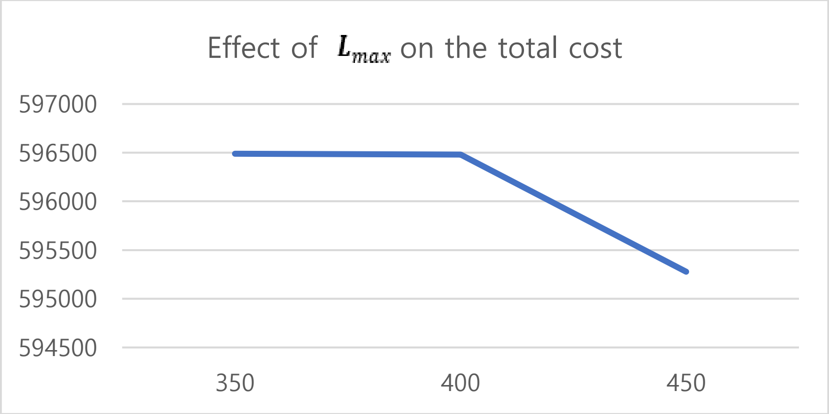


Figure 4.4: Effect of maximum delivery distance (L_{max}) on the total cost

We found that the total cost decreases as the maximum delivery distance increases. This is to be expected, because when the maximum delivery distance increases, one can have more options when choosing a location to which to deliver. Even though it is costly to set a maximum delivery distance, there is a limit on delivery distance in the PI in order to guarantee truckers' satisfaction and well-being.

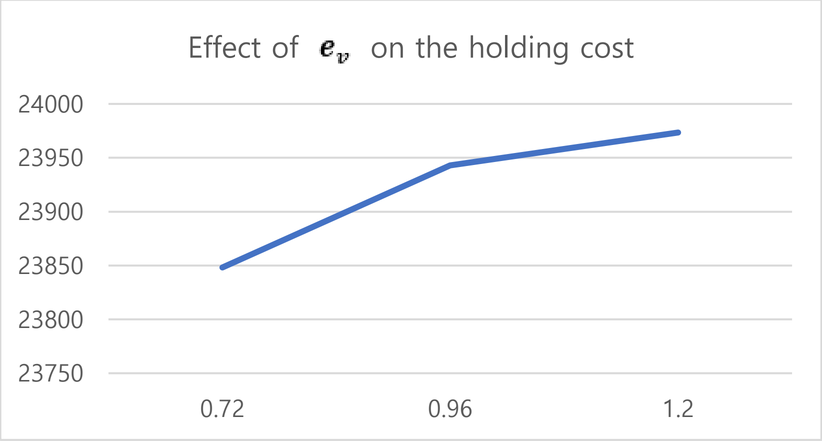


Figure 4.5: Effect of empty penalty cost (e_v) on the holding cost

Figure 4.5 depicts the effect that the empty running penalty cost has on the holding cost. If an empty running penalty cost increases, the holding cost increases as well. This may be because when it is expensive to run a truck because of a high empty running penalty cost, more items are stored at a warehouse rather than moved through the supply chain.

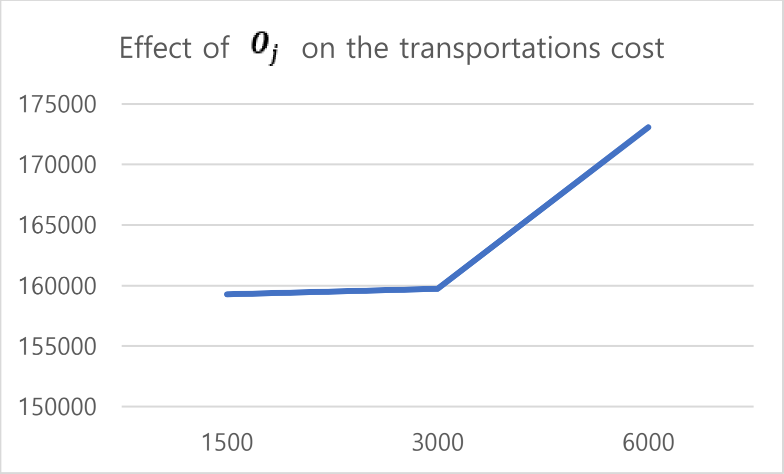


Figure 4.6: Effect of maintenance cost (O_j) on the transportations cost

When maintenance costs increase, instances in which warehouses shut down increase as well. When there are relatively fewer warehouses, it is natural for freight transportation costs to increase. Figure 4.6 shows the effect that maintenance costs have on transportation costs.

Chapter 5

Cost Savings Allocation Problem

To encourage companies to join a PI, it is essential that they be made aware of the number of benefits they will gain through joining the new system. Therefore, setting an allocation rule is important. In this chapter, we will estimate the cost savings obtained through the PI using the MILP model we developed in chapter 4, and allocate them using three methods—the setup with no pre-set rules, the setup that allocates the cost savings of collaboration proportional to customer demand, and the setup with the application of the Shapley value.

5.1. No Pre-set Rules

The physical internet was inspired by the digital internet, in which the owners of a local network pay for their own resources, even though other players may use the information present in the local network. Likewise, participants in the physical internet can choose not to allocate the cost savings and can pay for their own resources. In other words, if there are no rules set in advance to allocate cost savings, a company must pay for the costs incurred by using their own resources, regardless of who else also uses those resources. If participants choose this strategy, however, there is a chance that some companies will take a loss after the collaboration, as we have mentioned previously. Companies will refrain from joining the PI if they expect to incur losses by participating in the system. An example of a company experiencing loss after joining the PI is shown in Table 5.1.

Table 5.1: Supply chain costs of when they are operated independently, and when they are in the PI

Costs	When operated independently	When in the PI	Changed value
Company A	272466.18	199140.20	-73325.98
Company B	258884.92	275739.33	16854.41
Company C	275906.16	224551.20	-51354.96
Company A, B, C	807257.27	699430.73	-107826.54

When we experimented with a type 1 supply chain collaboration and a demand pattern 1 with 6000 as a maintenance cost per unit period of time (as was outlined in chapter 4.3), the total cost of operating the supply chain for all three companies was reduced from 807257.3 to 699430.7. However, when we specifically looked at company B, the cost they had to pay in order to run the supply chain increased from 258884.9 to 275739.3. The company had to pay more after the collaboration, and they would likely not join the PI.

5.2. Proportional to Customer Demand

Allocating the total cost savings of collaboration proportional to customer demand is a simple way to set a rule for the cost savings allocation problem. By setting a simple proportional rule, inventory costs and transportation costs can be divided somewhat effectively.

To give an example, we used the same experimental data as in chapter 5.1. The experiment that we used had the setup of a warehouse location type 1 and a demand pattern 1 with 6000 as a maintenance cost per unit period of time. We allocated the cost savings obtained from the experiment proportional to the customer demands. The results are shown in Tables 5.2 and 5.3.

Table 5.2: Proportional cost savings allocation (production cost excluded)

	D_{all}	P_{demand}	When operated independently	Cost savings	When in the PI
Company A	7312.00	0.34	165970.19	44720.96	121249.22
Company B	7029.00	0.33	154652.92	42990.1`	111662.81
Company C	7213.00	0.34	170202.16	44115.47	126086.69
Company A, B, C	21554.00	1	490825.27	131826.54	358998.73

D_{all} in Table 5.2 represents the sum of customer demands of the company's items through entire periods of the planning horizon. P_{demand} represents the customer demand for items a company owns divided by the customer demands of all players in the PI. In Table 5.2, we excluded the production cost from the calculation. This is because, unlike other factors in our model, such as storage facilities and transportation, the production facility is not shared among participants. Therefore, we first calculated the cost savings of the supply chain with production costs excluded, and then allocated the result proportionally to the demand of customers.

Table 5.3: Proportional cost savings allocation (production cost included)

	When in the PI (production cost excluded)	Production cost in the PI	Total cost when in the PI
Company A	121249.22	114496.00	235745.22
Company B	111662.81	112232.00	223894.81
Company C	126086.69	113704.00	239790.69
Company A, B, C	358998.73	340432.00	699430.73

After allocating the cost savings, we added the production cost to each company to determine the total cost for a company when it joined the PI. As can be seen in Table 5.3, the results are different from those obtained in chapter 5.1.

While the simple proportional rule may be an easy way to allocate cost savings, this also is not a fair method to allocate the cost savings. Allocating cost savings proportional to customer demands does not capture the difference one can achieve by having a warehouse close to a customer zone or by having it far from the warehouse. As we have demonstrated in chapter 4, the total cost of a PI can vary depending on the location of a warehouse. This is because transportation costs differ depending on vehicle types. Moving freight to a warehouse is cheaper than delivering it to a customer zone. Thus, if the delivery distance from a warehouse to a customer zone increases, transportation costs will increase as well, resulting in a total cost increase. Table 5.4 shows how warehouse location can affect the total cost of a PI.

Table 5.4: The total cost of a PI in regards to a warehouse location

Type	Avg. distance from a warehouse to the nearest customer zone	Total cost of the PI
Type 1	167.97	580102.61
Type 2	132.67	566984.65
Type 3	108.66	541812.71

Results used in Table 5.4 are from the average value of five instances using the demand pattern 1, which was estimated in chapter 4.2. Even when using the same data, the total cost of the PI changes depending on warehouse locations that have different average distances to the nearest customer zones. The table shows that when the last-mile delivery distance decreases, the total cost decreases as well. This means that the total cost clearly depends on the location of the warehouse. Therefore, a simple proportion rule that allocates cost savings according to customer demand might not be a fair way to distribute cost savings.

5.3. The Shapley Value

A theoretically grounded approach to finding a fair way to allocate cost savings is to use a game theory, more specifically a cooperative game theory with transferable utility. The key aim of cooperative game theory is to calculate every possible coalition the joined parties can make and then calculate one agent's contribution by evaluating the synergy of including the agent in the coalition. In our case, we considered three potential players in a PI in order to achieve simplicity in the calculation, which resulted in possible coalitions of (A), (B), (C), (AB), (AC), (BC), and (ABC). Computing the total cost of different types of coalitions, their corresponding cost savings, and their synergies could be computed as well. Generally, when cost savings allocation problems are considered, cost savings are zero when companies act independently. Therefore, by comparing the total cost of different types of coalitions, the total cost savings of a network can be calculated.

In this thesis, we use the Shapley value, one of the most common solution concepts for cooperative games used to allocate cost savings. The Shapley value was introduced by Shapley [37], and it calculates the amount of each company's contribution to each possible coalition and allocates cost savings based on each company's marginal contributions.

The Shapley value can be calculated as follows. A set of players, $N = \{1, 2, \ldots, n\}$, form a cooperative game, and each possible coalition is denoted by S. $v(S)$ is the value of coalition, S. The grand coalition value can be expressed as $v(N)$. By definition, $v(\emptyset) = 0$. The Shapley value, (φ_i), for a company, i, is the weighted sum of all marginal costs of a company, i, in each sub coalition, S [38]:

$$\varphi_i = \sum_{S \subseteq N \setminus \{i\}} \frac{|S|!(|N|-|S|-1)!}{N!} (v(S \cup \{i\}) - v(S)) \qquad \forall i \in N$$

Using the Shapley value, we performed cost savings allocations using the data that were used in chapters 5.1 and 5.2. The results are shown in Table 5.5.

Table 5.5: Optimal total cost and cost savings for each of the possible coalitions

Coalition *S*	Total cost of coalition *S*	Cost savings of coalition *S*	Shapley value	Cost, when in the PI
{A}	272466.19	0	37511.27	234954.92
{B}	258884.92	0	33562.12	225322.80
{C}	275906.16	0	36753.15	239153.02
{A,B}	473912.37	57438.73		
{A,C}	484551.56	63820.79		
{B,C}	478868.59	55922.49		
{A,B,C}	699430.73	107826.54		

Notice that the result obtained by using the Shapley value is different from the result obtained by using no pre-set rules or by using the simple proportional rule. The Shapley value requires more computational time than does the simple proportional rule, but it directly calculates the marginal contribution a company can bring to the coalition, providing a more grounded solution to allocate cost savings.

Chapter 6

Conclusions

The physical internet was developed to improve the sustainability of a supply chain. When various players can be encouraged enough to join the physical internet, improvements in sustainability previously considered unattainable can be achieved. In order for players to join the physical internet, they must first know how much they can gain by implementing the new system. Therefore, it is important to reasonably estimate the amount of cost savings when participating in a physical internet, and to present a rule to allocate the benefits of participating in a physical internet.

In our thesis, we suggested that the MILP model be used to estimate the cost savings of the physical internet. The model incorporates several properties of the physical internet, such as the maximum delivery distance and the empty running penalty cost. We used three different warehouse combinations and three different demand patterns to estimate the cost savings effect under different situations. In this study, we found that collaboration among supply chains with warehouses focused on specific customer zones brought the most cost savings through the physical internet, while supply chains with warehouses that can cover all customer zones, even before their joining the physical internet, brought the least amount of cost savings. To summarize, however, we found that all types of warehouse locations and demand patterns of collaboration within the physical internet resulted in cost savings.

The cost savings were allocated using three methods: a setup with no pre-set rules, a setup with allocation of the total cost savings of collaboration proportional to customer demands, and a setup with the Shapley value. If there are no pre-set rules to allocate cost savings, players need to pay for their own resources, such as warehouse usage fees and transportation fees. We used a numerical example to show that with no pre-set rules to allocate cost savings, instances in which players sustain losses after participating in the physical internet can occur, which will decrease players' participation in the system. When allocating cost savings proportional to customer demands, we showed that while such a setup is easy to compute, it does not reflect the players' location of warehouses in relation to the allocation, thereby making the allocation unfair. Additionally, we used the Shapley value to allocate cost savings, as this method is known to be a fair solution method for transferable utility games. Because the Shapley value calculates the marginal contribution of a player to the collaboration, the cost savings allocation effectively reflects the player’s features, such as customer demands and resources. However, a shortcoming of the Shapley value is that its computational complexity increases exponentially with the number of players in the game.

Further extension of this thesis might include suggesting a heuristic method to lessen the computational complexity of estimating the cost of using the physical internet. The structure of a physical internet supply chain increases computational time. Horizontal trans-shipment between a warehouse is normal in the physical internet. Thus, an increase in the number of warehouses causes an increase in transportation options, in turn causing an exponential increase in computational time. Moreover, while using the Shapley value is a fair method to apply to a physical internet, utilizing the Shapley value to allocate cost savings in the real world might not be a realistic approach because of its computational complexity. Therefore, suggesting an approximation method for the Shapley value would be a potential research extension to make our work more applicable in the real world.

Bibliography

[1] Montreuil, Benoit, Russell D Meller, and Eric Ballot, *Towards a physical internet: The impact on logistics facilities and material handling systems design and innovation.* (2011).

[2] Institute, The Korea Transport, *Survey on national cargo transportation*, I.a.T. Ministry of Land, (2017), Korea Transport DataBase.

[3] Taejong Shin, Juhan Lee, *Labor data about truckers in seoul and policy improvement measures*, S.L. Center, (2017).

[4] Zäpfel, Günther and Michael Wasner, *Planning and optimization of hub-and-spoke transportation networks of cooperative third-party logistics providers.* International journal of production economics, 78(2) (2002), p. 207-220.

[5] Leung, KH, King Lun Choy, Paul KY Siu, George TS Ho, HY Lam, and Carman KM Lee, *A b2c e-commerce intelligent system for re-engineering the e-order fulfilment process.* Expert Systems with Applications, 91 (2018), p. 386-401.

[6] Gevaers, Roel, Eddy Van de Voorde, and Thierry Vanelslander, *Characteristics of innovations in last-mile logistics-using best practices, case studies and making the link with green and sustainable logistics.* Association for European Transport and contributors, (2009), p. 1-21.

[7] Wang, Yong, Xiaolei Ma, Mingwu Liu, Ke Gong, Yong Liu, Maozeng Xu, and Yinhai Wang, *Cooperation and profit allocation in two-echelon logistics joint distribution network optimization.* Applied Soft Computing, (2017), 56: p. 143-157.

[8] Markillie, Paul, *The physical internet: A survey of logistics*. (2006), The Economist Newspaper: The Economist.

[9] Lin, Yen-Hung, Russell D Meller, Kimberly P Ellis, Lisa M Thomas, and Barbara J Lombardi, *A decomposition-based approach for the selection of standardized modular containers.* International Journal of Production Research, 52(15) (2014), p. 4660-4672.

[10] Sallez, Yves, Benoit Montreuil, and Eric Ballot, *On the activeness of physical internet containers*, in *Service orientation in holonic and multi-agent manufacturing*. (2015), Springer. p. 259-269.

[11] Landschützer, Christian, Florian Ehrentraut, and Dirk Jodin, *Containers for the physical internet: Requirements and engineering design related to fmcg logistics.* Logistics Research, 8(1) (2015), p. 1-22.

[12] Meller, Russell D, Benoit Montreuil, Collin Thivierge, and Zachary Montreuil, *Functional design of physical internet facilities: A road-based transit center.* (2012).

[13] BALLOT, ERIC, OLIVIER GOBET, AND BENOIT MONTREUIL, *Physical internet enabled open hub network design for distributed networked operations*, in *Service orientation in holonic and multi-agent manufacturing control*. (2012), Springer. p. 279-292.

[14] SOHRABI, HELIA AND BENOIT MONTREUIL. *From private supply networks and shared supply webs to physical internet enabled open supply webs*. in *Working Conference on Virtual Enterprises*. (2011), Springer.

[15] FAZILI, MEHRAN, UDAY VENKATADRI, PEMBERTON CYRUS, AND MAHDI TAJBAKHSH, *Physical internet, conventional and hybrid logistic systems: A routing optimisation-based comparison using the eastern canada road network case study.* International Journal of Production Research, 55(9) (2017), p. 2703-2730.

[16] PAN, SHENLE, MICHELE NIGRELLI, ERIC BALLOT, ROCHDI SARRAJ, AND YANYAN YANG, *Perspectives of inventory control models in the physical internet: A simulation study.* Computers & Industrial Engineering, 84 (2015), p. 122-132.

[17] YAO, JIANMING, *Optimisation of one-stop delivery scheduling in online shopping based on the physical internet.* International Journal of Production Research, 55(2) (2017), p. 358-376.

[18] KONG, XIANG TR, JIAN CHEN, HAO LUO, AND GEORGE Q HUANG, *Scheduling at an auction logistics centre with physical internet.* International Journal of Production Research, 54(9) (2016), p. 2670-2690.

[19] CRAINIC, TEODOR GABRIEL AND BENOIT MONTREUIL, *Physical internet enabled hyperconnected city logistics.* Transportation Research Procedia, 12 (2016), p. 383-398.

[20] BEN MOHAMED, IMEN, WALID KLIBI, OLIVIER LABARTHE, JEAN-CHRISTOPHE DESCHAMPS, AND MOHAMED ZIED BABAI, *Modelling and solution approaches for the interconnected city logistics.* International Journal of Production Research, 55(9) (2017), p. 2664-2684.

[21] VENKATADRI, UDAY, KASINADHUNI SHYAMA KRISHNA, AND M ALI ÜLKÜ, *On physical internet logistics: Modeling the impact of consolidation on transportation and inventory costs.* IEEE Transactions on Automation Science and Engineering, 13(4) (2016), p. 1517-1527.

[22] CABALLINI, CLAUDIA, MASSIMO PAOLUCCI, SIMONA SACONE, AND EVRIM URSAVAS. *Towards the physical internet paradigm: A model for transportation planning in complex road networks with empty return optimization*. in *International Conference on Computational Logistics*. (2017) Springer.

[23] JI, SHOU-FENG, XIAO-SHUAI PENG, AND RONG-JUAN LUO, *An integrated model for the production-inventory-distribution problem in the physical internet.* International Journal of Production Research, 57(4) (2019), p. 1000-1017.

[24] YANG, YANYAN, SHENLE PAN, AND ERIC BALLOT, *Innovative vendor-managed inventory strategy exploiting interconnected logistics services in the physical internet.* International Journal of Production Research, 55(9) (2017), p. 2685-2702.

[25] CRUIJSSEN, FRANS, WOUT DULLAERT, AND HEIN FLEUREN, *Horizontal cooperation in transport and*

logistics: A literature review. Transportation journal, (2007), p. 22-39.

[26] Guajardo, Mario and Mikael Rönnqvist, *A review on cost allocation methods in collaborative transportation.* International transactions in operational research, 23(3) (2016), p. 371-392.

[27] Myerson, Roger B, *Game theory.* (2013), Harvard university press.

[28] Kim, Sungwook, *Cooperative game theoretic online routing scheme for wireless network managements.* IET communications, 4(17) (2010), p. 2074-2083.

[29] Kim, Sungwook, *Game theory applications in network design*. (2014), United states of America: United states of America Information Science Reference.

[30] Fiestras-Janeiro, M Gloria, Ignacio García-Jurado, and Manuel A Mosquera, *Cooperative games and cost allocation problems.* Top, 19(1) (2011), p. 1-22.

[31] van Campen, Tjeerd, Herbert Hamers, Bart Husslage, and Roy Lindelauf, *A new approximation method for the shapley value applied to the wtc 9/11 terrorist attack.* Social Network Analysis and Mining, 8(1) (2018), p. 1-12.

[32] Peters, Hans, *Game theory: A multi-leveled approach*. (2015), Springer.

[33] Littlechild, Stephen C and GF Thompson, *Aircraft landing fees: A game theory approach.* The Bell Journal of Economics, (1977), p. 186-204.

[34] Fragnelli, Vito, Ignacio García-Jurado, Henk Norde, Fioravante Patrone, and Stef Tijs, *How to share railways infrastructure costs?*, in *Game practice: Contributions from applied game theory.* (2000), Springer. p. 91-101.

[35] Ma, Richard TB, Dah Ming Chiu, John CS Lui, Vishal Misra, and Dan Rubenstein, *Internet economics: The use of shapley value for isp settlement.* IEEE/ACM Transactions on networking, 18(3) (2010), p. 775-787.

[36] Lozano, Sebastián, Placido Moreno, Belarmino Adenso-Díaz, and Encarnacion Algaba, *Cooperative game theory approach to allocating benefits of horizontal cooperation.* European Journal of Operational Research, 229(2) (2013), p. 444-452.

[37] Shapley, Lloyd S, *17. A value for n-person games*. (2016), Princeton University Press.

[38] Vanovermeire, Christine and Kenneth Sörensen, *Integration of the cost allocation in the optimization of collaborative bundling.* Transportation Research Part E: Logistics and Transportation Review, 72 (2014) p. 125-143.

국문 초록

피지컬 인터넷은 최첨단의 공유 글로벌 공급망 네트워크로 다양한 학자 및 실무자들의 관심을 끌고 있습니다. 피지컬 인터넷은 표준화된 컨테이너를 이용하여 상호 연결된 네트워크를 통해 제품 및 재화를 발송합니다. 이 때, 정보, 보관 시설 및 운송 수단은 참여자들 간에 공유됩니다. 이 네트워크는 비용을 절감하고 변동성이 큰 수요와 정보를 처리하고 사회적, 환경적으로 지속가능성을 유지하는 것을 목표로 합니다. 지금까지 피지컬 인터넷에 대한 연구는 주로 그 개념과 프레임워크의 개발, 그리고 사회에 도입하였을 때의 장점을 주로 다루었습니다. 피지컬 인터넷 속에서 운송 수단의 공차 운행, 자원의 한계 용량, 절감한 비용의 배분 등과 같은 현실적인 요소들에 대한 고려를 한 연구들은 아직 제한적입니다. 피지컬 인터넷은 전체적으로 보았을 때 기존의 공급망에 비해 더 큰 효율성과 지속 가능성을 얻을 수 있지만 특정한 상황에서는 일부 참가자는 현실적인 제약 상황으로 인해 오히려 손해를 보는 경우가 존재할 수 있습니다. 따라서 더 큰 효율성과 지속 가능성을 얻을 수 있는 피지컬 인터넷에 기업들을 참여시키기 위해선 그들이 참여함으로써 손해를 보는 상황을 만들지 않는 것이 필수적인 조건입니다. 본 논문에서는 먼저 운송 수단의 공차 운행 페널티 비용, 최대 운송 가능 거리, 창고의 폐쇄를 고려한 통합 생산-재고-물류 최소 비용 혼합 정수 선형 계획법 모형을 제안하였습니다. 그 후, 개별적인 공급망의 비용과 피지컬 인터넷 하에서 협업한 통합 공급망의 비용을 비교하여 비용 절감 효과를 계산한 후 협력 게임의 일종인 섀플리 값을 포함한 세 가지 배분 방법을 통해 비용 절감 효과 배분을 살펴보았습니다.

주요어: 피지컬 인터넷, 협업, 비용 절감 배분, 협력 게임, 섀플리 값

학번: 2019-29485