Physical Internet-Enabled Hyperconnected Distribution Assessment

Thèse

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Résumé

L'Internet Physique (IP) est une initiative qui identifie plusieurs symptômes d'inefficacité et non-durabilité des systèmes logistiques et les traite en proposant un nouveau paradigme appelé logistique hyperconnectée. Semblable à l'Internet Digital, qui relie des milliers de réseaux d'ordinateurs personnels et locaux, IP permettra de relier les systèmes logistiques fragmentés actuels. Le but principal étant d'améliorer la performance des systèmes logistiques des points de vue économique, environnemental et social.

Se concentrant spécifiquement sur les systèmes de distribution, cette thèse remet en question l'ordre de magnitude du gain de performances en exploitant la distribution hyperconnectée habilitée par IP. Elle concerne également la caractérisation de la planification de la distribution hyperconnectée. Pour répondre à la première question, une approche de la recherche exploratoire basée sur la modélisation de l'optimisation est appliquée, où les systèmes de distribution actuels et potentiels sont modélisés. Ensuite, un ensemble d'échantillons d'affaires réalistes sont créé, et leurs performances économique et environnementale sont évaluées en ciblant de multiples performances sociales. Un cadre conceptuel de planification, incluant la modélisation mathématique est proposé pour l'aide à la prise de décision dans des systèmes de distribution hyperconnectée.

Partant des résultats obtenus par notre étude, nous avons démontré qu'un gain substantiel peut être obtenu en migrant vers la distribution hyperconnectée. Nous avons également démontré que l'ampleur du gain varie en fonction des caractéristiques des activités et des performances sociales ciblées.

Puisque l'Internet physique est un sujet nouveau, le Chapitre 1 présente brièvement l'IP et hyper connectivité. Le Chapitre 2 discute les fondements, l'objectif et la méthodologie de la recherche. Les défis relevés au cours de cette recherche sont décrits et le type de contributions visés est mis en évidence. Le Chapitre 3 présente les modèles d'optimisation. Influencés par les caractéristiques des systèmes de distribution actuels et potentiels, trois modèles fondés sur le système de distribution sont développés. Chapitre 4 traite la caractérisation des échantillons d'affaires ainsi que la modélisation et le calibrage des paramètres employés dans les modèles. Les résultats de la recherche exploratoire sont présentés au Chapitre 5. Le Chapitre 6 décrit le cadre conceptuel de planification de la distribution hyperconnectée. Le chapitre 7 résume le contenu de la thèse et met en évidence les contributions principales. En outre, il identifie les limites de la recherche et les avenues potentielles de recherches futures.

Abstract

The Physical Internet (PI) is an initiative that identifies several symptoms of logistics systems unsustainability and inefficiency and tackles them by proposing a novel paradigm called Hyperconnected Logistics. Similar to the Digital Internet, which connects thousands of personal and local computer networks, PI will connect the fragmented logistics systems of today. The main purpose is to enhance the performance of logistics systems from economic, environmental and social perspectives.

Focusing specifically on the distribution system, this thesis questions the order of magnitude of the performance gain by exploiting the PI-enabled hyperconnected distribution. It is also concerned by the characterization of the hyperconnected distribution planning. To address the first question, an exploratory research approach based on optimization modeling is applied; first, the current and prospective distribution systems are modeled. Then, a set of realistic business samples are created, and their economic and environmental performance by targeting multiple social performances are assessed. A conceptual planning framework is proposed to support the decision making in the hyperconnected distribution system.

Based on the results obtained by our investigation, it can be argued that a substantial gain can be achieved by shifting toward Hyperconnected Distribution. It is also revealed that the magnitude of the gain varies by business characteristics and the targeted social performance.

Since the Physical Internet is a novel topic, chapter 1 briefly introduces PI and Hyperconnected Logistics. Chapter 2 discusses the research foundations, goal and methodology. It also describes the challenges of conducting this research and highlights the type of contributions aimed for. Chapter 3 presents the optimization models including a core distribution network design modeling approach. Influenced by the characteristics of the current and prospective distribution systems, three distribution system-driven models are developed. Chapter 4 engages with the characterization of the business samples, the modeling and calibration of the parameter that are employed in the models. The exploratory investigation results are presented in Chapter 5. Chapter 6 describes the hyperconnected distribution planning framework. Chapter 7 summarizes the content of the thesis and highlights the main contributions. Moreover, it identifies the research limitations and potential future research avenues.

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To my parents, my sister and grandmother

To Nicolas

And the everlasting memory of Pegah

Acknowledgment

Every page of this thesis reminds me of encouraging words and support of those who believed in me, loved me and were there for me, so I have made it through. Here, I share my true admiration and deepest appreciation with them.

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Chapter 1

Brief introduction to Physical Internet and Hyperconnected Logistics

1.1 Fundamental definitions

The Physical Internet is defined to be a "*hyperconnected global logistics system enabling seamless asset sharing and flow consolidation*" (Montreuil, 2015). Montreuil (2015) defines a hyperconnected system as *one whose components are intensely interconnected on multiple layers, ultimately anytime and anywhere*.

Let us first discuss the definition of the term, *interconnection*. It means the purposeful connection of more than one entities without altering their independency (based on Cambridge dictionary and Kahn and Cerf, 1999). The interconnection can be created for various purposes such as information transmission, financial transactions, collaboration in operations or physical asset sharing.

A well-known instance of interconnected systems is the digital Internet. The Internet is defined as a global information system formed by the interconnection of numerous independent computers that is federated into a seamless whole without changing any of the underlying networks (Kahn and Cerf, 1999). Our personal computers, same as hundreds of thousands of local and global computer networks interconnect with each other by transmitting data through Internet protocols.

When the level of interconnectivity intensifies by interconnection of entities on multiple layers, such as digital, physical, operational, business and legal to name a few, it is called hyperconnectivity (based on Montreuil, 2015). The Physical Internet aims to create hyperconnectivity by enabling intensive interconnection among currently dedicated and privately operated logistics systems without altering their independency. A large part of the potential to develop such hyperconnection already exists. Most of the current logistical facilities are owned or leased by an individual firm or a group of collaborative firms (Montreuil et al, 2013). Only in United States, there are in order of five hundred thousand distribution centers and warehousing facilities (Montreuil, 2011) and more than 10 million trucks (US Department of Transportation-Bureau of transportation studies, 2012). The average utilization rate of DCs and warehouses is reported to be on average 70% (Ecklund, 2010) and commercial trucks, almost 60% (McKinnon et al., 2010; Sarraj et al., 2014). These statistics indicate an existing opportunity to interconnect businesses by sharing assets and consolidating transportation flows (physical and operational interconnectivities).

In the Physical Internet, products are embedded in standard and modular size PI-containers equipped with RFID technologies to carry and transmit information. The size of PI-containers ranges from box size to cargo container size in a Lego shape that enables consolidation of tens of PI-containers to enhance the filling rate of the transportation vehicles, as depicted in Figure 1-1 and Figure 1-2.

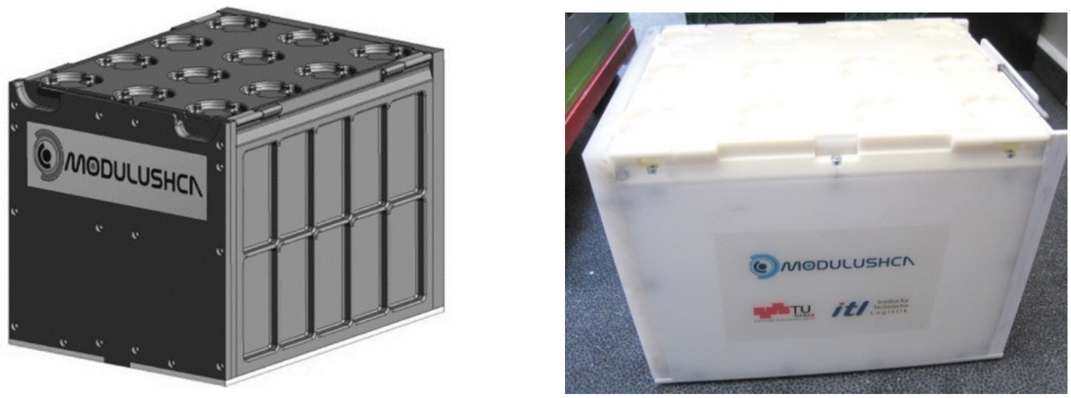


Figure 1-1. The first PI-container design (left) and product (right) by MODULUSHCA project (Landschützer et al., 2014)

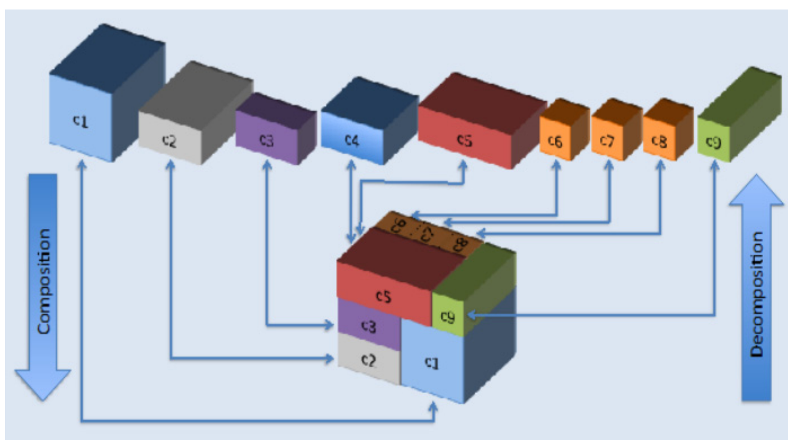


Figure 1-2. Schematic representation of the composition-decomposition of PI-containers based on the Physical Internet manifesto (Montreuil, 2012)

The standard size of PI-containers facilitates their handling and movement with standard material handling equipment Papers by Montreuil et al. (2012 and 2013) and Ballot et al. (2013) provide in depth coverage of PI-containers application and their impact on material handling technology and unimodal and multimodal PI-facilities.

The PI digital interconnectivity can be achieved by the exchange of information, such as the origin and destination of the product stored inside the container between users, service providers and operators. The digital interconnectivity ensures a seamless exchange of meaningful information and fact-based decision-making and action between PI-users. Moreover, it enables their distributed controlling and planning, for example for the purpose of efficient routing and consolidation (Sarraj et al., 2014).

Similar to the digital Internet and its web sites and applications built upon the digital Internet, businesses can exploit the Physical Internet through PI-enabled Logistics Web (Montreuil et al., 2013). The term "*web*" is used to represent a network of networks (Hakimi et al., 2009). The Logistics Web involves the network of open facilities, technologies and services. The openness feature refers to the characteristics of PI components (such as facilities and technologies) to be available for the use of PI-certified users other than their owner. As summarized in Figure 1-3, the Logistics Web embraces five sub-webs including Realization Web, Service Web, Supply Web, Mobility Web and Distribution Web.

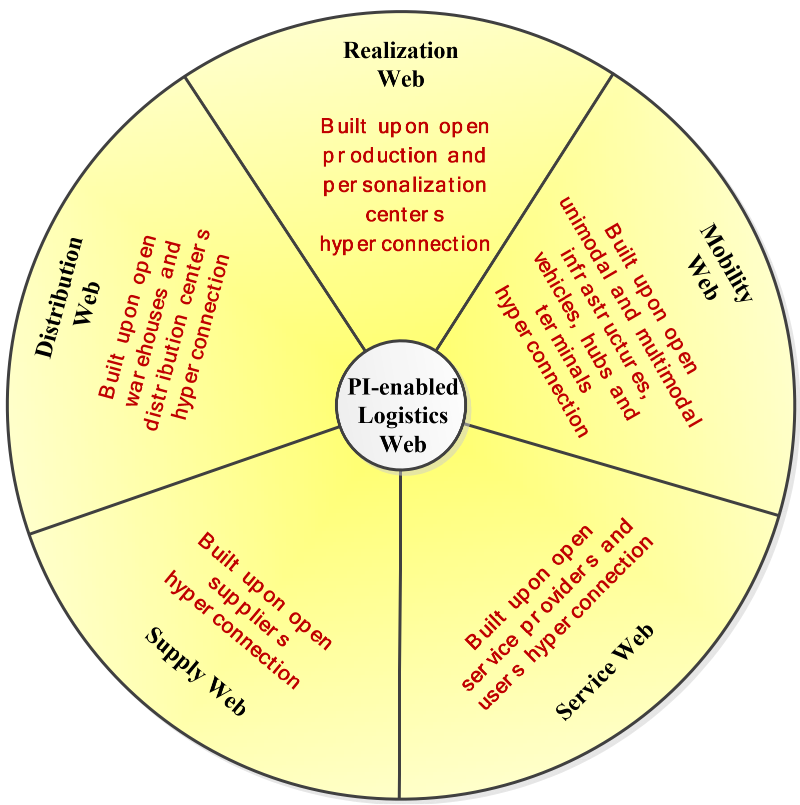


Figure 1-3. Physical Internet enabled Logistics Web and its key constituents (adapted from Montreuil et al., 2013)

In accordance to the subject of this thesis, more insights about the Mobility Web (MW) and the Distribution Web (DW) are provided in the following section.

1.2 PI-enabled Mobility Web

The Mobility Web is enabled by the Physical Internet for the purpose of efficiently and seamlessly moving and handling goods encapsulated in PI-containers between their individual sources and destinations. MW is built upon the hyperconnection of unimodal and multimodal transportation infrastructure, transporters, vehicles, drivers, hubs and terminals (Montreuil et al., 2013). For more insights, let us contrast in this section the conventional truck mobility networks and the PI-enabled truck mobility web.

The conventional truck mobility network is dedicated to a single firm or a group of partnering firms. The dedication can be in the form of infrastructure ownership, lease or outsourcing. In contrast, the PI-enabled Mobility Web is open to all certified PI-users. For instance, the available space in an open truck can be exploited by multiple PI-users for the entire or a part of the truck's shipment path. The trailer of an open truck is unloaded completely or partially in a PI-hub, and then off loaded containers will travel the remaining of the path in other trucks. The decisions regarding the selection of the hub(s) to load/unload PI-containers are controlled and implemented in a distributed manner (Sarraj et al., 2014). Influenced by such an open pooling, the truck filling rate is subject to increase (Ballot et al. 2014). Accordingly, higher filling rates are to result in lower transportation cost, fuel consumption, and GHG emission production.

The Physical Internet intends to improve the quality of life of truck drivers. Montreuil (2011) refers to truck drivers as "*modern cowboys*" whose lives are affected the most by long distance travels and absences from home. Hence, the Physical Internet implements a geographically extended web of open transportation hubs and terminals that are strategically located so that truck drivers can potentially work in short-distance from their hometown. For instance, selecting the location of PI-hubs at the junction of states' border and interstates highway/railroad, gives the drivers the chance to operate inside a single state or within a limited region. Figure 1-4 envisions an open PI-hub backbone network for road transportation mode in US and Canada. The stars indicate attractive potential open hub zones that are strategically located at the intersection of major highways and the border of US States/Canadian provinces. More advanced versions of the backbone network should include many more hub zones to take into account other transportation modes such as air, rail and maritime and the multi modal hubs.

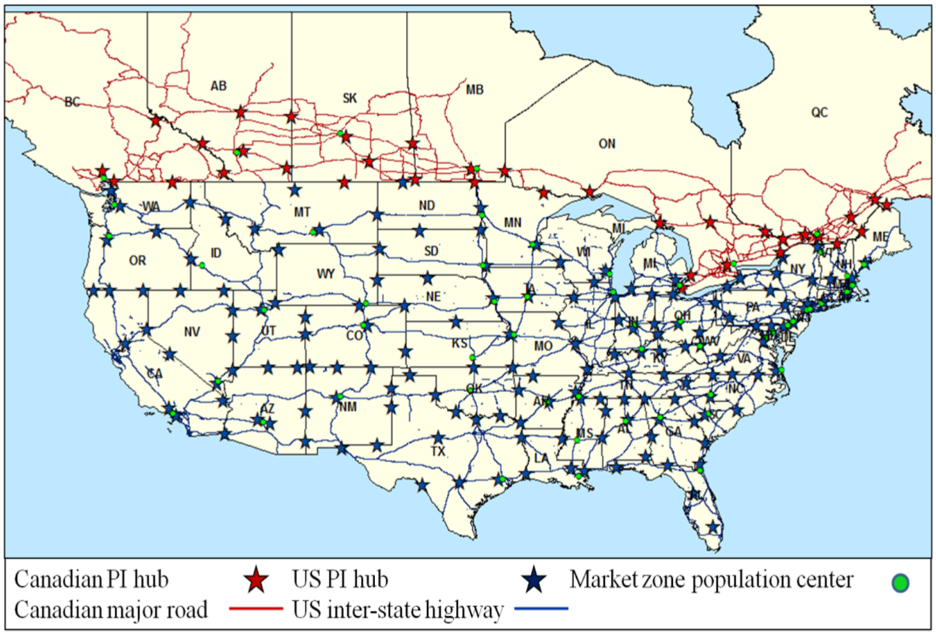


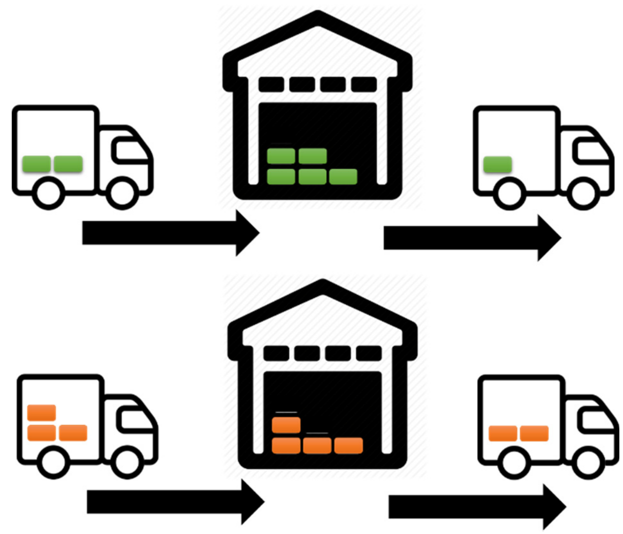
Figure 1-4. Illustrative road-based hub network of Physical Internet-enabled Mobility Web

It should be noted that, businesses may create a combination of dedicated and hyperconnected mobility. Extremes have a business relying only on its own dedicated network and a business relying only on the Mobility Web. Many businesses will take a hybrid position, for example selecting to keep steady full-truckload shipments for their inbound transportation and relying on the MW for the rest.

In chapter 2 and 3, we discuss the benefits of the truck conventional mobility in terms of savings through economies of scale and distance.

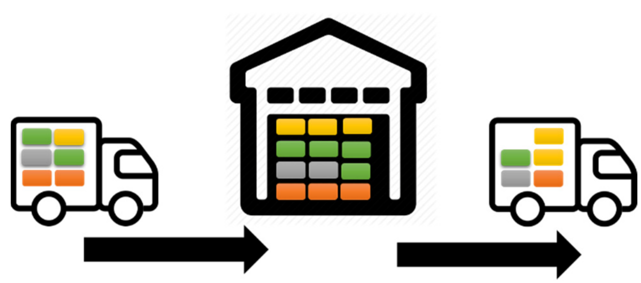
1.3 PI-enabled Distribution Web

The Distribution Web is enabled by the Physical Internet for the purpose of efficient and seamless storage, deployment and cross docking of goods encapsulated in PI-containers. DW is built upon the hyperconnection of users with open distribution centers and warehouses. Similar to our discussion about Mobility Web, conventional distribution networks are dedicated to a single or a group of individual businesses, while capacities and technologies of an open DC can be exploited by any PI-users. Figure 1-5 contrasts a distribution center operated by a single company (part *a*), operated by a group of companies (part *b*) and open to any PI-user (part *c*). It also shows the similar concept for conventional and open truck.



a) Conventional DC operated by a single business

b) Conventional DC operated by a group of partnering businesses



c) PI-enabled open DC exploited by any PI-user

Figure 1-5. Conventional DC and PI-enabled open DC contrast

Suppose that a PI-user connects to the database of the Distribution Web and searches for available open DCs in the cloud. According to Montreuil et al. (2013), a plausible scenario is that a set of openly available DCs would appear in the search result indicating the offered capacity by open DC, availability duration and price. A PI-user interested in an open DC can request to exploit the available capacity partially or entirely. After the agreement of both parties (the open DC owner and user), the capacity requested by the PI-user will be reserved in the open DC for the duration of their agreement.

The open DC can store, pick, move and consolidate the PI-containers belonging to all of its users. High throughput and application of both modular material handling technologies and standard PI-containers enables a high level of efficiency in an open DC. Hence, it is expected that capacity utilization rate of open DCs becomes higher than the conventional DCs and the unitary cost to exploit an open DC would be much lower than conventional DCs.

A real world instance of a nearly open DC can be found in the ES3 distribution facility in York, PA[1]. This is the biggest automated grocery warehouse in USA. It stores around 2000 different items, and its throughput arrives in more than 100,000 boxes per day or 1,300 pallets per day. The complex is 140,000 m^2 at and can potentially store 400,000 pallets. ES3 has established a successful collaborative distribution model, storing and consolidating products of 60 manufacturers, creating seamless operations, providing real-time information and almost 30% reduction in total cost of getting products from manufacturer to retailer for both parties (Hambleton and Mannix, 2014).

Handling of the slow moving products is fully automated and the remaining is handled both automatically and manually (based on the statistics provided by ES3 executives and the supplier of their automation system; SSI SCHAEFER[2]). According to Hambleton and Mannix (2014), ES3's automated material handling system can result in fewer operations, which translate in lower required labor, energy savings (almost 40%) and lower accident rates.

1.4 Conclusion

In this chapter a brief review of Physical Internet principles, particularly related to the distribution and transportation is provided. The full presentation and description of Physical Internet is beyond the scope of this thesis. The reader is invited to consult pioneering PI documents such as Montreuil

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1- http://www.es3.com/
2- http://automation.ssi-schaefer.us/intelligent-automated-case-picking-for-the-distribution-center/

(2011), Montreuil et al. (2013) and Ballot et al, 2014. The website of the research initiative is also regularly updated by the recent progress and findings (www.physicalinternetinitiative.org).

The next chapter defines the research foundations, presents the research questions and goals, and describes the research approach.

Chapter 2

Research foundations and approach

2.1 Introduction

Physical distribution is about channeling the products of a business to its customers. The decisions and operations involved in distribution strongly impact the economy and environment. The costs related to distribution, mainly transportation, inventory holding cost and storage represent almost 90% of logistics operations costs (Rushton, 2010). Moreover, the transportation sector largely contributes to the Greenhouse Gas emission; almost 26% of the total USA emission in 2013 and 24% of Canada's emission in 2011 is accounted for transportation activities (based on US Environmental Protection Agency and Environment Canada). On the other hand, distribution and transportation operations strongly impact the customer service. One of the key business competitive dimensions is customer satisfaction, which results in revenue increase. Based on the discussion above, the distribution is one of the most potentially value adding areas of logistics operations.

Despite its important role, several studies provide evidence of distribution inefficiency and unsustainability. For instance, Montreuil (2011) criticizes the centralization of storage and distribution operations to a few large facilities as it negatively impacts the response time and customer service quality. Frankle (2006) reports that 8.2% of shoppers fail to find product(s) on-shelf and retailers suffer 3.1% net lost sales while huge inventory valued at 1.1 trillion$ have been available. Significant portions of consumer products that are made never reach the right market on time, ending up unsold and unused (Montreuil, 2011). These findings can be simply summarized to the right product is not at the right place at the right time at the right cost in the right quantity!

Moreover, capacities and technologies within the distribution and storage facilities are being poorly used (Montreuil, 2011); Ecklund (2010) indicates the capacity utilization rate of warehouse to be on average 70%. The capacity of transportation fleet is also inefficiently used; almost one-third of kilometers traveled by freight transport vehicles are run empty (McKinnon, 2000) and the mean load factor of road transport is approximately 60% (Sarraj et al., 2014; McKinnon et al., 2010). From social performance perspective, Montreuil (2011) highlights the truck drivers' quality of life; he refers to them as "*modern cowboys*" who are often far away from home for long duration.

This Ph.D. thesis aims to assess a novel distribution system, called Physical Internet-enabled hyperconnected distribution that is claimed to provide means to enhance the efficiency and sustainability of distribution systems by an order of magnitude (Montreuil, 2011; Montreuil et al., 2013).

Through the first part of this chapter, the evolution of distribution systems to the date is reviewed and our categorization of the existing and prospective distribution systems is presented. This categorization serves as the foundation of our research methodology. The second part of this chapter describes the research question and goal and details our research approach.

2.2 Distribution system definition

Inspired by system dynamics (Forrester, 1958; Forrester, 1992), we define the distribution system of an individual business as the logical and physical manifestation of all the strategies, decisions and operations intended for deploying, storing, handling and delivering products. Noteworthy, here by using the term *business*, we refer to an organization that acquires products (whether by producing or purchasing them) and is concerned by their physical distribution. Figure 2-1 represents the distribution system as here defined.

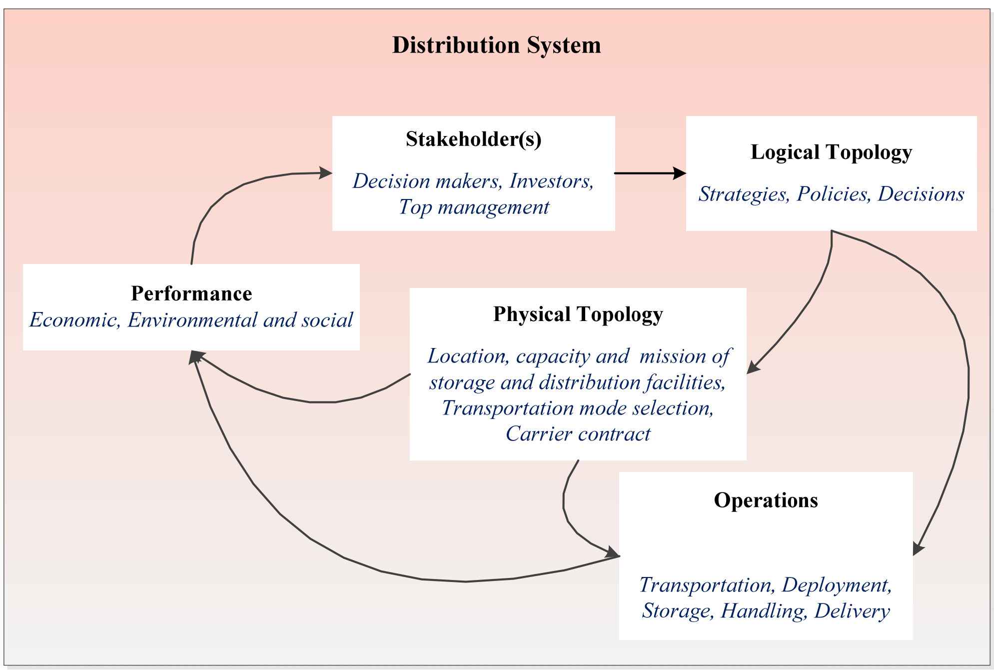

Figure 2-1. The distribution system as a dynamic system

The entities of the distribution system include the stakeholder(s), the physical topology, the logical topology, the operations and the performance. The term *stakeholder* refers to the decision makers and managers whose opinion, decisions and actions impacts the entire system. They can be the owners or investors of a business. Stakeholder(s) define a set of rules and policies for the distribution-related decision making that is called *logical topology*. Following such rules, they form the physical topology by determining the location and mission of various facilities including the distribution center(s) and warehouse(s). The logical and physical topologies of the system prepare the foundation for the distribution operations. The resulting distribution performance provides a feedback, whether in forms of return on investment, distribution-related costs, customer satisfaction or environmental performance, to the stakeholder(s).

2.3 Distribution system evolution

Before 1960, distribution activities were unplanned and unformulated (Rushton, 2010). At this period, management did not view the distribution as an integrated task; thus, it was carried out with a series of fragmented, uncoordinated movement of goods and information (Rushton, 2010). The logistics at this period is called atomistic by Montreuil (2015).

The concept of *physical distribution* as a valid area for managerial involvement was developed in the 1960s and early 1970s. Subsequently, the 1980s was the growth of the Third-Party Logistics Providers or 3PLs (Rushton, 2010). By outsourcing the distribution operations to 3PLs, firms can benefit from reduction in asset investment, labor and equipment maintenance cost, focusing on core competencies and exploiting the external expertise. The globalization trend and increased importance of partnership in staying competitive distinguished the 3PL concept as a differentiator in company's competitive business (Papadopoulou and Macbeth, 1998). Besides its advantages, outsourcing reduces the control of an organization over logistics functions and impacts in-house capability and customer contact (Selviaridis and Spring, 2007).

In late 1980s and early 1990s, the interrelation between distribution-related activities such as transportation, storage, material handling was recognized and the potential for effectively managing them as an integrated task was discovered. Driven by competitive business environment, the integrated logistics management gained momentum (Daugherty et al., 1996). Because of this recognition, the concept of trade-offs between cost and customer service emerged; this preceded by management practices that could reduce cost while improving the customer service. Later, the integrated distribution trend was broadened to encompass beyond the functional boundaries of a single organization, which lead to the Supply Chain Management (SCM) trend. SCM incorporates both internal and external integrations (Daugherty et al., 1996); internally, supply chain management involves working to achieve a seamless logistics integration with other functional areas of the organization. Externally, the trading partners should plan, execute, and co-ordinate logistical performance jointly. Supply chain management is still a popular topic in academia and practice (Fawcett et al., 2014; Stadtler, 2015).

One of the main topics of business conversations in 2000s was the collaboration (Mi et al., 2005). It is referred as *the union of two or more companies sharing the responsibility of exchanging common planning, management, execution, and performance measurement information* (Mi et al., 2005). The main driver of collaboration is to benefit from the synergy between partnering companies and to reach out for levels of performance not achievable individually. There are two types of logistical collaboration: vertical and horizontal. The vertical partnerships are created between firms operating at different levels of the supply chain while in horizontal collaboration partnering companies operate at the same level of the supply chain (Vanovermeire et al., 2014). Scientific research has proven that collaboration implementation has the potential for enhancing the economic and environmental performance of the collaborating companies (Pan et al., 2013; Nagurney et al., 2010; Nagurney, 2009). However, collaboration is inherently challenged by some difficulties. Cruijssen et al. (2007) discuss that several areas such as partner selection, trust, gain division, negotiation, and information and communication technology capabilities trouble the logistical collaboration.

Recently and in line with the advent of Internet and electronic commerce, companies like Amazon.com are rewriting the rules of competition (Kotha, 1998). More precisely, they are offering some customer service initiatives that require highly efficient distribution system such as same day delivery and free same day delivery to prime members in top metropolitan statistics areas (announced in 2015)[1]. Yang (2013) stresses that nowadays the performance dimensions of cost, quality, efficiency and customer service level should be all taken into consideration equally.

In addition to today's highly competitive business environment, there are boundaries on the logistical capabilities, which demonstrate a frontier on distribution performance. Take for instance the limited land available for production and distribution operations (McKinnon, 2009) and expensive and scarce fuel resources (Beamon, 2008).

Physical Internet (Montreuil, 2011; Montreuil, 2012; Montreuil et al., 2013) introduces a novel distribution era; hyperconnected distribution in which businesses exploit the available storage and distribution capacities and technologies belonging to other businesses. According to Montreuil et al.

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[1]-From http://www.logisticsmgmt.com/

(2013), the hyperconnection enables companies to deploy their products close to their geo-markets and eventually offer fast and efficient customer service without the economic burden of high capital investment. The punctuality of the business relationship through hyperconnection, can relax the challenges inherited by long-term commitment involved in logistical collaboration. While a large percentage of operations related to a hyperconnected firm are not performed by them, technologies such as smart PI-container provide visibility and control to Physical Internet users.

Following the evolution of distribution systems discussed here, the next section categorizes the current and prospective distribution systems.

2.4 Distribution system categorization

The eras of atomistic, managerial involvement, outsourcing to 3PLs and integrated distribution, contribute to a system devoted to distributing the products of a single business. It is possible that more than one business operates in this system (e.g. the focal company and 3PLs); however, their involvement is decided and planned by the stakeholders of a single business. Thus, we identify them as *dedicated distribution system*.

The logical topology of businesses adopting dedicated distribution system is called *individualistic*. Such businesses invest in storage and distribution facilities individually and create a chain (having one facility for each function such as storage or production) or network (more than one facility for at least one of the functions) dedicated to their own business. They perform deployment, distribution and transportation independently from other businesses; thus, their operations are called *private*. All the costs related to their distribution system are incurred to the stakeholder(s) of the individual business.

The collaborative distribution era creates the second category called *collaborative distribution system*. In such systems, the partnering companies form a coalition of more than one dedicated system. When a group of partnering businesses create a collaborative distribution system, their logical topology embraces collective goal and behavior. Their physical collaborative topology includes nodes (facilities) and links (operations) which can be exploited by more than one partnering business. However, we distinguish the collaborative physical topology as a *shared web* to stress that the exploitation of this web is limited to the partnering businesses who formed in the first place. Similarly, the logical topology of the collaborative distribution systems limits the pooling of the operations and facilities to the partnering companies; thus, it is called *shared pooling*. The costs and savings incurred in a collaborative distribution system would be divided among the stakeholder(s) of the partnering businesses (stakeholders).

Lastly, the distribution systems of those businesses practicing distribution by exploiting PI-enabled Mobility Web and Distribution Web are categorized as *hyperconnected distribution system*. Based on the idea of exploiting DW and MW in a hyperconnected distribution system, the logical topology of hyperconnected distribution systems is called *open*. Their physical topology would be an *open web*, since it shapes a network of open distribution networks. The distribution-related operations of hyperconnected distribution systems are recognized as *open pooling*. The stakeholder(s) of the single business that exploits DW and MW would be responsible for the total distribution costs. Figure 2-2 depicts the differences between entities of each distribution system category.

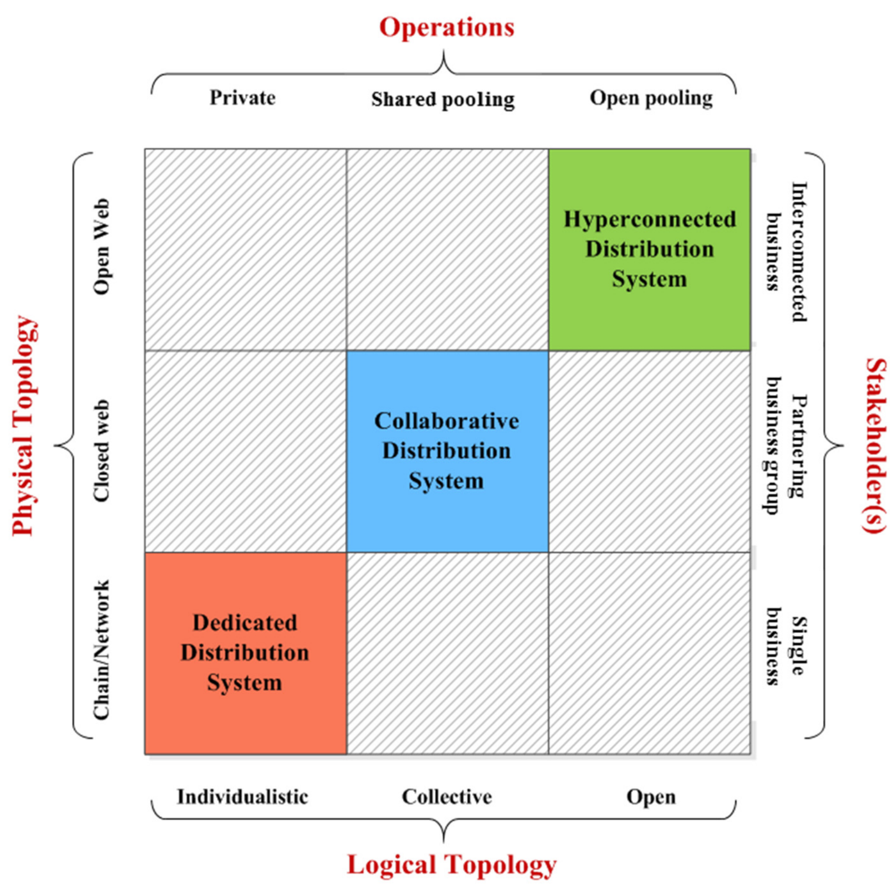
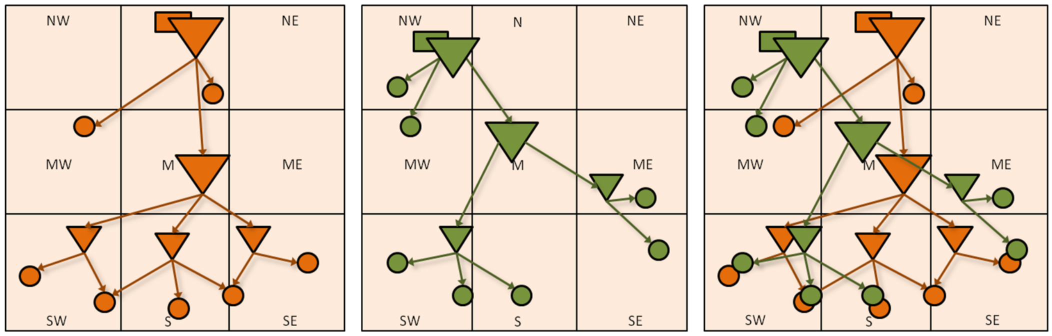
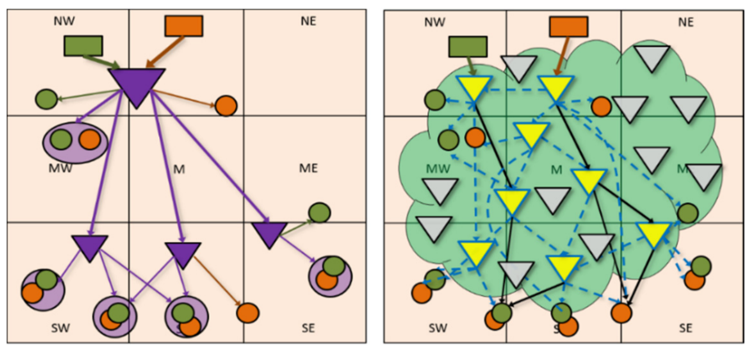


Figure 2-2. The distribution system categorization according to the dynamic system entities

Figure 2-3 contrasts the physical topology of the alternative distribution systems using simple schematics. Part a) and b) respectively depict dedicated distribution networks for businesses A and B. Part c) depicts the juxtaposition of the dedicated networks of businesses A and B: two networks overlap, yet there is no connection between them in terms of product flow or shared facility. Part d) depicts the collaborative distribution web for a coalition between businesses A and B. Within the collaborative web, some of the facilities and transportation flows are operated by only one of the two businesses, while several are shared. Part e) depicts the hyperconnected distribution web exploited by businesses A and B, as well as many other PI-certified businesses. The distribution web is depicted as a cloud in rough analogy with cloud storage, currently a strong trend in the Digital Internet. In such a web, the hyperconnected distribution network of each business becomes much more dynamic, evolving to navigate the variations in supply and demand across the territory. Conventional mobility is represented by plain arrows while the dashed (blue) arrows, represent hyperconnected transportation through the Mobility Web. It should be noted that the topologies depicted in Figure 2-3 do not aim to show optimized networks or webs, but to provide a virtual representation of the concepts discussed previously.



a) Business A, dedicated distribution   b) Business B, dedicated distribution   c) A& B, disconnected distribution



d) A& B, collaborative distribution   e) A& B, Hyperconnected distribution

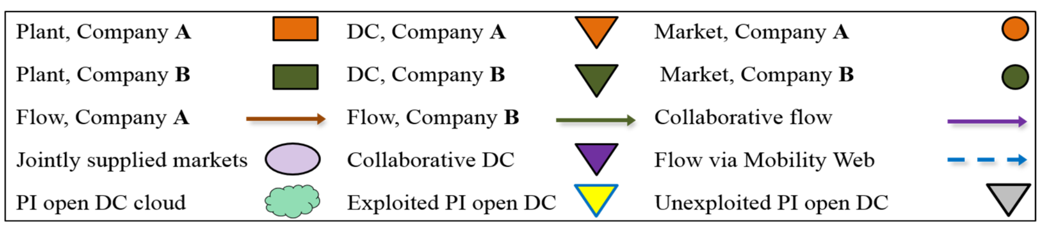


Figure 2-3. Schematic contrast of dedicated, collaborative and hyperconnected distribution systems

(Adapted from Montreuil 2011 and 2012)

Table 2-1 summarizes the evolution of the distribution systems and their categorization.

Table 2-1. The evolution of the distribution era

Time	Distribution era	Distribution system category
< 1960	Atomic	Dedicated
1960s and 1970s	Managerial involvement	
1980s	3PL	
1990s	Integration	
2000s	Collaboration	Collaborative
2009 <	Hyperconnection	Hyperconnected

Based on the research foundations previously presented in this chapter, the next section indicates the questions of this research. They point to the contributions and describe the research methodology.

2.5 Research question and goal

The hyperconnected distribution system is claimed to create potential for drastic economic, environmental and social performance improvements (Montreuil, 2011; Montreuil et al., 2013). The two main questions that have motivated this Ph.D. thesis include:

I. What is the potential economic, social and environmental performance gain by adopting the hyperconnected distribution systems?

II. If the gain is significant, how should a hyperconnected distribution system be planned and managed?

To answer the questions above, the goal of this research is twofold; first, to investigate the potential economic, environmental and social gain enabled by hyperconnected distribution system. Second, it intends to develop conceptual and analytical tools to plan and manage hyperconnected distribution systems.

2.6 Research methodology

An exploratory approach is adopted in this thesis in order to assess the performance of hyperconnected distribution systems through a set of illustrative businesses cases. The economic, environmental and social performance of each business is investigated at existing and prospective distribution systems and the performance gains/loss is analyzed. Our investigation is somehow conservative since we suppose that the dedicated and collaborative systems only have access to the current distribution and transportation capacities and technologies, while hyperconnected system is assumed able to exploit both current and PI-enabled Mobility Web and Distribution Web (shown in Figure 2-3). In real life, the exploitation of MW is not limited only to businesses that exploit DW as well (and vice versa). For instance, businesses can exploit open DCs while employing a dedicated transportation system (owned or outsourced transportation). Similarly, they can run owned or leased distribution centers while using MW for transportation.

Multiple approaches have been used in the literature to investigate the performance gain by collaborative logistical systems. Nagurney (2009) quantifies the strategic advantages associated with horizontal collaboration applying a system-optimization perspective. The pre-merger and horizontal-merger transportation networks of two sample firms are optimized and the total transportation costs are compared. Pan et al. (2013) explore the economic and environmental effect of distribution pooling for two French retailers using optimization model at the strategic level. Ghaderi et al. (2012) examined the effect of successful horizontal collaboration among a group of small and medium size enterprises by data collection through quantitative questionnaires. Sarraj et al. (2014) apply multi-agent simulation to assess the efficiency of exploiting PI-enabled mobility web. They develop several transportation and consolidation protocols to enable exploiting mobility web, then simulate both the current and hyperconnected transportation system of two French retailers and their top 106 suppliers.

In this research, optimization is used as the main investigation approach; network modeling helped us to estimate the costs associated with each distribution system at strategic level. Furthermore, the topology of the optimized network/web helped us to assess the associated environmental performance respecting a target social performance. The reason behind selecting optimization is twofold; first, our goal is to reach preliminary results, which can either encourage or discourage hyperconnected distribution systems. For this purpose, optimization at strategic level has been widely applied. Second, other approaches such as simulation, requires more insights about the deployment and distribution practices at operational level. Contrary to the distribution operations of the dedicated and collaborative systems, the hyperconnected distribution operations were unknown for us at the time of performing the investigation.

Hence, in our investigation, first a core modeling approach is developed. Then, it is adjusted to the characteristics of each distribution system to develop three distribution system-driven optimization models. All the optimization models are single-product, single period and deterministic mixed integer programming (MIP) problems. Afterward, a set of illustrative business cases are developed.

Employing the distribution system-driven MIPs, the distribution network/web of these businesses are designed responding to a set of predetermined policies for customer service. Using a set of Key Performance Indicators (KPIs), the economic and environmental performance of each businesses is obtained and analyzed over each distribution system-service level strategy.

In our quest to reply the second research question, we have developed a conceptual planning framework and a set of analytical tools that can be applied to a future simulation study of hyperconnected distribution assessment.

Figure 2-4 presents the methodology applied in this research.

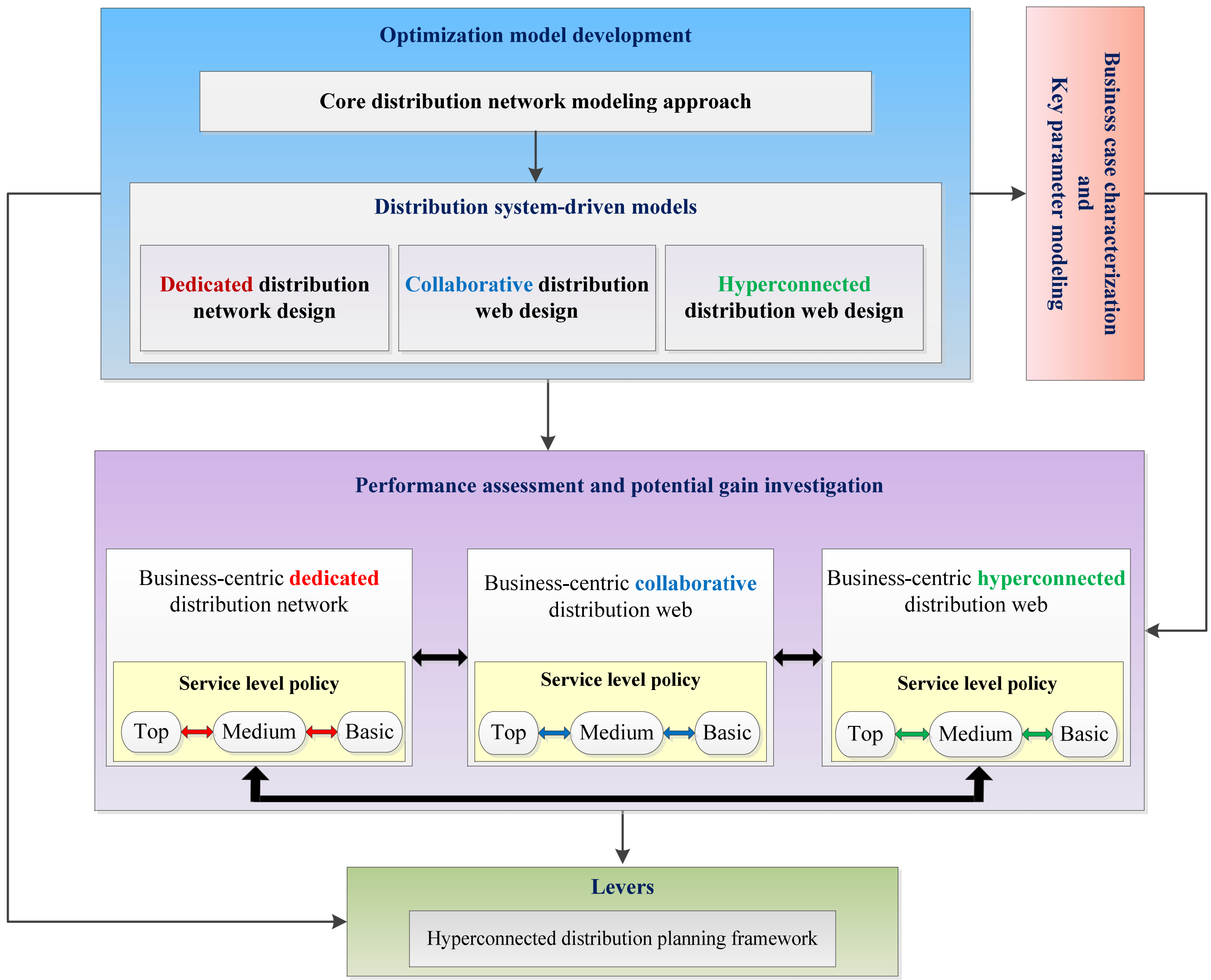


Figure 2-4. The research methodology through four major contributions

2.7 Research challenges

While addressing the research questions, we faced several challenges mainly raised from the modeling aspect. The characterization of the distribution system user was a demanding task. A large amount of time and effort were invested in this part of research. Particularly, modeling the hyperconnected distribution system was complex; since at the time that this Ph.D. thesis was conducted, the Physical Internet and Logistics Web were in their infancy.

Designing the collaborative distribution webs and dividing the savings between partnering businesses were complicated. It was our intention to follow the core modeling approach and adjust it to the characteristics of each distribution system in order to develop distribution system-driven models. Thus, taking into consideration the effect of transportation pooling in a single-period strategic design model required a meaningful anticipation of the operational level. In addition, developing an efficient method to divide the savings fairly among the partnering businesses is one of the concerns in logistical collaboration modeling. Since the performance gain between multiple distribution systems are to be compared in this research, our approach had to be able of taking into account the potential benefits available for businesses if they operate solely instead of collaboratively.

Furthermore, the modeling and calibration of transportation and distribution costs required data gathering from multiple sources. It was also crucial to adapt the parameter modeling to the characteristics of each distribution system.

The fine-tuning of the solver parameters (here CPLEX), was another challenging aspect, because the optimization models are NP-hard. On the other hand, modeling the operational level details has increased the number of variables, constraints and more importantly the non-zero coefficients. Furthermore, application of piecewise linear cost functions in the objective function intensified the difficulty of solving the optimization problems. These functions linearize the transportation and DC opening and warehousing costs which are modeled as non-linear parameters. At last, the analysis of large amount of numerical results obtained by our experimentation for several businesses and multiple customer service targets required precision to derive meaningful conclusions.

By overcoming the research challenges, we provided answers to the research questions and contributed to the network modeling, optimization and Physical Internet research areas as listed in the following section.

2.8 Research contributions

By overcoming the previously discussed challenges, this thesis contributes to (a) Physical Internet and (b) Distribution/Supply Chain Modeling and Optimization fields.

a) Physical Internet:

- Systematic performance investigation
- Hyperconnected distribution planning framework

b) Distribution/Supply Chain Modeling approach and Optimization:

- Core distribution network design modeling approach
- Three distribution system-driven models
- Transportation modeling
- Formulation of stochastic hyperconnected distribution web design model
- Development of nonlinear functions
- Development of coalition savings division approach
- The business case development and parameter estimation
- Environmental performance assessment approach

Table 2-2. summarizes the main blocks of our research approach.

Table 2-2. Summary of the main research blocks

Research motivation
• Investigate the potential gain by adopting hyperconnected distribution system • Provide conceptual and analytical tools to plan and manage hyperconnected distribution systems
Research challenges
• Characterization of the user level (anticipation of the operational level) • Collaborative distribution web design and savings division approach • Parameter modeling for status-quo and hyperconnected distribution system • Solve the large MIPs obtained efficiently • Interpret and analyze the large information provided by MIP solutions
Research contributions
• Physical Internet field • Distribution/Supply Chain Modeling and Optimization field
Research results/vision
• The magnitude of performance gain by exploiting the hyperconnected distribution system • Conditions and assumption • Levers

Chapter 3

Optimization model development

3.1 Introduction

The goal of developing optimization models in this chapter is to design the distribution network of a set of business cases by adopting the principles of the dedicated, collaborative and hyperconnected distribution systems and eventually, assess their economic and environmental performance.

Distribution Network Design Problems involve strategic decisions on the number, location, capacity and mission of a set of distribution centers, their allocation to a set of demanding customers while optimizing the performance of the entire network by either minimizing the total associated costs or maximizing the profit (Klibi et al., 2010). Model formulations and solution algorithms which address this issue vary widely in terms of fundamental assumptions, mathematical formulation and solution approach.

In this section, first the literature of the discrete facility location problem, particularly the Mixed Integer Programming category to which our model belongs, is reviewed. Then, the context of the problem on hand is described and our core modeling approach is provided. Three system driven models are derived from the proposed core modeling approach.

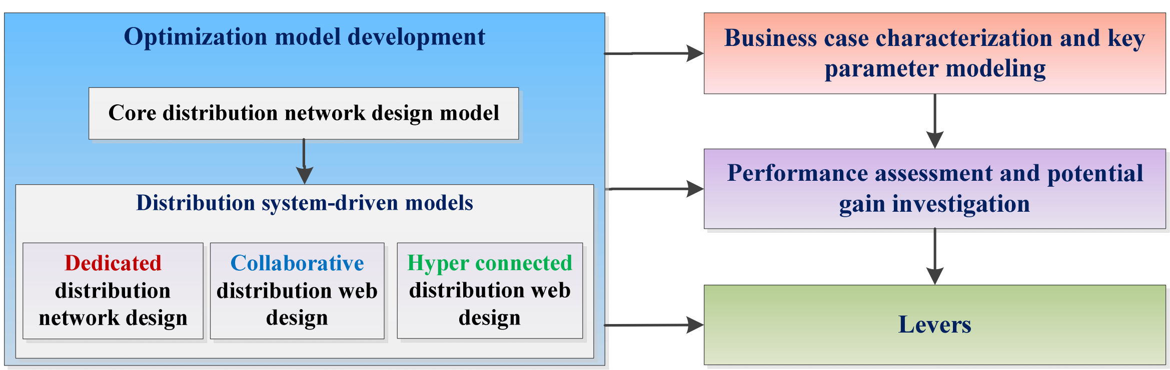


Figure 3-1. Optimization phase within the research approach

3.2 Literature review

The strategic decision to design the distribution network, mainly involves decisions regarding the location of distribution and storage facilities. Facility location is a well-established field within Operations Research. More than a century ago, Weber pioneered the Location Theory. He searched for the location of a single facility to be served by two sources and to supply a single market while minimizing the total transportation cost (English translation of the original work in 1909 in German: Weber and Friedrich, 1929). In 1960s, Hakimi extended the location theory by developing the *p*-median problem, where *p* facilities have to be located on a graph such that the sum of distances between the nodes of the graph and the nearest facility is minimized (Hakimi 1964 and 1965). Since then, various forms of location models have been created.

Facility location problems can be categorized as continuous and discrete. The solution space of the first category is continuous; thus, facilities can be located on any point in the solution plane. Moreover, the distance between points is measured while solving the model applying a suitable metric (such as Euclidean distance metric). Discrete facility locations however, locate facilities among a predetermined set of potential sites. Klose and Drexl (2005) divide this category of models into Network Location models and Mixed-Integer Programming models (MIP). The former includes models inspired by *p*-median to locate a predetermined number of facilities on a graph while minimizing the total distance in the network. While MIP models go beyond simply minimizing the total distance by taking into account various decisions such as production/storage, capacity acquisition, customer service level, transportation mode selection and integration of tactical and operational decisions in the strategic facility location problem.

Several classification and revision of facility location models exist in the literature. Owen and Daskin (1998) and Drezner and Hamacher (2002) review the early works in this field. Furthermore, Geoffrion and Powers (1995) and Shapiro et al. (1993) discuss the evolution of the strategic supply chain design models. For more recent reviews, the reader is referred to Şahin and Süral (2007), Klibi et al. (2010) and Arabani and Farahani (2012).

Since our core modeling approach will be aggregating operations on the planning horizon without loss of generality, the focus of our literature review is given to the single period models. Klibi et al. (2015) discuss that when the demand behavior is more stable, a single period model can provide near optimal solution.

The single-period network design MIPs in the literature, mostly incorporate cost minimization objective function. However, these models vary in terms of fundamental assumptions, mathematical formulation and solution approach. Jayaraman and Ross (2003), Geoffrion and Grave (1974) introduce single-echelon multi-product distribution network design models where, the costs are modeled as linear parameters and customers are single-sourced. The former is solved by Simulated Annealing and the latter, by Bender Decomposition. Syarif et al. (2002) develop a single-echelon single-product production and distribution network design problem with linear costs and multi-sourcing. They have solved the problem with a spanning tree-based genetic algorithm.

Some contributions involve more precision in modeling cost parameters. Amiri (2006) has developed a single-product multi-sourcing problem with non-linear DC opening costs. Baumgartner et al. (2012) and Fleischmann (1993) modeled warehousing and transportation cost by taking into account the economies of scale. Shen and Daskin (2005) modeled the inventory and safety stock cost as nonlinear functions. Tsao and Lu (2012), take into account the impact of both economies of distance and scale on the transportation cost. The latter does not model these nonlinearities simultaneously; the economies of scale is only associated with the inbound transportation and the economies of distance, solely with the outbound (DC-to-Market zone flow).

Several single-period contributions have introduced transportation modeling. In Sadjady and Davoudpour (2012), the transportation mode selection is invoked by the monetary value of the overall lead time in addition to the cost. The latter has also introduced a capacitated version of the model where transportation modes are attributed a total volume/weight-based capacity. However, the application of the model is uncapacitated. The single-period network design model developed by Eskigun et al. (2005) pre-assigns rail transportation to inbound links and road transportation, to the outbound. However, shipping through a DC or directly to the customer is influenced by the monetary value of the lead time. In Cordeau et al. (2006), the space required by each product is constrained to the available capacity offered by each mode on each network link. However, in the numerical application the link capacity is not binding the flow (serves as a “big M”). Thus, on each transportation link, the cheapest mode is selected. Lapierre et al. (2004) involves direct and indirect transportations (through a transportation/consolidation center) costs. The characteristics of transportation cost function for various options including truckload, less than truckload and parcel is detailed. However, no modeling effort is devoted to the selection of the transportation option in the mathematical model.

The customer service has been modeled in several single-period models. Amrani et al. (2011) ensure the customer service quality by applying an upper bound on the permitted distance between DC and customer. Eskigun et al. (2005) model the customer service by embedding the monetary value of the total lead time in the minimization objective function. In Ambrosino and Scutella (2005) customers are classified based on their demand level. The customer service is modeled by ensuring a minimum inventory level at each DC influenced by the classification of customers supplied by it to guarantee product availability especially for the most valued customers.

Only a few models in this category consider two-echelon storage and distribution settings. Sadjady and Davoudpour (2012) model storage at plant and warehouse and Ambrosino and Scutella (2005), in both regional and central DCs.

In addition to designing the physical structure, network design models have been applied to investigate the impact of managerial insights on overall performance. Particularly, single-period deterministic models serve this purpose, since they can be fairly easy to solve. For instance, Nagurney (2009) explores the strategic advantages of merging supply chain networks by comparing the total cost of two firms before and after being merged. The total cost however, has been calculated by modeling the economic activities of firms with a single-period network design model.

The ease of solving single-period models is unwantedly accompanied by lower accuracy of anticipating the user response to design decisions. Klibi and Martel (2015) argue that the transportation quantity in these models, can easily fall into bulky transportation modes such as truckload, which incur lower cost compared to less than truckload. To our knowledge, anticipating transportation operations at operational level is poorly addressed in single-period network design problems to date. Regardless of some modeling efforts and usage of real world data, often, the model simply selects the cheapest transportation mode available. Moreover, estimating the costs associated with them is challenging. Since distribution-related costs manifest nonlinear behavior, the accuracy of their estimation strongly depends on the quality of user response anticipation.

Table 3-1 summarizes our review of several single-period Distribution Network Design models. The intention of providing this table is to highlight the diversity of modeling assumptions, approaches and solution algorithms within this group of models for the rather than offering a taxonomy or literature classification. Besides, this table can indicate the current gap in literature and underline the value contributions of our model.

Table 3-1. The modeling aspects incorporated in a selected set of single-period MIP distribution network design models

Selected Reference / Modeling Aspect	**Geoffrion and Grave** (1974)	**Fleischmann** (1993)	**Cole** (1995)	**Tsiakis et al.** (2001)	**Nozick and Turnquist** (2001)	**Syarif et al.** (2002)	**Jayaraman and Ross** (2003)	**Eskigun et al.** (2005)	**Ambrosino and Scutella** (2005)	**Shen and Daskin** (2005)
Objective function (**Min**imize cost/ **Max**imize profit)	Min	Min	Min	Min	Min	Min	Min	Min	Min	Min
Number of product (**S**ingle/**M**ultiple)	M	M	M	M	S	S	M	S [6]	S and M [9]	S
Type of facility to locate (DC/Plant/Hub)	DC	DC & Hub	DC	DC	DC	Plant & DC [4]	DC & Hub [4]	DC	DC & Hub	DC
Facility capacity (**C**apacitated/ **U**ncapacitated)	C	C	C	C	U	C	C	C	C	U
Number of facility echelon to locate	1	2 (DC) & 1(hub)	2	2	1	1	1	1	2	1
Demand behavior (**D**eterministic/ **S**tochastic)	D	S	S	Both are provided	S	D	D	D	D	S
Customer sourcing (**S**ingle/**M**ultiple)	S	S	S [2]	S	S	M	S [5]	S	M	S
Customer service	X	√ [1]	√ [1]	X	√ [3]	X	X	√ [7]	√ [10]	√ [11]
Cost modeling	All linear	Nonlinear DC and transportation cost	Nonlinear DC cost	Nonlinear transportation cost	Nonlinear DC cost	All linear	Nonlinear transportation cost	Nonlinear transportation cost	All linear	Nonlinear inventory and transportation cost
Transportation mode selection	X	X	X	X	X	X	X	√ [8]	X	X
Solution approach	Bender decomposition	Iterative linearization technique	Commercial Solver	Commercial Solver	Hybrid heuristic	Genetic algorithm	Simulated Annealing	Lagrangian heuristic	Commercial Solver	Genetic algorithm-based

Table 3-1. The modeling aspects incorporated in a selected set of single-period MIP distribution network design models (continued)

Selected Reference / **Modeling Aspect**	**Cordeau et al.** (2006)	**Amiri** (2006)	**Yang et al.** (2007)	**Shu et al.** (2010)	**Park et al.** (2010)	**Amrani et al.** (2011)	**Sadjady and Davoudpour** (2012)	**Tsao and Lu** (2012)	**Baumgartner et al.** (2012)
Objective function (**Min**imize cost/ **Max**imize profit)	Min	Min	Min	Min	Min	Min	Min	Min	Min
Number of product (**S**ingle/**M**ultiple)	M	S	S	S	S	M	M	S	M
Type of facility to locate (DC/Plant/Hub)	Plant & DC	Plant & DC	DC (4)	DC	Plant & DC	Plant & DC	Plant & DC	DC	DC
Facility capacity (**C**apacitated/ **U**ncapacitated)	C	C	C	U	C	C	C	U	U
Number of facility echelon to locate	1	1	1	1	1	1	1	1	1
Demand behavior (**D**eterministic/ **S**tochastic)	D	D	S	S	S	D	D	S	D
Customer sourcing (**S**ingle/**M**ultiple)	M	M	M	S	S	S	M	S	M
Customer service	X	X	X	X	X	√ (1)	X	√ (16)	X
Cost modeling	All linear (12)	Nonlinear DC cost	fuzzy DC and inventory turnover cost	Nonlinear DC operating cost (14)	Nonlinear inventory cost	Nonlinear inventory cost	All linear	Nonlinear inventory and transportation cost	Nonlinear DC and transportation cost
Transportation mode selection	√ (13)	X	X	X	X	X	√ (15)	X	X
Solution approach	Bender decomposition and valid inequalities	Lagrangian heuristic	Tabu search	Column generation	Lagrangian heuristic	Variable neighborhood search	Lagrangian heuristic	Two-phase approximation technique	Iterative linearization technique

(1) By applying an upper bound on the permitted distance between DC and customer

(2) Each warehouse has a single source per product and each customer is supplied by one warehouse per product

(3) By incorporating the stockout cost into the fixed DC opening cost and assigning a weight to the uncovered demand in the objective function.

(4) To respect the available budget for investing in new facilities, the number of selected facilities should be less than an upper bound.

(5) Single sourcing limitation is imposed in the strategic problem (P1) and it is relaxed in the operational problem (P2).

(6) The model is single-product; however, a unique product is produced at each plant. Each market demands one type of product. In other words, this problem is multi-product but each plant only produces one of the products.

(7) By taking into account the monetary value of the total lead time in the minimization objective function.

(8) Transportation mode selection is invoked by the monetary value of the overall lead time.

(9) In this paper both single and multi-period formulation of the problem are provided.

(10) Customers are classified based on their demand level. The customer service is modeled by ensuring a minimum inventory level at each DC. The quantity of the minimum inventory is influenced by the classification of customers supplied by it to guarantee product availability especially for the most valued customers.

(11) Measured by the fraction of the demand located within a specified distance from supplying DC.

(12) Authors suggest replicating sites and links with different costs to represent discounts available at a specific location or transportation links.

(13) The model incorporates multiple transportation modes. However, the characteristics of transportation modes are not modeled and their selection only depend on the associated cost (i.e. always the cheapest mode would be selected).

(14) DC opening decision incurs a fixed deterministic cost in the first-stage model. However, DC operating cost depends on the inventory and order quantity which are second-stage and scenario-based variables. Thus, in this model these two DC-related costs are separated and modeled differently.

(15) Transportation mode selection is modeled by assigning a lead time, cost and service frequency to each mode.

(16) Service level is incorporated in the safety stock quantity.

Our literature review shows that existing research has addressed subsets of the factors that are crucial in designing distribution networks. However, previous research has not addressed all of these simultaneously, i.e., transportation mode selection, customer service quality and multi-sourcing, impact of economies of scale in DC opening and warehousing, economies of scale and distance on transportation cost. We aim to fill this gap here.

3.3 Core modeling approach

In a single-period planning horizon, the strategic decision to select a set of distribution centers should be made at the beginning of the horizon and kept unchanged. However, other such as transportation and inventory holding, are unknown at the time strategic decisions should be made. Thus, inspired by Klibi et al. (2015), our modeling approach embeds the anticipation of the operational level decisions in the strategic level decision making. Figure 3-2 presents our modeling approach.

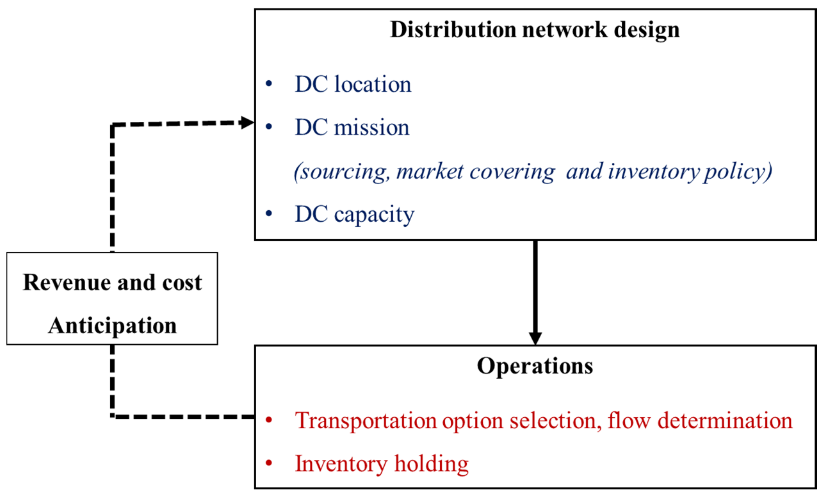


Figure 3-2. An anticipation-based modeling approach (based on Klibi et al., 2015)

This section starts by defining the structure of the distribution network to be designed. Furthermore, it introduces our modeling approach, assumptions and formulation.

3.3.1 Planning horizon

In capital intensive industries, decisions regarding the investment in new facilities require explicit consideration of a planning horizon of as long as ten years (Martel, 2005). However, according to Klibi et al. (2010), supposing that distribution centers are leased in yearly basis, it is sufficient to set the planning horizon length to one year. Melo et al. (2009) discuss that a single-period model may be enough to find a robust network design as well as a robust set of tactical/operational decisions.

3.3.2 Distribution network structure

In the Make to Stock context considered here, the flow of finished products starts from a source, referred to as *plant*. The activities involved in the product acquisition are not modeled here. Thus, the plant can be a production center or simply a former distribution platform. Let $p \in P$ denote the set of plants, then b_p represents the capacity or availability of product at plant p during the planning horizon. It should be noted that the storage function is not defined at plant.

The market location represents a group of geographically aggregated customers, called *market zone*. The annual demand of market zone z is assumed deterministic with a constant rate. Let $z \in Z$ be the set of market zones and d_z the annual demand of market zone z. The set of potential distribution center sites is denoted by $l \in L$. It is assumed that there is no status-quo distribution center at the beginning of the planning horizon. The potential DCs are characterized to obtain a single mission indicated by echelon $e \in E$. First-echelon DCs (e-1 DC) are supplied by plant(s); they keep higher inventory compared to the second echelon DCs (e-2 DC) and they supply both market zones and e-2 DCs. The second echelon DCs are only supplied by e-1 DCs and they only supply market zones. The technical and economical characteristics of a distribution center can be specified with a facility configuration (similar to Martel, 2005; Amiri, 2006 and Amrani et al., 2011). As depicted in Figure 3-3, the distribution network links represent the transportation flow from plant to e-1 DC, e-1 DC to e-2 DC and e-1 or e-2 DC to market zone. No lateral transshipment between DCs of the same echelon is considered.

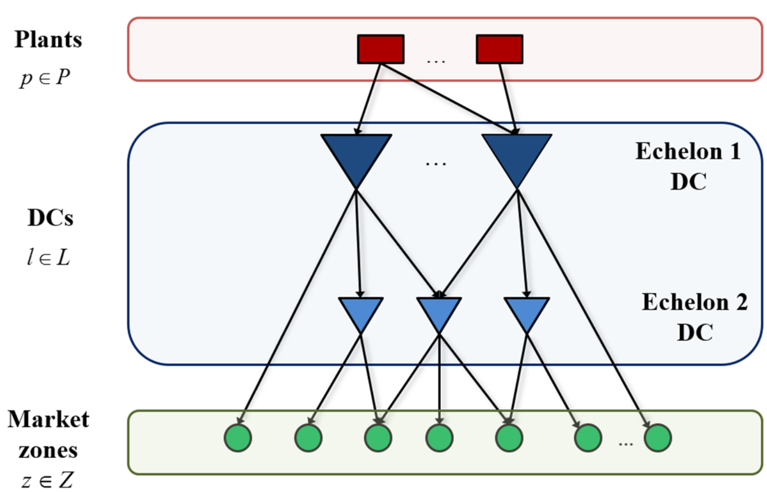


Figure 3-3. The distribution network structure

Let us denote the set of DC configurations $g \in G$; then b_g presents the DC storage capacity available within configuration *g*. We define the following binary decision variable:

O_{lg}^{e} : Equal to 1 if DC *l* is opened at echelon *e* and configuration *g* and zero otherwise.

Noteworthy, a selected DC can take only one mission. Hence, the following constraint set should be respected:

Single echelon-configuration per DC:

$$\sum_{e,g} O_{\mathrm{lg}}^{e} \leq 1 \qquad \forall l \in L \quad (3.1)$$

The road transportation by truck is the only transportation mode considered in our study; it is assumed that businesses do not own the fleet. The cost charged by transportation carrier varies by different shipment weight/volume through. Hence, four shipment options are modeled including single-drop Truckload (TL), Multi-drop Truckload (MTL), Less than Truckload (LTL) and exploiting PI-enabled Mobility Web (MW).

Here, the origin of full truck shipments is a single point, then they travel either a direct path to a specific destination (single drop TL) or a tour between a set of destination locations (multi-drop TL). The LTL shipments are moved through the hub and spoke network of 3PL carrier. Shipments sent by exploiting the PI-enabled Mobility Web travel through a web of open PI-hubs and terminals. The transportation by each shipment option is schematically illustrated in Figure 3-4, part a, b, c and d.

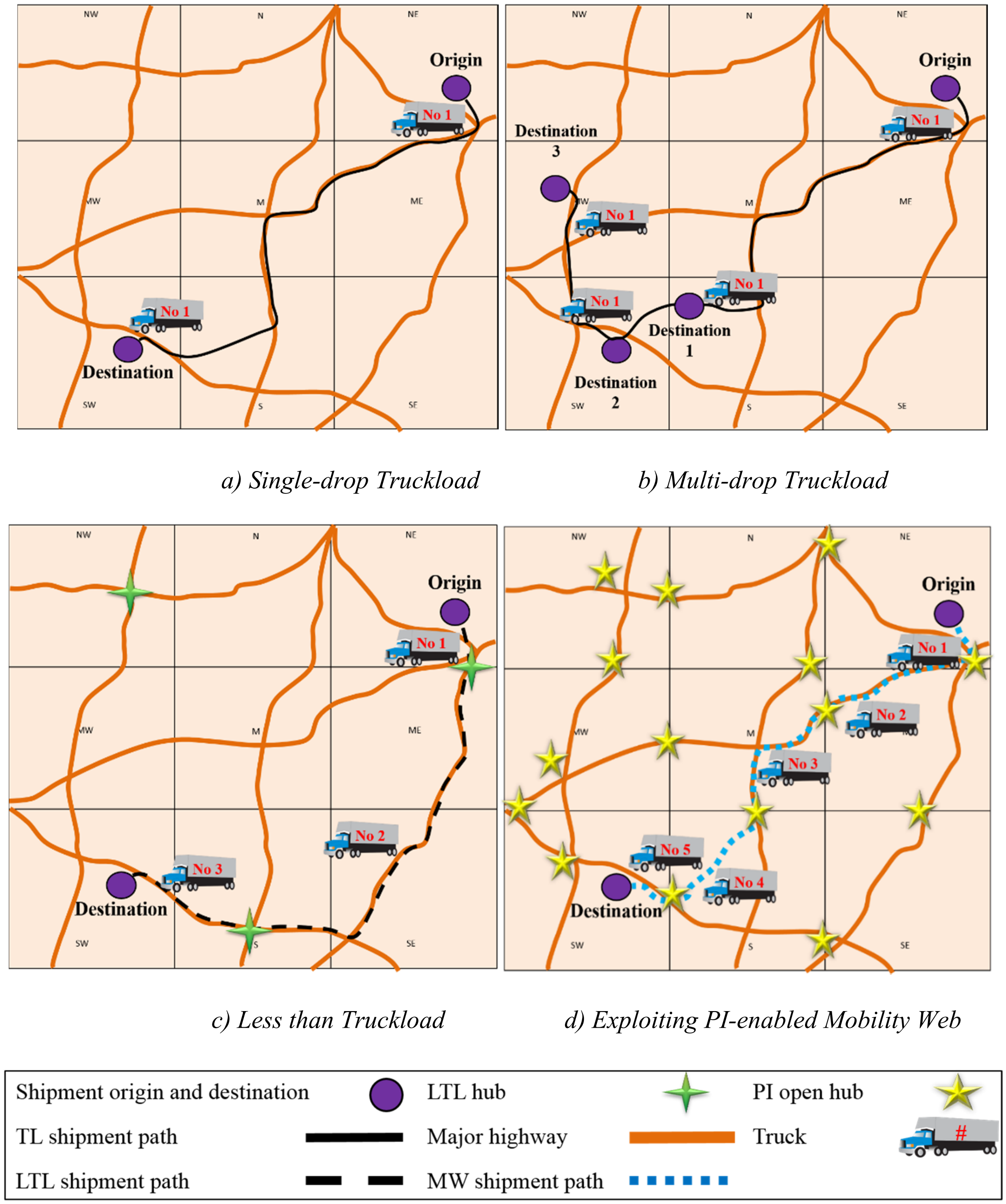


Figure 3-4. Schematic contrast of shipment options defined here

Let $m \in M$ be the set of shipment options. The following decision variables are defined:

$T_{pl}^{m}, T_{ll'}^{m}, T_{lz}^{m}$: Transportation flow quantity by shipment option *m* from plant *p* to DC *l*, from DC *l* to DC *l'* and from DC *l* to market zone *z* over the planning horizon.

In order to respect the network structure defined above, the following constraints should be added to the optimization model.

Outbound flow is allowed from opened DCs:

$$\sum_{z,m} T_{lz}^{m} \leq N \sum_{e,g} O_{\lg}^{e} \qquad \forall l \in L \quad (3.2)$$

E-1 DC is supplied only by plant(s):

$$\sum_{p,m} T_{pl}^{m} \leq N \sum_{g} O_{\lg}^{1} \qquad \forall l \in L \quad (3.3)$$

Only e-1 DC supplies e-2 DC(s):

$$\sum_{l' \in L-\{l\},m} T_{ll'}^{m} \leq N \sum_{g} O_{\lg}^{1} \qquad \forall l \in L \quad (3.4)$$

E-2 DC is supplied only by e-1 DC(s):

$$\sum_{l' \in L-\{l\},m} T_{l'l}^{m} \leq N \sum_{g} O_{\lg}^{2} \qquad \forall l \in L \quad (3.5)$$

Constraints (3.2) ensure that market zones are allocated only to the DCs, which are already opened (regardless of their echelon). Constraints (3.3) ensure that only e-1 DCs are sourced by the plant. Constraints (3.4) indicate that DCs supplying other DCs are first echelon. Similarly, constraints (3.5) identify DCs sourced by other DC(s) as the second echelon. These two constraints are necessary to avoid transshipment among DCs of the same echelon.

3.3.3 Modeling service level

Market zones are classified according to their annual demand. Notably, a service level (SL) is associated to each market in terms of response time that is influenced by their classification. In other words, higher demand markets are more competitive, thus a positioning with higher service level is crucial. In order to implement the SL requirements in the optimization model, a maximum distance between DC and market zone should be respected. Let τ_z denote the predetermined service level required by market zone *z*; then $L_z^{\tau_z}$, $Z_l^{\tau_z}$ the subset of DCs allowed to serve market zone *z* and the subset of market zones, which can be potentially served by DC *l* respecting service policy τ_z . It should be noted that back order and lost order are not permitted and the entire market demand should be satisfied. Hence, the following constraint set should be respected.

Market demand satisfaction:

$$\sum_{l \in L_z, m} T_{lz}^{m} = d_z \qquad \forall z \in Z \quad (3.6)$$

3.3.4 Modeling inventory holding policy

The average inventory quantity is determined as a percentage of DC's annual throughput. We define the following decision variable:

I_l : Average inventory level at DC *l* over the planning horizon.

Supposing a linear relationship between annual throughput and average inventory level, we apply factor f_e^b to convert the DC throughput to the average inventory quantity at echelon *e*. The e-1 DCs are modeled to keep higher level of inventory and lower turnover rate (e.g. once per month or season), while e-2 DCs keep lower inventories with higher turnover (e.g. once a week or bi-weekly). In other words, $f_{e=2}^b < f_{e=1}^b$ .The distinction in terms of the inventory level aims to avoid magnifying the quantity of inventory kept in the two-echelon distribution network. Usually, businesses acquire higher storage capacity than average estimated inventory. Hence, factor f^i is applied to convert the annual average inventory to the maximum required storage space. Two constraints below should be added to the optimization model:

Average inventory level lower bound:

$$f_{e=1}^b \sum_{p,m} T_{pl}^m + f_{e=2}^b \sum_{l',m} T_{l'l}^m \le I_l \qquad \forall l \in L \quad (3.7)$$

Storage capacity respect:

$$I_l \le \sum_{e,g} f^i b_g O_{lg}^e \qquad \forall l \in L \, (3.8)$$

3.3.5 Modeling transportation flow and shipment option selection

As previously described, the transportation flow initiates from the plant, where the product availability is subject to a maximum capacity. Constraint set (3.9) guarantee that this capacity is respected.

Production capacity respect:

$$\sum_{l,m} T_{pl}^{m} \leq b_{p} \qquad \forall p \in P \quad (3.9)$$

Assuming the inventory level at the beginning of a year is equal to the end of the year, constraints set (2.10) balance the transportation flow to and from a DC.

Transportation flow balance:

$$\sum_{p,m} T_{pl}^{m} + \sum_{l' \in L-\{l\},m} T_{l'l}^{m} = \sum_{l' \in L-\{l\},m} T_{ll'}^{m} + \sum_{z,m} T_{lz}^{m} \qquad \forall l \in L \quad (3.10)$$

The shipment option selection is an operational level decision. In order to select the shipment option, essentially the transportation quantity at operational level should be estimated. Here, we suppose that when the quantity of the anticipated daily flow on any network link is at least equal to the maximum number of pallets allowed in a full truck (respecting the maximum weight regulation), a full truck shipment option (TL/MTL) should be selected and a non-restricting shipment option (LTL/MW) otherwise. We identify LTL and exploiting MW as non-restricting modes because in our modeling approach, their incorporation does not require a minimum flow. Similarly, in real practices, shipping with LTL requires no minimum quantity.

In order to anticipate the transportation quantity at operational level, the transportation flow over the planning horizon is divided to the transportation frequency. It is assumed that the frequency of inbound and DC-to-DC shipments is once per day. Thus, the annual transportation flow on each network link can be divided to the number of working days in a year to obtain the average daily flow.

A precision is made regarding the frequency of outbound shipments to take into account the opportunity of consolidation. When a market zone is located in shorter distance from the supplying DC than the distance imposed by their required service level, shipments to this market can be delayed and consolidated. For instance, when a market zone requires 3-days response time but is supplied by a DC located in 1-day response time, this customer can be served once every three days. Hence, instead the frequency of transportation would be number of workdays over the planning horizon divided by 3. When the frequency is decreased the anticipated transportation quantity at operational level, increases. This can impact the selection of a full truck option instead of non-restricting option. The consolidation opportunity is modeled by applying f_{lz}^{c} factor that is indeed the actual distance between DC *l* to market zone *z* divided to the distance representing the service level required by market zone *z*. since the distance and target response time are known before solving the problem, the consolidation factor is pre-calculated and provided to the model as an input parameter. Note that for markets requesting one-day response time, this factor is set to one. Hence, no consolidation is modeled in such cases regardless of the distance

Let,

f_{lz}^{c} : Load consolidation opportunity factor from DC *l* to market zone *z,*

q : Maximum number of product units allowed in a truck*,*

w : Number of working days in a year.

The following binary parameters are defined to distinguish the shipment option at operational level.

A_{pl}^{TL} , $A_{ll'}^{TL}$, A_{lz}^{MTL} : Equal to 1 if shipment option TL is selected from plant *p* to DC *l* and from DC *l* to DC *l'* or shipment option MTL, from DC *l* to market zone *z* and zero otherwise.

Constraints (3.11-3.16) indicated the transportation flows to be shipped by TL and MTL. The flow balance constraint (3.10) guarantees that flows that are illegible for full truckload shipment options will be shipped by either LTL or MW.

Inbound TL shipment option selection:

$$T_{pl}^{TL} \leq NA_{pl}^{TL} \qquad \forall l \in L, p \in P \quad (3.11)$$

Inbound TL flow lower bound:

$$qwA_{pl}^{TL} \leq T_{pl}^{TL} \qquad \forall l \in L, p \in P \quad (3.12)$$

DC-DC TL shipment option selection:

$$T_{ll'}^{TL} \leq N A_{ll'}^{TL} \qquad \forall\, l \in L, l' \in L - \{l\} \quad (3.13)$$

DC-DC TL flow lower bound:

$$qwA_{ll'}^{TL} \leq T_{ll'}^{TL} \qquad \forall\, l \in L, l' \in L - \{l\} \quad (3.14)$$

Outbound MTL shipment option selection:

$$T_{lz}^{MTL} \leq N A_{lz}^{MTL} \qquad \forall l \in L, z \in Z_l \quad (3.15)$$

Outbound MTL flow lower bound:

$$qwf_{lz}^{c} A_{lz}^{MTL} \leq T_{lz}^{MTL} \qquad \forall l \in L, z \in Z_l \quad (3.16)$$

Constraints (3.11), (3.12) guarantee that shipment option TL is selected for the inbound transportation flow which represent daily flows higher than a full truck. Similarly, constraints pairs (3.13) and (3.14), (3.15) and (3.16) follow the same reasoning for TL shipment on DC-DC links and MTL shipments on outbound links.

3.3.6 Modeling costs

3.3.6.1 Distribution center opening and warehousing cost

We partition the costs associated with distribution center opening and warehousing into area-based and throughput-based costs. The former is composed of lease cost, tax, insurance, electricity and building maintenance fees. While the latter, takes into account the expenses related to employee salary and material handling equipment. Our approach details how to calculate both DC area and the throughput parameters as a function of DC storage capacity. The impact of the geographical location of the DC on the rent, utility and worker salary is also taken into consideration by applying a factor. Let us define,

$$c_{lg}^{o}(b_g) = f_l^{Geo}\left(c(a_g) + c(v_g)\right) \quad (3.17)$$

Where,

a_g : DC area within configuration *g*

$c_{lg}^{o}(b_g)$: DC l opening and warehousing cost as a function of the storage capacity within configuration g

$c(a_g)$: Total DC area-based cost function within configuration g

$c(v_g)$: Total DC throughput-based cost function within configuration g

f_l^{Geo} : Geographical impact factor at DC l

v_g : Annual DC throughput within configuration g

A general layout of DC includes storage area, maneuvering area, office and trucker lounge. Let,

$$a_g = a_g^1 + a_g^2 + a_g^3 + a_g^4 \tag{3.18}$$

Where:

a_g^1 = Storage area

a_g^2 = Maneuvering area

a_g^3 = Office area

a_g^4 = Trucker lounge area

Supposing that DCs have rectangular shape with length twice larger than the width, the required storage area for the predetermined capacity (in pallet) can be calculated based on De Koster and René (2010).

$$a_g^1 = \frac{b_g \xi}{n} \tag{3.19}$$

Where,

ξ = Single pallet storage space influenced by load storage orientation (deep Vs wide)

n = Number of storage level

Based on the map of several DC layout and rules of thumb, we have modeled the maneuvering, office and trucker lounge areas as a function of the storage area. Furthermore, the average daily throughput at each DC configuration is obtained by modeling the distribution center as a queuing system and applying Little's Law (Bartholdi and Hackman, 2008):

$$\overline{v_g} = \frac{\theta b_g}{w} \tag{3.20}$$

Where θ is the annual inventory turnover.

The cost functions $c(a_g)$ and $c(v_g)$ are repeatedly recognized as nonlinear functions (Martel and Klibi, 2015; Amiri, 2006; Fleischmann, 1993). The larger capacity configurations manifest higher efficiency in the utilization of material handling and workers' capacity in addition to discounts offered by facility owner to encourage higher involvements in the lease. Because of this economy of scale, the total DC opening and operating costs per product unit should be lower at large capacity configurations compared to the smaller configurations.

In order to avoid the complexity of adding nonlinear functions in the optimization model, several discrete values of the DC capacity including small, average and large DC size are used to calculate the total DC cost. Plotting the value of discrete DC costs for multiple storage capacities, we should observe a nonlinear function. Because of this approximation, we use the notation c_{lg}^{o} in the objective function for DC opening and operations cost parameter.

It should be noted that modeling the DC cost for PI-enabled open DCs entails different assumptions that are elaborated in chapter 4. In the core modeling approach, c_{lg}^{o} is applied independent from the DC type (conventional Vs PI-enabled open).

3.3.6.2 Transportation flow cost

The transportation cost represents a major component of the total distribution cost. This is why adequate precision should be given to take this cost into account while designing distribution networks. Tsao and Lu (2012) stress that the unit transportation cost is a non-increasing function of both quantity and distance. LTL service providers offer discounts to shippers ordering larger quantities to improve the truck filling rate and save on fuel expenses. The full truck companies offer lower costs for more frequency of the truck request to ensure a fixed rate of truck request also, creating strong relationship and commitment with the shipper. According to (Tsao and Lu, 2012), the impact of distance on transportation cost is reasonable since the amount of fuel consumption depends on the distance, and the labor salary is a function of distance. Thus, the longer transport distance the products will be transferred, the lower the unit distance transportation cost will be.

Let, $c_m^t(T_{nn'}^m, \delta_{nn'})$ denote the transportation cost as a function of the flow quantity and distance from any origin node n to destination n'. Since the distance and transportation flow are independent variables, the 3-dimensional transportation cost function can be divided into two 2-dimensional nonlinear function, as follows:

$$c_m^t(T_{nn'}^m, \delta_{nn'}) = \Upsilon_m(T_{nn'}^m) \times (\chi_m + \Psi_m(\delta_{nn'}) \times \delta_{nn'}) \quad (3.21)$$

Where,

$\Upsilon_m(T_{nn'}^m)$: Discounted transportation quantity in [Pallets]

χ_m : Constant unitary cost by mode m in [$/Pallets]

$\Psi_m(\delta_{nn'})$: Unitary transportation cost as a function of distance shipped by mode m in [$/Pallets-Km]

$\delta_{nn'}$: Distance between n-n' in [Km]

By taking into account two types of economies, it is not possible to calculate both functions $\Upsilon_m(T_{nn'}^m)$ and $\Psi_m(\delta_{nn'})$ in monetary values; otherwise the final cost $c_m^t(T_{nn'}^m, \delta_{nn'})$ would be in [$^2]! Thus we have proceeded by segregating costs; the impact of economies of quantity is modeled in terms of discounts on the flow quantity and the impact of economies of distance, on the unitary transportation cost. Then the discounted flows and unitary costs are multiplied to the distance. Thus, in the equation (3.21), we have [$] = [Pallets] × ([$/Pallets] + [$/Pallets-Km] × [Km]).

Figure 3-5 shows the approximation of $\Upsilon_m(T_{nn'}^m)$ by a piecewise linear function. Let $h \in H$ be the set of flow quantity intervals, T_h the flow upper bound in interval h, α_h^m the slope of the linear interpolant in the interval h for shipment option m and β_h, the value of cost function for highest quantity in interval h. Hence, $\Upsilon_m(T_{nn'}^m) = \beta_h + \alpha_{h+1}^m(T_{nn'}^m - \beta_h)$ when $T_{nn'}^m \in [T_h, T_{h+1})$.

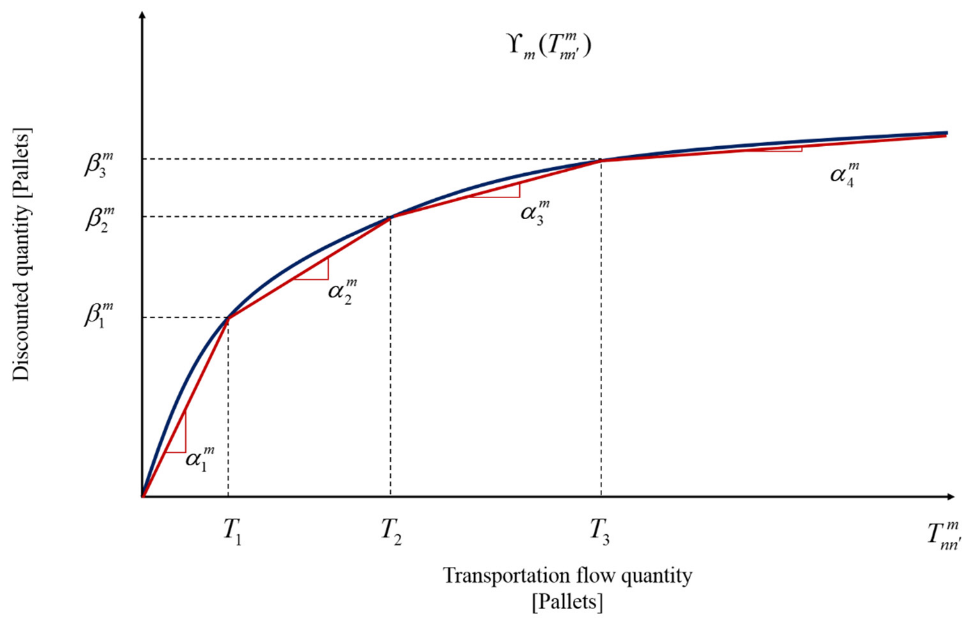


Figure 3-5. Discounted transportation flow as a piecewise linear function of quantity

To better characterize the impact of economies of distance on the unitary cost, we have obtained data from FedEx ground LTL rate web page. Our findings revealed that for short distances, the transportation cost decrease sharply by distance. However, it changes slightly for longer distances. Thus, a stepwise function is applied to approximate $\Psi(\delta_{nn'})$ (as shown in Figure *3-6*). Knowing the potential links of each distribution network, the effect of economies of distance is pre-calculated to simplify the model.

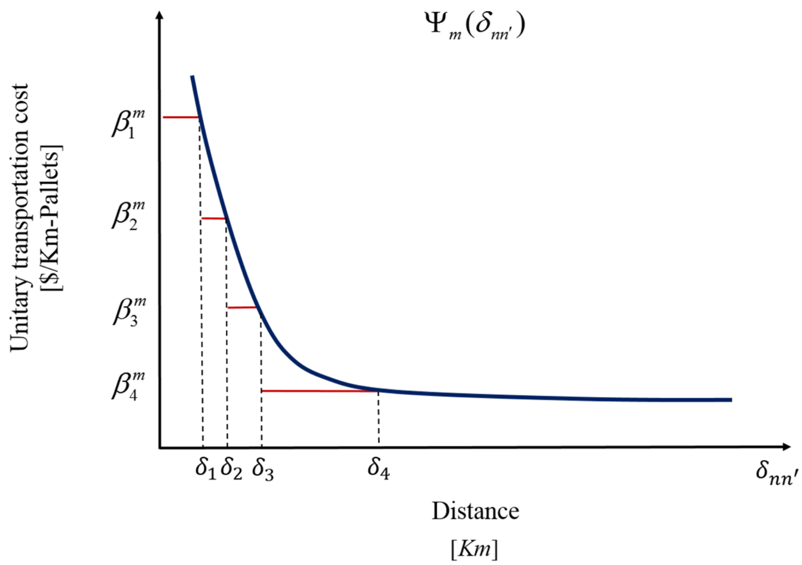


Figure 3-6. Unitary transportation cost as a stepwise function of distance

The parameters involved in the transportation cost approximation are carefully calibrated (details are provided in chapter 4).

3.3.6.3 Inventory holding cost

The inventory holding cost is modeled as the linear function of the annual inventory level. However, this cost is influenced by the distance of potential of DCs from the plant (or the closest plant). The unitary value of this cost can be determined as a percentage of the inventory value. As transportation is a value adding operation, the value of inventory at DCs located farther than the plant should be higher compared to others. Thus, we define:

c_l^i : Unitary inventory holding cost at DC l over the planning horizon,

3.3.7 Objective function

The goal of our model is to minimize the Total Distribution Cost (TDC) over the planning horizon including DC opening and operation, transportation and inventory holding costs respecting a predetermined market service level. Employing the decision variables and parameters previously modeled, the objective function of the single-period distribution network design problem can be formulated as in (3.22).

$$TDC = Min\left(\begin{array}{l}\sum_{l,g} c^{o}_{\lg} O^{e}_{\lg} + \sum_{l} c^{i}_{l} I_{l} + \\ \sum_{p,l,m} c^{t}_{m}\ (T^{m}_{pl}, \delta_{pl}) + \sum_{l\in L, l'\in L-\{l\}, m} c^{t}_{m}\ (T^{m}_{ll'}, \delta_{ll'}) + \sum_{l, z\in Z_l, m} c^{t}_{m}\ (T^{m}_{lz}, \delta_{lz})\end{array}\right) \quad (3.22)$$

This objective function should be optimized subject to the constraints:

- Network structure constraints (3.1) -(3.5)
- Demand satisfaction and service level (3.6)
- Inventory level and distribution capacity respect (3.7) and (3.8)
- Transportation flow and shipment option modeling (3.9) -(3.16)
- The integrality and non-negativity of the decision variables

$$O^{e}_{\lg}, A^{TL}_{pl}, A^{TL}_{ll'}, A^{MTL}_{lz} \in \{0,1\}, T^{m}_{pl}, T^{m}_{ll'}, T^{m}_{lz}, I_{l} \geq 0$$

$$\forall e \in E, g \in G, l \in L, m \in M, p \in P, z \in Z \quad (3.23)$$

3.4 Distribution system-driven models

3.4.1 Dedicated distribution system

When considering a dedicated distribution system, distinct businesses design their distribution network independently. In such a context, each business is the sole responsible for the incurred costs. As described in chapter 1, our investigation of distribution systems is quite conservative and PI-enabled open DC and Mobility Web, are only available for hyperconnected distribution system. Subsequently, the dedicated distribution network design problem can be modeled similar to the core modeling approach with limitations resulted by our investigation approach.

Let TDC^{d} denote the Total Distribution Cost of a dedicated distribution network. Then,

$$TDC = Min\left(\begin{array}{l}\sum_{l,g} c^{o}_{\lg} O^{e}_{\lg} + \sum_{l} c^{i}_{l} I_{l} + \sum_{p,l,m} c^{t}_{m}\ (T^{m}_{pl}, \delta_{pl}) + \\ \sum_{l\in L, l'\in L-\{l\}, m} c^{t}_{m}\ (T^{m}_{ll'}, \delta_{ll'}) + \sum_{l, z\in Z_l, m} c^{t}_{m}\ (T^{m}_{lz}, \delta_{lz})\end{array}\right) \quad (3.24)$$

Subject to:

- Constraints sets (3.1) -(3.16)
- The integrality and non-negativity of the decision variables

$$O^{e}_{lg}, A^{TL}_{pl}, A^{TL}_{ll'}, A^{MTL}_{lz} \in \{0,1\}, T^{m}_{pl}, T^{m}_{ll'}, T^{m}_{lz}, I_l \geq 0$$

$$\forall e \in E, g \in G, l \in L, m \in \{TL, MTL, LTL\}, p \in P, z \in Z \quad (3.25)$$

3.4.2 Collaborative distribution system

The collaborative distribution in this study potentially includes both joint DC investment and consolidation of full truckload transportation operations. Noteworthy, dedicated behavior is not prohibited in the collaborative system.

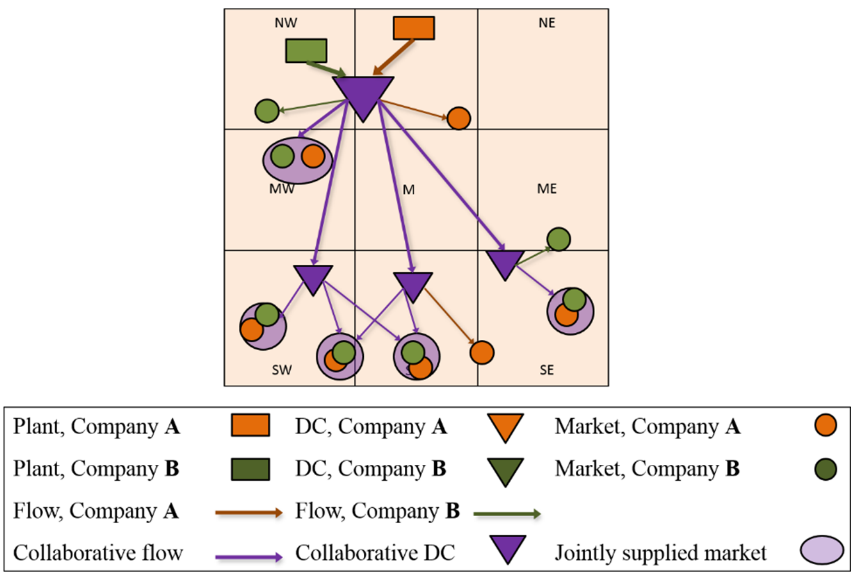


Figure 3-7. Schematic demonstration of a 2-business collaborative distribution web

(Adapted from Montreuil 2011 and 2012)

There are two fundamental questions that need to be answered while forming a coalition: first, which businesses can create a successful collaboration and second, how will the joint benefit be shared between them (Audy et al., 2011). To address the first question, here the partnering businesses are pre-selected and the role of the optimization model is to design their joint collaborative distribution web in a way to minimize the global distribution cost. Audy et al., (2012) stress that the selection of one or many partners should be made carefully and based on multiple characteristics such as organization size, culture and the preparedness to share benefits and risk. While it is possible to investigate the performance of any potential collaboration between businesses in terms of number of partnering businesses, for simplicity we have limited our study to two-business settings. Hence, we have selected the two most likely coalitions between businesses considering similarity in their annual throughput and geographical location of market zones.

To answer the second question, the individual business costs will be calculated after designing the collaborative web by applying a new approach called Volume-based Savings Allocation (VSA). In the course of the two following sections, first the collaborative distribution web design model then the VSA approach are presented.

3.4.2.1 Collaborative distribution web design model

Let $j \in J$ denote the set of all businesses in the study and $k \in K$ the set of pair businesses participating in a mutually exclusive coalition. Decision variables employed in the core model (2.1-2.18) should be augmented with *j* index as $O^{e}_{l\,g\,j}, T^{m}_{plj}, T^{m}_{ll'j}, T^{m}_{lzj}, I_{lj}$. A new decision variable, $X_{l\,g}$ should be added to model the joint selection of DC *l* opened within configuration *g*. A collaborative DC can operate in different echelons for each business; as a result, $X_{l\,g}$ is independent from echelon *e*. The role of $O^{e}_{l\,g\,j}$ decision variable is essential to indicate the mission of DCs for each business and eventually to determine business's inventory level and final required capacity at the joint DC. Transportation pooling is modeled from jointly opened DCs toward mutually supplied DCs and market zones. Here we assume that each business performs the inbound shipments individually. According to the assumptions made, the collaborative distribution web design model is presented in (3.26-3.45) minimizing the Total Distribution Cost of collaborative distribution web $TDC^{c}_{k:\{j\}}$. Note that *k* denotes the type of coalition in terms of number of business involved and *j* identifies the businesses involved in the coalition.

$$TDC^{c}_{k:\{j\}} = Min\left(\begin{array}{l} \sum\limits_{l,g} c^{o}_{\lg} X_{\lg} + \sum\limits_{l,j\in k:\{j\}} c^{i}_{l} I_{lj} + \sum\limits_{p,l,j\in k:\{j\},m} c^{t}_{m}\ (T^{m}_{plj}) + \\ \sum\limits_{l\in L,l'\in L-\{l\},m} c^{t}_{m}\left((\sum\limits_{j\in k:\{j\}} T^{m}_{ll'j}), \delta_{ll'} \right) + \sum\limits_{l,z\in Z_l,m} c^{t}_{m}\left((\sum\limits_{j\in k:\{j\}} T^{m}_{lzj}), \delta_{lz} \right) \end{array} \right) \quad (3.26)$$

Subject to:

Single echelon –configuration per DC per business:

$$\sum_{e,g} O^{e}_{l\,g\,j} \leq 1 \qquad \forall l \in L, j \in k:\{j\} \quad (3.27)$$

Joint DC opening for the coalition:

$$\sum_{e,g,j} O^{e}_{l\text{g}\,j} \leq N \sum_{g} X_{\text{lg}} \qquad \forall l \in L \quad (3.28)$$

Single echelon –configuration per joint DC:

$$\sum_{g} X_{l\,\text{g}} \leq 1 \qquad \forall l \in L \quad (3.29)$$

Outbound flow is allowed from opened DCs:

$$\sum_{z,m} T^{m}_{lzj} \leq N \sum_{e,g} O^{e}_{l\text{g}\,j} \qquad \forall l \in L, z \in Z_l, j \in k:\{j\} \quad (3.30)$$

E-1 DC is supplied only by plant(s):

$$\sum_{p,m} T^{m}_{plj} \leq N \sum_{g} O^{1}_{l\,\text{g}\,j} \qquad \forall p \in P, l \in L, j \in k:\{j\} \quad (3.31)$$

Only e-1 DC supplies e-2 DC(s):

$$\sum_{l' \in L-\{l\},m} T^{m}_{ll'j} \leq N \sum_{g} O^{1}_{l\,\text{g}\,j} \qquad \forall\, l \in L,\, j \in k:\{j\} \quad (3.32)$$

E-2 DC is supplied only by e-1 DC(s):

$$\sum_{l' \in L-\{l\},m} T^{m}_{l'lj} \leq N \sum_{g} O^{2}_{l\,\text{g}\,j} \qquad \forall\, l \in L,\, j \in k:\{j\} \quad (3.33)$$

Market demand satisfaction:

$$\sum_{l \in L_z,\, m} T^{m}_{lzj} = d_{zj} \qquad \forall z \in Z,\, j \in k:\{j\} \quad (3.34)$$

Transportation flow balance:

$$\sum_{p,m} T^{m}_{plj} + \sum_{l' \in L-\{l\},m} T^{m}_{l'lj} = \sum_{l' \in L-\{l\},m} T^{m}_{ll'j} + \sum_{z,m} T^{m}_{lzj} \qquad \forall\, l \in L,\, j \in k:\{j\} \quad (3.35)$$

Inbound TL shipment option selection:

$$T_{plj}^{TL} \leq N \times A_{plj}^{TL} \qquad \forall l \in L, p \in P, j \in k : \{j\} \quad (3.36)$$

Inbound TL flow lower bound:

$$qwA_{plj}^{TL} \leq T_{plj}^{TL} \qquad \forall l \in L, p \in P, j \in k : \{j\} \quad (3.37)$$

DC-DC TL shipment option selection:

$$\sum_{j} T_{ll'j}^{TL} \leq N \times \sum_{j} A_{ll'}^{TL} \qquad \forall l \in L, l' \in L - \{l\} \quad (3.38)$$

DC-DC TL flow lower bound:

$$qw\sum_{j} A_{ll'}^{TL} \leq \sum_{j} T_{ll'j}^{TL} \qquad \forall l \in L, l' \in L - \{l\} \quad (3.39)$$

Outbound MTL shipment option selection:

$$\sum_{lzj} T_{lzj}^{MTL} \leq N \times \sum_{j} A_{lz}^{MTL} \qquad \forall l \in L, z \in Z_l \quad (3.40)$$

Outbound MTL flow lower bound:

$$qwf_{lz}^{c} \sum_{j} A_{lz}^{MTL} \leq \sum_{j} T_{lzj}^{MTL} \qquad \forall l \in L, z \in Z_l \quad (3.41)$$

Average inventory level lower bound:

$$f_{e=1}^{b} \sum_{p,m} T_{plj}^{m} + f_{e=2}^{b} \sum_{l' \in L - \{l\}, m} T_{l'lj}^{m} \leq I_{lj} \qquad \forall l \in L, j \in k : \{j\} \quad (3.42)$$

Joint DC storage capacity respect:

$$\sum_{j} I_{lj} \leq f^{i} \sum_{g} b_{g} X_{\mathrm{lg}} \qquad \forall l \in L \quad (3.43)$$

Production capacity respect:

$$\sum_{l,m} T_{plj}^{m} \le b_{pj} \qquad \forall p \in P, j \in k:\{j\} \quad (3.44)$$

Integrality and non-negativity constraints:

$$O_{l\,\mathrm{g}\,j}^{e}, X_{l\,\mathrm{g}}, A_{plj}^{TL}, A_{ll'j}^{TL}, A_{lzj}^{MTL} \in \{0,1\}, T_{plj}^{m}, T_{ll'j}^{m}, T_{lzj}^{m}, I_{lj} \ge 0$$

$$\forall e \in E, g \in G, j \in k:\{j\}, m \in \{TL, MTL, LTL\}, p \in P, l \in L, z \in Z \quad (3.45)$$

Constraints (3.28) ensure that if a DC is opened for at least one business, the joint DC decision is set to one (i.e. one time opening cost will be incurred). Single configuration selection at joint DC is guaranteed by constraint (3.29). Constraints (3.38-3.41) guarantee that if TL/MTL shipment options are selected, the consolidated daily transportation flow should be higher than a full truck. Constraint (3.43) makes sure that joint DC capacity is respected by total storage requirements in the coalition. The remaining of the constraints set the same boundaries as described in the core model.

3.4.2.2 Volume-based Savings Allocation method

One of the difficulties of the logistics collaboration is dividing the gain among partners (Cruijssen et al., 2007). The simplest solution to a cost allocation problem would be to split the common cost weighted with each participant's volume (Frisk et al., 2010). However, our experiments indicated that this method neglects the savings each business could already achieve in dedicated system due to the economies of scale in transportation quantity or DC storage capacity. Hence, it can result in negative savings by collaboration (compared to the dedicated distribution). To respect our primary preselection of the collaborating businesses, the savings allocation method should ensure a positive gain for each business, otherwise their pre-selection is meaningless.

Another approach is called Activity Based Costing (ABC) (Vanovermeire and Sörensen, 2014), where the coalition cost is allocated according to individual business activities. For instance, each joint transportation cost is divided based on the share of each business on the total quantity shipped. The ABC method assigns higher costs to companies who contributed more to the consolidation and discounts offered by higher throughput. Contrarily, larger business should be entitled to less cost since their individual operations is more efficient compared to the small businesses. ABC approach assigns unfair costs to large businesses.

The third approach taken into consideration is called Proportional Allocation. In this method, the total collaborative distribution cost is assigned to each business according to their share of the global dedicated distribution cost of all businesses in the coalition. This method is one of the easiest and most used cost allocation approaches yet it does not guarantee that each business can obtain a positive gain (Özener and Ergun, 2008; Liu et al., 2010).

Here, a cost allocation method is developed which has similarities to some existing methods yet is adapted to the characteristics of our problem. Noteworthy, we do not aim to identify either a best cost allocation method. Our goal is to investigate the global potential gain (for the coalition and individual business) in comparison to the dedicated distribution cost. Thus, to avoid complexity, game theory-based cost allocation approaches such as Nucleolus (Schmeidler, 1969), Shapley value (Shapley, 1953) and Equal Profit Method (Frisk at al., 2010) which require additional model solving algorithms to divide the coalition cost are not taken into account.

In our cost allocation approach, the coalition's savings (compared to total dedicated distribution cost of all participating businesses) is divided among the partners in the proportion of their annual throughput. Then the collaborative distribution cost of each business is calculated by subtracting the share of savings from their dedicated cost. We call this approach Volume-based Savings Allocation. Equation (3.46) presents the collaborative distribution cost for business j obtained by VSA method.

$$TDC_j^c = TDC_j^d - \left(\frac{\sum_z d_{zj}}{\sum_{z,j} d_{zj}}\right) \times \left(\left(\sum_j TDC_j^d\right) - TDC_{k:\{j\}}^c \right) \quad (3.46)$$

As an illustration, suppose that two businesses j_1 and j_2 form a coalition with throughput 86000 and 155000 unit/year and dedicated distribution cost of 50 and 66 M\$/year respectively. If the total collaborative distribution cost of their coalition is 103 M\$/year, the collaborative distribution cost associated with each business applying VSA method can be determined as follows.

$$TDC_1^c = 50 - \left(\frac{86000}{86000+155000}\right) \times (50+66-103) = 46 \text{ M\$/year}$$

$$TDC_2^c = 66 - \left(\frac{155000}{86000+155000}\right) \times (50+66-103) = 57 \text{ M\$/year}$$

The VSA method ensures that each business has a positive gain by participating in the coalition. It is also an efficient approach as it divides the entirety of the gain among players.

3.4.3 Hyperconnected distribution system

In the thesis introduction, the Physical Internet, Distribution and Mobility Webs were introduced. We have discussed the characteristics of PI-enabled open DCs. Figure 3-8 schematically depicts the hyperconnected distribution web of two individual businesses.

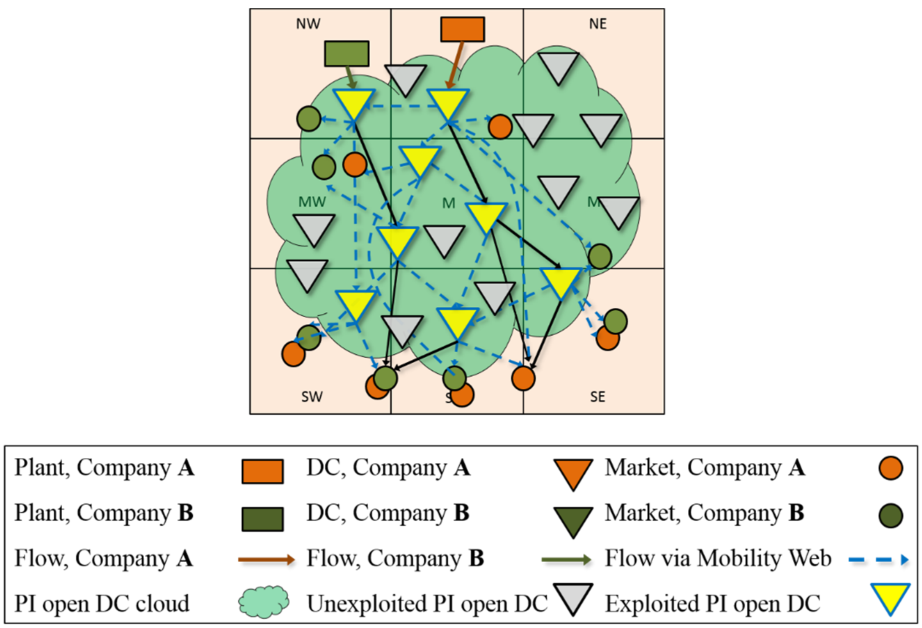


Figure 3-8. Schematic demonstration of a hyperconnected distribution web

(Adapted from Montreuil 2011 and 2012)

Although the collaborative behavior while exploiting the distribution web is possible, here it is assumed that businesses deploy their products independently from each other. The main reason for this presumed behavior comes from two privileges of distribution web. First, numerous open distribution centers and warehouses are available at affordable prices. Second, it exempts businesses from collaboration-inherited problems such as trust and gain division (Cruijssen et al., 2007). Hence, the core modeling approach can be applied to determine the total hyperconnected distribution cost. However, some changes in the parameter modeling are necessary.

Let L^{π} denote the set of open DCs and $c_{lg}^{o^{\pi}}$ the open DC $l \in L^{\pi}$ exploitation cost within configuration g. To provide a conservatively fair cross investigation of the distribution systems, the geographical location of open DCs remains the same as the previous set L even though the distribution web is bound to make available much more open DCs than can be considered for exploitation in dedicated and collaborative distribution. The open DC exploitation cost is obtained by assuming that influenced by the implementation of the highly advanced modular technologies in open DC, material handling operations are performed with high efficiency. As a result, the DC opening cost per pallet at the highest capacity configuration (most efficient) as determined for the dedicated and collaborative systems is selected for the hyperconnected system. In other words,

$$c_{l\mathrm{g}}^{o^{\pi}} = b_{g}\left(\frac{c_{l\mathrm{g}'}^{o^{\pi}}}{b_{l\mathrm{g}'}}\right) \qquad \forall l \in L \quad (3.47)$$

Where *g'* represents the configuration with the highest capacity.

Based on the discussions above, the hyperconnected distribution web design problem minimizing Total Distribution Cost of hyperconnected distribution web, TDC^{h} is modeled as in (3.48).

$$TDC^{h} = Min\left(\begin{array}{l}\sum\limits_{l,g} c_{\mathrm{lg}}^{o^{\pi}} O_{\mathrm{lg}}^{e} + \sum\limits_{l} c_{l}^{i} I_{l} + \\ \sum\limits_{p,l,m} c_{m}^{t}(T_{pl}^{m}, \delta_{pl}) + \sum\limits_{l \in L, l' \in L-\{l\}, m} c_{m}^{t}(T_{ll'}^{m}, \delta_{ll'}) + \sum\limits_{l, z \in Z_{l}, m} c_{m}^{t}(T_{lz}^{m}, \delta_{lz})\end{array}\right) \quad (3.48)$$

Subject to:

- Constraints set (3.1) -(3.16)
- The integrality and non-negativity of the decision variables

$$O_{\mathrm{lg}}^{e}, A_{pl}^{TL}, A_{ll'}^{TL}, A_{lz}^{MTL} \in \{0,1\}, T_{pl}^{m}, T_{ll'}^{m}, T_{lz}^{m}, I_{l} \geq 0$$

$$\forall e \in E, g \in G, l \in L^{\pi}, m \in \{TL, MTL, LTL, MW\}, p \in P, z \in Z \quad (3.49)$$

3.5 Conclusion

This chapter presents the core modeling approach developed in this study. This model takes into account the economies of scale and distance related to the transportation operations and the economies of scale associated with the DC opening and warehousing costs. It also models various shipment options by taking into account the frequency of shipment at operational level. We have linearized the nonlinear costs by stepwise and piecewise linear functions.

The next chapter provides insights about the calibration of parameter applied in the optimization models presented in this chapter.

Chapter 4

Business case characterization and key parameter modeling

4.1 Introduction

Since the goal of our study is to assess the economic and environmental performance of multiple distribution systems, it is essential to develop illustrative business cases and apply reasonably realistic parameters to perform a meaningful investigation. The content of this chapter can be used for reproduction of similar experimentations.

As Figure 4-1 highlights, the output of the current chapter and chapter 2, will be applied in the performance assessment and investigation.

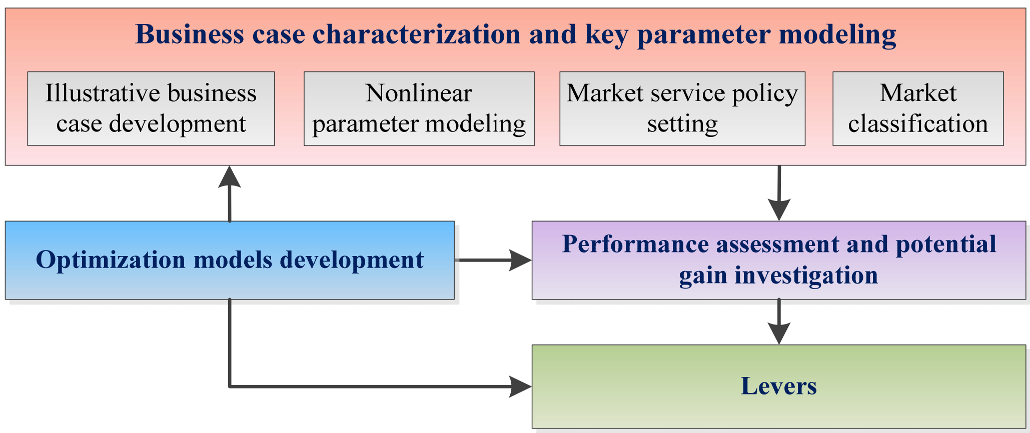


Figure 4-1. The business case characterization and key parameter modeling highlighted in the research approach

4.2 Business case generation

Here, generating the business cases involves determining the location of market zones and plants, the set of locations considered for potential DCs, the annual throughput and demand for each market zone. Our investigation introduces ten make-to-stock businesses, each distributing a single product to markets in United States and Canada. The set of market zones include 49 mainland US states and six Canadian provinces (British Columbia, Alberta, Saskatchewan, Manitoba, Ontario and Quebec). Each market zone is represented by its most populated city of the state/province. In order to diversify the experimentation, businesses serve various subsets of 55 market zones. The location of plant(s) is based on some existing industrial regions and known companies' implementations.

A set of 40 potential DC locations was determined by combining several real distribution center sites and the locations with high accessibility at the intersection of interstate/provincial highways. Figure 4-2 presents the location of potential distribution centers and market zones.

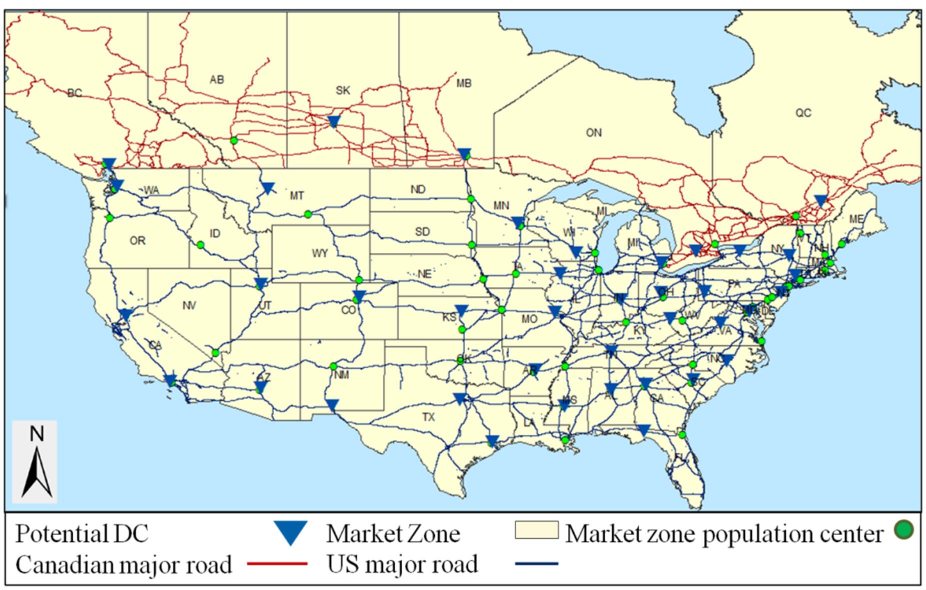


Figure 4-2. Location of the complete set of market zones and potential distribution centers

In order to build a wide range of small, medium and large size businesses, the annual throughput per business is selected between 13000 to 540000 pallet per year as shown in Table 4-1. The demand per market zone for each business is set to a percentage of its overall annual throughput based on the market penetration factor (uniformly distributed random variable [0, 1]) and the ratio of the market population vs total population served by the business (population census of United States 2010 and Canada 2011).

Table 4-1. Developed businesses cases characteristics summary

Business ID	Market territory	Plant(s) location	Number of market zones	Annual demand [Pallets]
QC-CH	Canada and USA	Quebec (Canada) and Chihuahua (Mexico)	55	5 E4
ON		Ontario (Canada)	22	1.7 E4
CA		California (USA)	55	8.6 E4
AZ		Arizona (USA)	55	6 E4
MD		Maryland (USA)	43	5.4 E5
PA	US	Pennsylvania (USA)	49	5.3 E4
OR		Oregon (USA)	14	2.3 E4
CO		Colorado (USA)	49	4.9 E5
TX		Texas (USA)	49	1.6 E5
BC	Canada	British Columbia (Canada)	6	1.3 E4

4.2.1 Market classification and service level

Applying Jenks Natural breaks method (Jenks, 1967), the market zones of each business are categorized according to their annual demand by ABC classification. Three sets of service level requirement have been generated, simply denoted top, medium and basic service. For each set, the service level is specified in terms of the required maximal response time (i.e. delivery delay) for each market class. For instance, the top service level is set to 1, 2 and 3-days response time respectively to the class A, B and C markets. The medium and basic service levels require 3, 5, 7 and 5, 7 and 10-days response time to the A, B and C market class. Noteworthy, the maximum distance that truck drivers can travel between a DC and a market zone in one day is set to 650 Km (Klibi and Martel, 2012a). Table 4-2 presents the market classification and their respective maximum distance for each service level.

Table 4-2. The target service level in terms of maximum tolerated outbound distance by truck for three market zone classes

Service Level	Market zone class					
	A		B		C	
	Response time [day]	Maximum distance [km]	Response time [day]	Maximum distance [km]	Response time [day]	Maximum distance [km]
Top	1	650	2	1300	3	1950
Medium	3	1950	5	3250	7	4550
Basic	5	3250	7	4550	10	6500

Figure 4-3, Figure 4-4 and Figure 4-5 show the business territory, demand distribution and market classification of three typical businesses with low, average and high annual throughput.

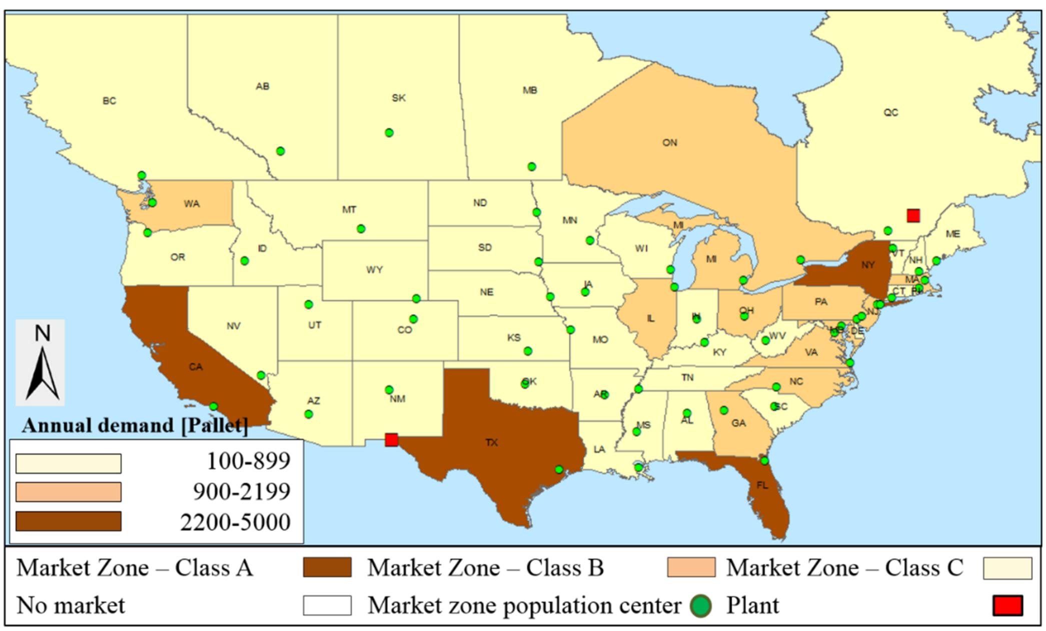


Figure 4-3. Low throughput business typical business territory, demand distribution and market classification

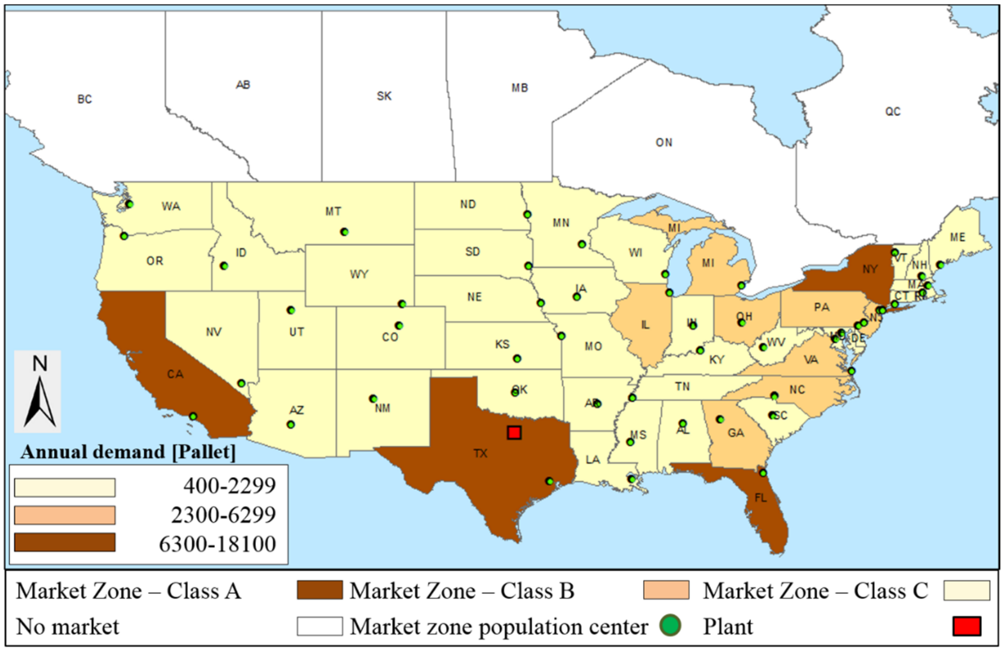


Figure 4-4. Average throughput business sample territory, demand distribution and market classification

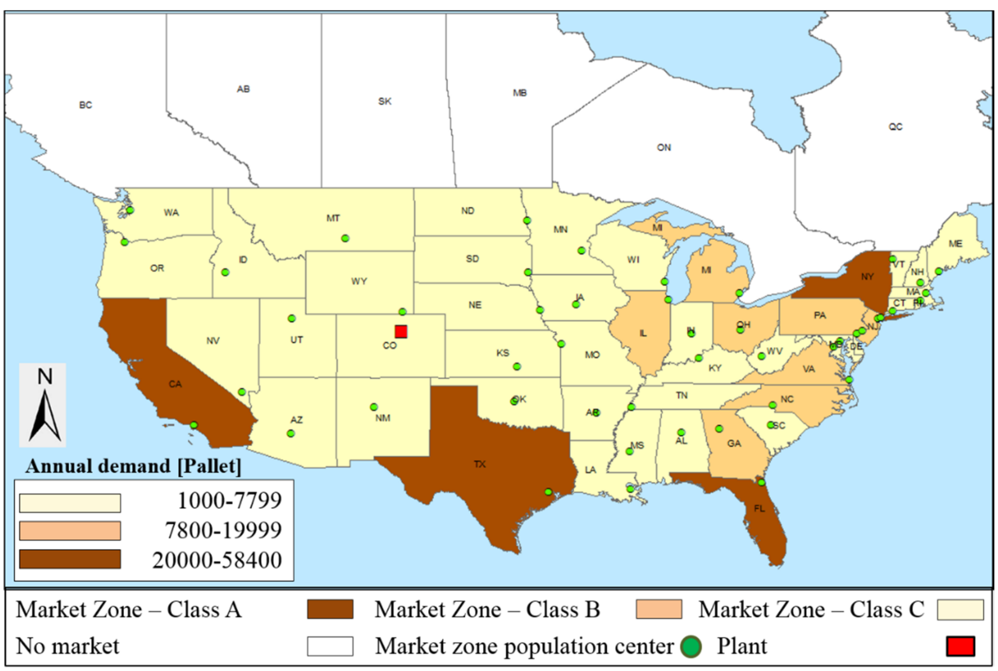


Figure 4-5. High throughput business sample territory, demand distribution and market classification

4.3 Key parametric estimation

4.3.1 DC capacity and associated costs

A wide range of very small to very large storage capacities is attributed to potential DCs. The largest storage capacity is set to 100000 pallets and smaller capacities are calculated as a percentage of it. The selected layout has rectangular shape with vertical aisles and I/O stations that are located at the top of the storage area, as depicted in Figure 4-6. We use this layout to estimate the total DC area (in m^2) required for each storage capacity (in pallet).

Inspired by BizCosts report (2010), the area-based DC cost is set to 117 $\$/m^2$/year. The tax, utility and insurance of a leased warehouse ranges between [0, 0.6] of the total rent (if zero, then the lease is called gross, meaning that the tenant pays no share of the so called costs). Here the area-based cost is increased by 30%, assuming that the tenant has to pay an average share of the tax, insurance and utilities cost.

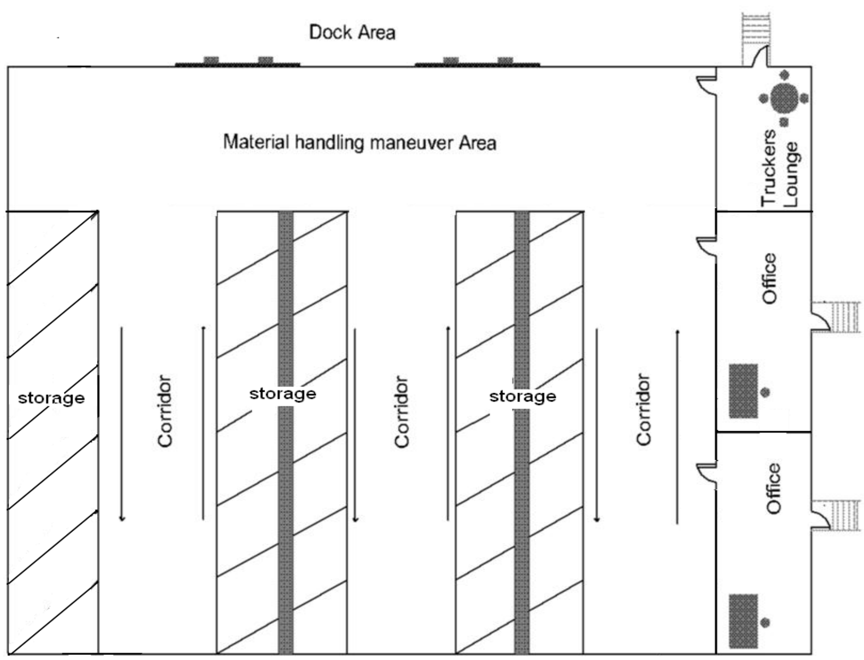


Figure 4-6. Typical layout considered here for potential DCs

The scale curve shown in Figure 4-7 is applied to the unitary area-based cost to reflect the economies of scale. The curve is adjusted in a way to find reasonable final costs compared to the information that we obtained from two real distribution centers.

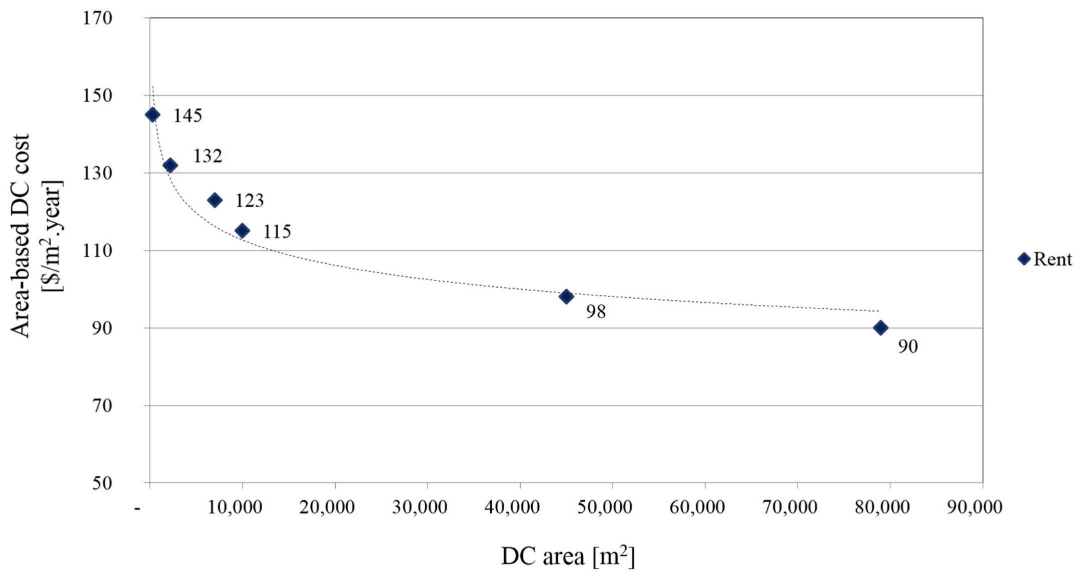


Figure 4-7. The scale curve applied to area-based DC cost to capture the impact of the economies of scale

In order to calculate the throughput-based DC costs, the daily throughput should be estimated for each configuration by formula (3.20). Here the number of workers and material handling equipment should be determined.

The number of workers required at each configuration is obtained by dividing the average daily throughput to the total duration of the main material handling operations. Here, these operations include truck loading/unloading, checking and sorting and finally picking and wrapping. The average duration of these operations is obtained from managerial experience of a consulting business[1]. Supposing that each 10 workers should be managed by one supervisor, the number of supervisors and total number of employees are determined. Based on the United States bureau of Labor Statistics, the

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[1]- Dan Derry, Managing director, OPS Logistics Consultancy Ltd, London, ON, Canada

average warehouse material handling worker and supervisor salary is 15 and 42 $/hour respectively. The work shift is set to 8 hours/day.

Lastly, the cost associated with the material handling equipment should be calculated. Here, this cost includes the forklift lease, energy usage and maintenance. Electric forklift is selected, as it is suitable for the operations inside DC. The technical information about electric forklift is retrieved from a sample manufacturer website[1]. The energy usage is calculated based on the battery characteristics, then multiplied to the average energy cost in US per kWh. Overall, a leased electric forklift cost in average 26000 $/year. To determine the number of forklifts required, the efficiency of each forklift is set to 15 pallets per hour (Rules of thumb: Warehousing and Distribution Guidelines by TranSystem, 2010[2]).

Taking into account all the sub-costs discussed above, the average annual DC cost for each configuration is given in Table 4-3.

1- http://www.still.co.uk/forklift-hire.0.0.html and http://www.still.co.uk/16307.0.0.html
2- Retrieved from: http://www.werc.org/assets/1/Publications/TranSystems%20Rules%20of%20Thumb%202010%20v2.pdf

Table 4-3. The average annual costs associated with DC opening and operations

Configuration	**Storage capacity** [Pallets]	**Average daily throughput** [Pallets/day]	**Area** [m^2]	**Area-based DC cost** [M$/year]	**Number of employees**	**Number of forklifts**	**Throughput-based DC cost** [M$/year]	**Total DC cost** [M$/year]
1	100000	2693	79000	9.2	217	40	9	18.2
2	50000	1347	45000	5.7	109	21	4.5	10.2
3	10000	270	10000	1.5	22	5	0.9	2.4
4	5000	135	7000	1.1	11	3	0.5	1.6
5	1000	27	2200	0.4	3	2	0.2	0.6
6	100	3	300	0.05	2	1	0.14	0.19

Martel and Klibi (2015) suggest that influenced by economies of scale the total DC cost should be a power function of the capacity. They suggest that the power parameter is usually between 0.6 and 1 and better estimation is developed when R^2 is close to 1. Figure 4-8 validates our DC cost calibration by obtaining the power function of the trend line.

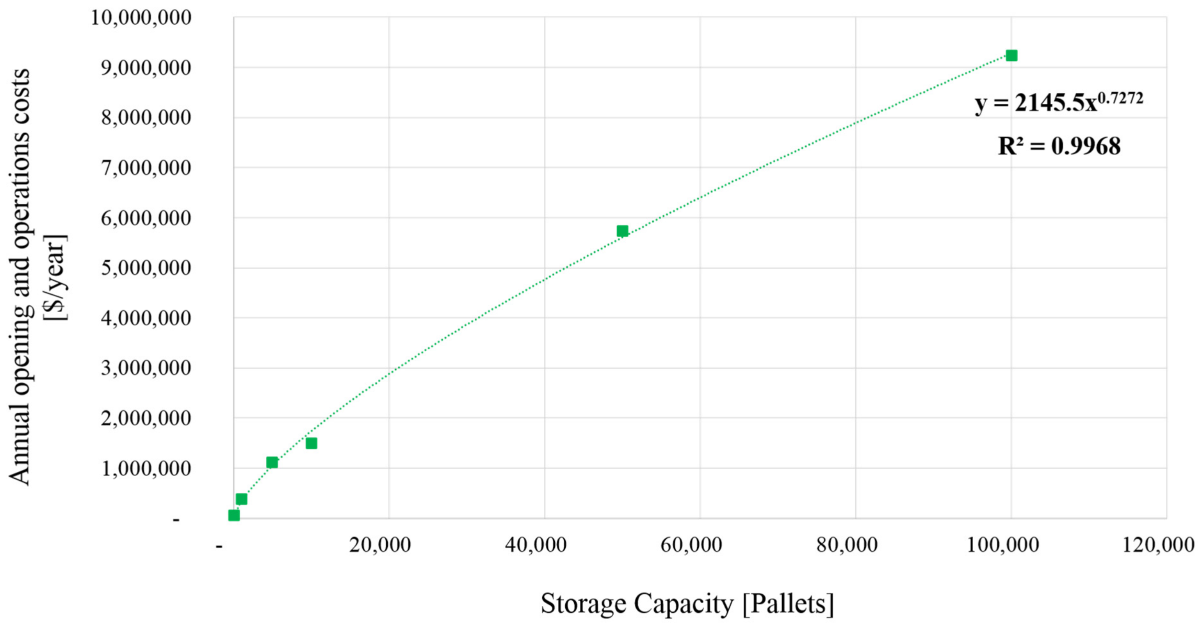

Figure 4-8. Validation of the estimated discrete values of total DC cost with the impact of economies of scale

The geographical impact factor is determined between [0.7, 1.4]; higher factor is applied to those DCs located closer to top metropolitan statistics areas to characterize higher cost and lower availability of land in these areas. Noteworthy, the factors are benchmarked with the costs provided in the BizCosts report (2010) and real estate websites for DCs located in various US states. Table 4-4 presents the geographical impact factor applied here.

Table 4-4. Geographical impact factor applied to the area-based DC cost

State	Geographical impact factor	Sate	Geographical impact factor	State	Geographical impact factor
Alabama	0.7	Maryland	1.1	Oregon	1.1
Alberta	1.1	Michigan	1.1	Pennsylvania	1.1
Arizona	1.0	Minnesota	0.9	Quebec	0.7
Arkansas	0.7	Mississippi	0.7	Saskatchewan	0.7
British Columbia	0.9	Missouri	0.8	South Carolina	0.8
California	1.4	Montana	0.9	South Dakota	0.7
Colorado	1.1	Nebraska	0.7	Tennessee	1.0
Florida	1.2	Nevada	1.0	Texas	1.0
Georgia	0.9	New Jersey	1.2	Utah	0.9
Idaho	0.7	New Mexico	0.8	Vermont	0.8
Indiana	0.8	New York	1.3	Virginia	0.9
Iowa	0.9	North Carolina	0.8	Washington	1.2
Kansas	0.8	North Dakota	0.8	West Virginia	0.8
Louisiana	0.8	Oklahoma	0.8	Wisconsin	0.7
Manitoba	0.7	Ontario	1.1	Wyoming	0.7

The exploitation cost of hyperconnected DCs, $c_{lg}^{o^{\pi}}$ is obtained by assuming that influenced by the implementation of highly advanced modular technologies, material handling operations are performed with much higher efficiency (Montreuil et al. 2010). Thus, the unitary cost of exploiting a hyperconnected DC, regardless of its total capacity, would be at least as low as the unitary cost of exploiting large dedicated DCs. This unitary cost is multiplied to the capacity of each configuration to obtain their opening and operations cost in hyperconnected distribution system.

4.3.2 Transportation cost

As discussed in chapter 3, the transportation cost is influenced by economies of distance and scale. Here the parameters involved in the transportation function are calibrated. It should be noted that since in this study only low transportation quantities are assigned to LTL, this mode is not influenced by economies of scale. In addition, shipments by exploiting the Mobility Web do not necessarily create tight business relationship between shipper and careers to encourage discounts. Thus, the cost associated with this shipment option is not influenced by economies of scales as well. Figure 4-9 shows the approximation of $\Upsilon_m(T_{nn'}^m)$ by a piecewise linear function. The breakpoints indicate the flow quantity related to specific frequency of truck request per day (details provided in Table 4-5). Various discounts are applied to flows larger than 1 truck per day. The value of discounts is between 20 to 60% (Audy et al., 2011).

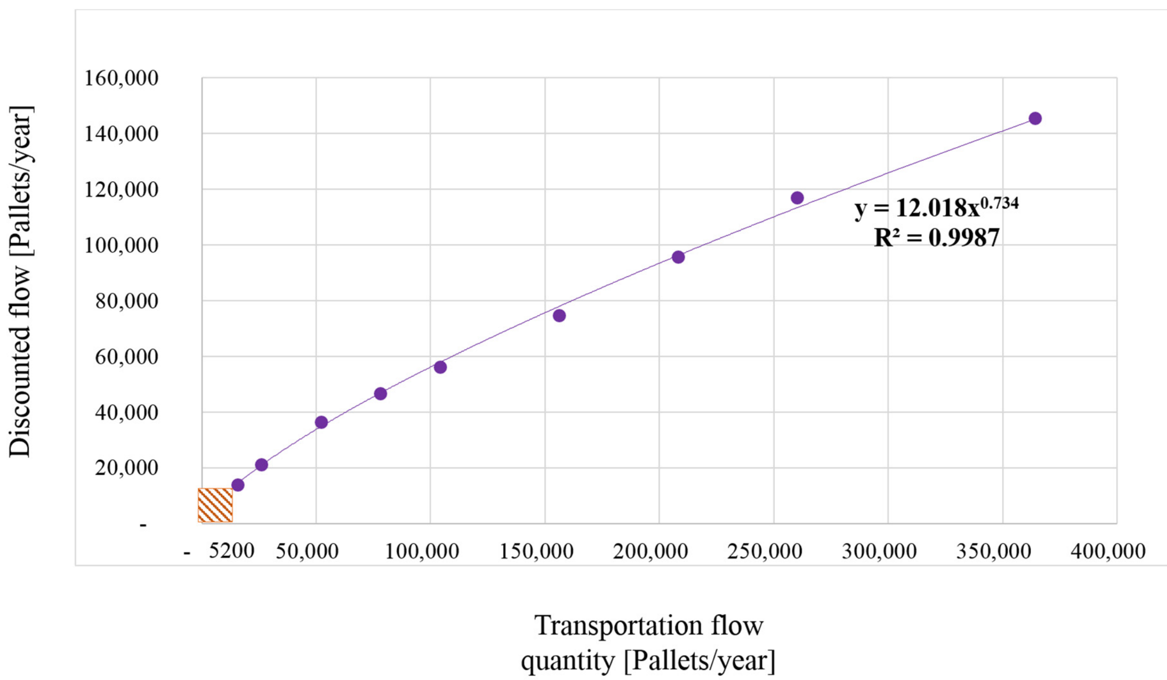

Figure 4-9. Function of the discounted flow because of economies of scale

Table 4-5. Discounted transportation cost as piecewise linear function of quantity

($\Upsilon_m(T^m_{nn'}), \forall m \in \{TL, MTL\}$)

Interval h	**Upper bound of the annual Throughput on the link *n-n'*** T_h [Pallets/year]	**Truck request frequency** [truck/day]	**Discount percentage**	**Slope** α^m_h	**Discounted flow** $\Upsilon_m(T^m_{nn'})$
1	0	0	0	1	0
2	5200	1	0	1	5200
3	15600	3	10	0.85	14040
4	26000	5	18	0.70	21320
5	52000	10	30	0.58	36400
6	104000	20	46	0.38	56160
7	364000	70	60	0.34	145600

Based on the information gathered from existing trucking companies, we found out that usually full truck shipment options incur fixed cost. Hence,

$$\chi_m = \begin{cases} 7, \forall m \in \{TL, MTL\} \\ 0, \forall m \in \{LTL, MW\} \end{cases} \tag{4.1}$$

Regarding the economies of distance, the savings are modeled for all modes rather than the mobility web. As previously discussed, each MW truck can transport a segment of the shipment path to prevent long distance hauls. Hence, applying the economies of distance would not be always relevant for this mode. Since one of the goals of the PI initiative is to enhance the quality of life of truck drivers, in hyperconnected transportation, the model imposes not to have drivers travel more than a single-day distance from their hometown. This setting lets them to come back home and reunite with their families more often. The multitude of PI-enabled open hubs and terminals and their geographical dispersion allow for short trips in the hyperconnected transportation system. Assuming that this opportunity would be preferred by most of the drivers, and knowing that the open exploitations improve the truck filling rates (Ballot et al, 2013), the unitary hyperconnected transportation cost is set equal to the MTL for a single-day distance

Two types of information should be given to obtain the LTL rate; the origin and destination zip code and the product class (related to the type of products on the pallet and the pallet dimension and weight). the location of several large cities was used as the origin and destination of LTL transportation to retrieve information from this website. A general class of products were selected including metal and woods placed in a 500 Kg pallet. We can argue that keeping the pallet specifications unchanged per business is a reasonable assumption. Our research introduces an exploratory multi-business investigation. Hence, to avoid replicating the transportation cost calculations for each business, a unique weight and dimension per pallet is assumed for all businesses. Noteworthy, this assumption does not imply that the weight and volume of the product of each business is equal. By respecting the constant maximum pallet weight, businesses can place various combination of products with different size and weight to optimize their palletization.

The fees estimated by FedEx website gives up to 60% discount while inviting the user to contact the company for details of the discount and negotiation. It is reasonable to assume that 60% savings would be offered to large shippers. To avoid unrealistically high LTL cost, a basic 25% discount is applied to the unitary LTL cost retrieved from FedEx website. Table 4-6 provides the parameters of the transportation cost function $\Psi_m(\delta_{nn'})$. The values in this table are obtained from a partnering company, which outsources full truck transportation to a trucking company and FedEx LTL rate website.

Table 4-6. Full truck load and less than truck load unitary transportation cost as stepwise function of distance ($\Psi_m(\delta_{nn'})$)

Distance interval	**Interval lower bound** [Km]	**Interval upper bound** [Km]	**TL per pallet variable cost** β_h^{TL} [$/Pallets-Km]	**LTL per pallet variable cost**[1] β_h^{LTL} [$/Pallets-Km]
1	0	300	0.13	1
2	300	650	0.11	0.6
3	650	1300	0.1	0.4
4	1300	1950	0.09	0.3
5	1950	3250	0.08	0.25
6	3250	6000	0.07	0.2

According to Klibi et al. (2012a), assuming that the shortest path is selected at operational level, the unitary cost of MTL should be always lower than LTL but higher than TL. Hence, $\Psi_{MTL}(\delta_{nn'})$ is obtained by a weighted average of the costs calculated for TL and LTL modes on the same link (*n*-*n'*). The value of φ_1, φ_2 is obtained by trial and error to ensure the share of the outbound cost from the total transportation cost remains in 70% norm (Carter and Burgess Inc., 2006).

$$\Psi_{MTL}(\delta_{nn'}) = \varphi_1 \Psi_{TL}(\delta_{nn'}) + \varphi_2 \Psi_{LTL}(\delta_{nn'}) \qquad \forall n, n' \quad (4.2)$$

Where, $\varphi_1 = 0.7, \varphi_2 = 0.3$.

Since it is assumed here that by exploiting the Mobility Web trucks do not drop-off PI-containers at a single destination and that they travel between the web of open hubs in less than one-day distance, their cost per Pallets-Km is set equal to the MTL mode in the second distance interval (less than 650 Km).

1- The weight of each pallet is assumed to be 500 Kg for all businesses.

Thus,

$$\Psi_{MW}(\delta_{nn'}) = (0.7*(7+650*0.13) + 0.3*(650*0.6))/650 = 0.28 \text{ [\$/Km-Pallets]} \qquad \forall n, n' \quad (4.3)$$

4.3.3 Inventory holding cost

The annual inventory holding cost is set to 20% of the inventory value (Richardson, 1995), which is itself between 60-70% of the product price at market. Products stored in locations further than the production plant have higher value influenced by the value-added transportation operations. Thus, for each business lower percentage of product value (60%) is assigned to DCs closer to the plant, 65 and 70% to further DCs.

4.3.4 Final remarks on parameter calibration

Table 4-7 highlights the value of other parameters applied in our numerical experimentation. In order to validate the calibration of the parameters employed in our experimentation, the average share of each sub-distribution cost in dedicated distribution system is compared to the norms provided by State of Logistics Report 2013. This report indicates that the transportation cost represents almost 63% of the total distribution cost and inventory carrying cost (warehousing and rent included), 33%. Similar results are obtained in our experiments, which qualify our parameter characterization estimation.

Table 4-7. Full truck load and less than truck load unitary transportation cost as stepwise function of distance

Parameter notation	Value	Remark
$f_{e=1}^{b}$	0.17	When demand coverage by stock in e-1 DC is set to 2 months and the number of months per year is set to 12
$f_{e=2}^{b}$	0.04	When demand coverage by stock in e-2 DC is set to 2 weeks and the number of weeks per year is set to 52
f^{i}	0.8	To enable higher storage capacity acquisition by order of 25% over the average required capacity
w	260	Number of workdays per year
θ	7	Annual inventory turnover ratio
q	20	Maximum number of pallets in a full truck
ξ	5.7	Wide pallet orientation

Chapter 5

Performance assessment and potential gain investigation

5.1 Introduction

This chapter looks into the potential economic and environmental performance gain by exploiting the hyper connected distribution system in contrast with the dedicated and collaborative distribution systems respecting a preset social performance. First, the set of Key Performance Indicators (KPI) applied in the investigation is presented. Then, the approach to estimate the environmental performance in terms of energy consumption and GHG emission is explained. Finally, the performance of ten business cases respecting three service levels by in three distribution systems are analyzed and the potential gain is investigated. Figure 5-1 highlights the content of chapter 5 in the overall research approach.

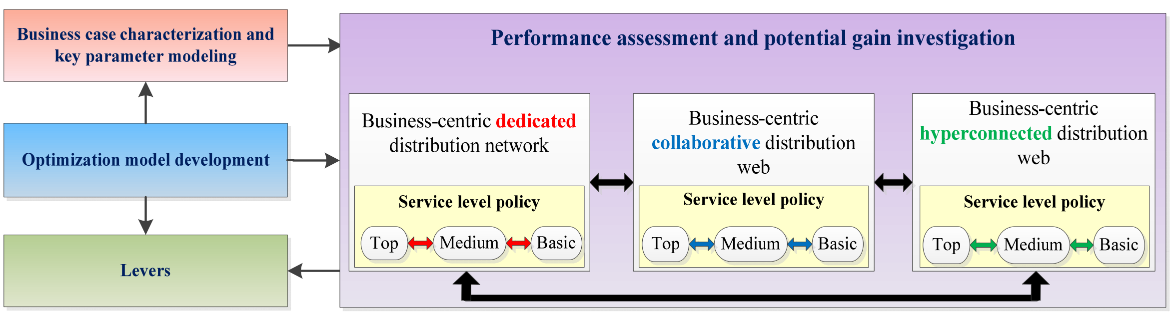

Figure 5-1. Performance assessment and potential gain investigation highlighted in the research approach

5.2 Key performance indicators

The set of Key Performance Indicators in this study can be arranged from three perspectives: first, according to the type of sustainability's triple bottom line (Elkington, 2004) to be measured. Second, based on their ability to calculate either the global performance (summation over all the businesses or *collective measures*) or single-business (called *individual measures*). Lastly, in regard to their measurement scope including the cross-distribution system and cross-service level.

The economic KPI involves the total distribution cost, total transportation cost and total DC-related costs denoted by ρ, λ, θ respectively. The environmental performance gain is measured by two KPIs; η indicates the Energy Consumption (EC) and γ, the Greenhouse Gas emission (GHG) production. Note that the value of indicators can take either positive or negative value to present the savings or penalty incurred by change of service level or distribution system. The economic KPIs are optimized by the MIP models presented in chapter 3 and the environmental measures are obtained by analyzing the optimized distribution networks/webs with an algorithmic approach described later in this chapter.

In this study the social performance is measured in terms of the impact of the distribution system on the societies involved with it. One, being the society that operates distribution and transportation tasks such as truck drivers. Another society involves customers/markets who receive products. Since the daily life of truck drivers is not explicitly modeled here, we investigate the social performance gain only based on the quality of service offered to customers in terms of response time.

Among the KPIs defined above, the total distribution cost impact is the sole KPI that can be measured both collectively and individually. There are two reasons behind this distinction that are resulted by the modeling approach applied in the collaborative distribution system. First, only the collective distribution web of the partnering businesses is optimized in the collaborative distribution system. Thus, comparing the environmental impact of individual business involved in a coalition with the dedicated and hyperconnected system, where the individual business networks are optimized would be unfair.

Second, a large part of the decision variables of the collaborative distribution design model are jointly make between companies in order to optimize the collective total distribution cost. For instance, the truckload flow between DCs, truckload outbound flow and DC opening are joint decisions. Hence, comparing the costs incurred by these joint decisions for minimizing the global cost, by similar decisions made individually in the dedicated and hyperconnected distribution system would be meaningless.

Lastly, the cross-distribution system KPIs determine the gain of responding to a single service level in various distribution systems. For instance, the gain of the total distribution cost of a single business by responding to the top service level in the hyperconnected distribution system compared to the total distribution cost of the same business responding to the same service level in dedicated distribution system is an example of a cross-distribution system KPI. Contrarily, the cross-service level KPIs, measure the ratio of an indicator within a single distribution system but through various service levels. The category of the distribution system is indicated using superscript s. The cross distribution system KPIs are denoted by a double superscript s-s'. Similarly, cross service level KPIs are indicated by $\tau - \tau'$. The two following examples describe the notation and calculation of KPIs.

Sample intra- distribution system KPI:

Business j dedicated total distribution cost gain by offering service level τ' *instead of* τ *:*

$$\rho^{d}_{j\tau-\tau'} = \frac{TDC^{d}_{j\tau'} - TDC^{d}_{j\tau}}{TDC^{d}_{j\tau}} \times 100\% \quad (5.1)$$

Sample cross- distribution system KPI:

Business j GHG emission production gain by offering service level τ in dedicated distribution system compared to the collaborative distribution system:

$$\gamma^{d-c}_{j\tau} = \frac{GHG^{c}_{j\tau} - GHG^{d}_{j\tau}}{GHG^{d}_{j\tau}} \times 100\% \quad (5.2)$$

Based on the three perspectives discussed previously, Table 5-1, summarizes the characteristics of the key performance indicators applied in this study from.

Table 5-1. Summary of the Key Performance Indicators characteristics

Key Performance Indicator	**Triple Bottom line**	**Collective/Individual business**	**Cross-Distribution System/Cross-Service Level**
Total Distribution Cost impact	Economic	Both	Both
Total DC Cost impact	Economic	Collective	
Total Transportation Cost impact	Economic	Collective	
Total Energy Consumption impact	Environmental	Collective	
Total GH emission production impact	Environmental	Collective	

5.3 Environmental performance estimation approach

Here, the environmental performance assessment of distribution systems takes into account the energy consumption and GHG emission generated by transportation activities and operating distribution centers as indicators of the environmental impact.

The key to estimate the transportation-induced environmental impact is to determine the total fuel consumption. Then applying the measures published by studies such as CLECAT guide (2012), the energy consumption and GHG emission production can be easily obtained. Regarding the environmental impact of distribution centers, the area of the building plays an important role in calculating its environmental impact. Figure 5-2 shows the methodology used in our investigation to analyze business-centric environmental performance. The detailed approach is described in the following section.

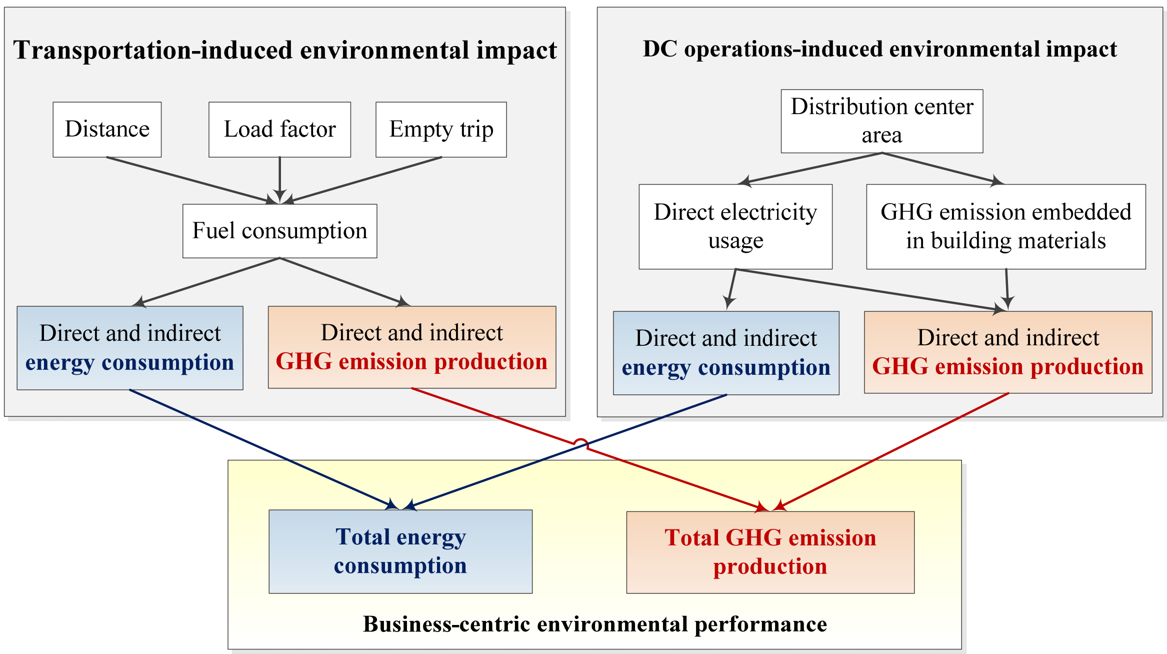

Figure 5-2. The environmental impact evaluation approach

5.3.1 Transportation-induced environmental performance

The European committee for standardization (CEN) has published standard measures and calculation methodology under EN 16258 name to determine the transportation-induced energy consumption and GHG emission. The general approach and emission measures provided by CEN are not limited to European countries. By selecting the right type of vehicle, road condition and other parameters, suitable measures can be derived and applied to the studies focusing on other territories. EN 16258 standards provide measures for direct and indirect impact (CLECAT guide, 2012); direct measures take into account the transportation operations and indirect measures, considers the impact of transportation-related processes such as fuel production, vehicle manufacturing and street construction. The summation of direct and indirect measures (called *total*) is applied in this study.

Table 5-2 represents the transportation-induced energy consumption and GHG emission generation indicated by CEN standards (CLECAT guide, 2012) for diesel fuel. It should be noted that, while CO_2 has the most extensive effects among all greenhouse gases, the measures provided by CEN take into account all five types of the greenhouse gases by using CO_2 equivalent units.

Table 5-2. Transportation-induced energy consumption and GHG emission generated (from CLECAT guide, 2012)

Fuel type	**Energy consumption** [TJ/L]		**GHG emission generation** [MKgCO_2.equivalent/L]	
	Direct	**Total**	**Direct**	**Total**
Diesel	3.59 E-5	4.27 E-5	2.67 E-6	3.24 E-6

Based on the measures provided in Table 5-2, the key is determining the total fuel consumed by transportation activities. According to European Association for Forwarding, Transport, Logistics and Customs Services (CLECAT guide, 2012), while calculating the fuel consumption, the impact of variables such as empty trips, load factor (truck filling rate) and distance traveled per shipment should be taken into account. These variables are influenced by the shipment options modeled in our study.

The TL trucks travel almost a direct route from the shipment origin to destination. We make similar assumption for MTL trucks as it is not trivial to estimate the length of the routing within each market zone. Undoubtedly, this assumption favors the environmental performance of transportation by MTL option. However, various size of market zones in this study, makes it somewhat impossible to estimate the length of total last mile delivery.

Usually, full trucks come back the same path partially or entirely empty Hence, the fuel consumption of the empty return should be considered within the responsibility of the products shipped forward (CLECAT guide, 2012). Contrarily, less than truckload and mobility web fleet travel through a network of hubs and terminals; each truck carries a part of a single shipment and might not return to the origin hub. Thus, considering the impact of the return trip becomes irrelevant. It should be noted that, the latter shipment options travel longer distance compared to full trucks between two nodes (because of passing through the network of hubs).

The TL filling rate of each shipment is directly derived from the solution of the distribution network design problem. The transportation quantity in the solution is represented in pallet/year unit. Thus, to find the filling rate it should be divided by both the number of working days in a year and the maximum number of pallets allowed in the truck. Rounding it to the next integer number, the average number of trucks per day per link or *daily shipment frequency* is calculated. Thus, the *average filling rate* of the flows shipped by TL is determined as follows:

$$v_{nn'j}^{m} = \frac{\left\lceil \frac{F_{nn'j}^{m}}{qw} \right\rceil - \frac{F_{nn'j}^{m}}{qw}}{\left\lceil \frac{F_{nn'j}^{m}}{qw} \right\rceil} \qquad m = TL, n' \notin Z \quad (5.3)$$

Where:

$v_{nn'j}^{m}$: Business *j* average daily truck filling rate from location *n* to *n'* by shipment option $m = TL$

$F_{nn'j}^{m}$: Number of pallets transported for business *j* from location *n* to *n'* by shipment option $m = TL$

q : Maximum number of pallets allowed in a full truck

w : Number of working days in a year

$\left\lceil \frac{F_{nn'j}^{m}}{qw} \right\rceil$: Average daily shipment frequency from location *n* to *n'* by shipment option $m = TL$

Note that, for outbound shipments the consolidation opportunity factor f_{lz}^{c} should be multiplied to qw as shown in (5.4).

$$v_{nn'j}^{m} = 1 - \left(\frac{\left\lceil \frac{F_{nn'j}^{m}}{qwf_{nn'}^{c}} \right\rceil - \frac{F_{nn'j}^{m}}{qwf_{nn'}^{c}}}{\left\lceil \frac{F_{nn'j}^{m}}{qwf_{nn'}^{c}} \right\rceil} \right) \qquad m = MTL, n' \in Z \quad (5.4)$$

Regarding LTL shipments, there is no means to calculate filling rate in our study, as we do not have information about the quantity transported by each truck. Thus, it is set to 60%, the average filling rate reported by McKinnon et al., (2010) and Sarraj et al., (2014). Based on Ballot et al., (2014), the filling rate by exploiting mobility web is assumed to experience 15% improvement compared to the current scenario. Hence, the MW filling rate is set to 75%.

To determine the last variable, shipment distance, the following approach is applied. Full truckload shipments travel a direct shortest path between any origin and destination. To take into account the impact of empty return trip, this distance is multiplied by two (assuming that trucks use the same path to return). The shipments by LTL pass through a hub and spoke network, which increases the travel distance compared to the direct shipments. In this study, the distance between all locations is determined by Google Map and represents the shortest path for a direct shipment.

The estimated shipment distance of LTL and MW relies on the preliminary results of a simulation-based research called BEIE in the laboratory of Professor Montreuil at Laval University. In this research several hub and spoke networks are simulated, among them the FedEx ground network (including 31 hubs in USA mainland in 2013), and PI-enabled Mobility Web hubs (including almost 160 hubs in US mainland). The results indicate that for the same origin and destination the distance traveled by LTL trucks is in average 34% longer than direct shipment and for MW, 12%. Derived from BEIE simulator, the distance through mobility web is on average 12% longer than the direct shortest distance. The reason behind lower percentage of distance increase compared to LTL is higher number of PI-hubs compared to LTL. The strategic location of the PI-hubs would enables creating routes similar to the direct shortest path.

It should be noted that the assumption made about the shipment distant do not impact the LTL/MW transportation cost and is only applied for the purpose of fair comparison between environmental performances of each shipment option. For instance, the LTL transportation cost per KM (Table 4-6) is directly derived from FedEx website for various distance intervals; it is assumed that the cost provided already takes into account the distance through hub and spoke network. Table 5-3 summarizes shipment options characteristics as applied in the environmental performance analysis.

Table 5-3. Environmental impact parameters associated with each shipment option

Shipment option	Filling rate $v_{nn'j}^{m}$	Empty return percentage over all shipments	Shipment distance influenced by return trip $\delta_{nn'}^{m}$
Full truckload TL/MTL	Derived directly from the distribution network design solution for each business and each *n-n'* link	25 %	75% of shipment, one-way 25% of shipments, round trip ($\delta_{nn'}^{m} = 1.25 \times \delta_{nn'}$)
Less than truckload LTL	v^{LTL} =60% Independent from the business characteristics and the distance of the link	Not included	One-way trip +34% ($\delta_{nn'}^{m} = 1.34 \times \delta_{nn'}$)
Mobility Web MW	v^{MW} =75% Independent from the business characteristics and the distance of the link	Not included	One-way trip +12% ($\delta_{nn'}^{m} = 1.12 \times \delta_{nn'}$)

Last step is to parameterize our approach based on the fleet type. Let $E_{nn'j}^{m}$ denote the fleet specific fuel consumption from *n* to *n'* in Liter/100 Km (adapted from CLECAT guide, 2012).

$$E_{nn'j}^{m} = A + B \times v_{nn'j}^{m} \tag{5.5}$$

Where,

A: Empty vehicle fuel consumption [L/100 Km]

B: Fully loaded vehicle consumption minus empty vehicle [L/ 100 Km]

In this study, truck 53 feet (or as indicated in the guide, articulated lorry with Gross Vehicle Weight of 24-40 t) is selected as the unique fleet type for all businesses regardless of the transportation mode. Thus, based on CLECAT guide 2012, the average value of parameter A and B among multiple tyoe of road are set to 22.1 and 11.3 respectively. Let I_j denote business *j* transportation-induced fuel consumption indicator. The value of I_j for a company can be calculated as follows (adapted from CLECAT guide, 2012).

$$I_j = \sum_m I_j^m \qquad \forall j \quad (5.6)$$

Where,

$$I_j^m = \sum_{n,n'} \left(\left\lceil \frac{F_{nn'j}^m}{qw} \right\rceil \times w \times \delta_{nn'}^m \times \frac{E_{nn'j}^m}{100} \right) \qquad m = TL \quad (5.7)$$

$$I_j^m = \sum_{lz} \left(\left\lceil \frac{F_{lzj}^m}{qwf_{lz}^c} \right\rceil \times w \times f_{lz}^c \times \delta_{lz}^m \times \frac{E_{lzj}^m}{100} \right) \qquad m = MTL \quad (5.8)$$

$$I_j^m = \sum_{n,n'} \left(\frac{F_{nn'j}^m}{qv^m} \times \delta_{nn'}^m \times \frac{E^m}{100} \right) \qquad m \in \{LTL, MW\} \quad (5.9)$$

Since the filling rate and the fleet specific fuel consumption for LTL and MW shipment options remain unchanged for all transportation links (indicated in Table 5-3), their notation is simplified to v^m and E^m.

In equation 5.7, the value of $E_{nn'j}^m$ and $\delta_{nn'}^m$ are multiplied to the annual shipment frequency since the fuel consumption $E_{nn'j}^m$ is measured per truck while the transportation flow data in this study is per pallets-year. Since in our modeling TL and MW flows represent less than one full truck per day, the transportation flow over the planning horizon by these options are not divided into the number of days. Mainly because the ceiling of such division would be one. Thus, each pallet carried by LTL/MW options is responsible for ($\frac{1}{qv^m}$) of the environmental impact generated by a truck.

Multiplying the fuel consumption indicator of each business, I_j, in the parameters provided in Table 5-2, the energy consumption and GHG emission production by transportation activities are calculated. These measures are summed to the DC-induced energy consumption and GHG emission production to determine the environmental KPIs (η and γ).

5.3.2 Distribution center-induced environmental performance

Usually, distribution centers impact environment from two sources; direct operations such as heating, lightning and material handling and indirect, as a result of activities that provided building construction materials (Rai et al., 2011).

Direct energy consumption and GHG emission generated by activities involved in a distribution center can be measured as a function of electricity usage per meter square (Rai et al., 2011). Greenhouse gases produced per electricity unit strongly vary from country to country depending on the source of electricity generation. Hence, the data provided in European CEN standard is not suitable to determine the electricity generation in North America.

On average, non-refrigerated warehouses in US consume 65.66 kWh/m^2-year electricity[1] in a year. It is known that each kWh electricity is equal to 3.6 E-6 TJ. Thus, using the DC area calculated per configuration in Table 4-3, the direct energy consumption of DC activities can be obtained. International Energy Agency reports the indirect energy content of electricity consumption to be 11.6 MJ/kWh (in 2008)[2], which gives the total energy consumption by electricity utilization in a DC to be 1.52 E-5 TJ/kWh.

According to the US Energy Information Administration, in 2014, on average 0.532 KgCO_2 is generated for each kWh electricity production. In order to unify the environmental performance measures associated with distribution centers and transportation, the CO_2 impact should be converted to CO_2 equivalent. The Center for Climate and Energy Solutions[3] states that in United States carbon dioxide makes up almost 99 percent of the greenhouse gas emissions produced by electricity generation. To this regard, the CO_2 equivalent generated directly by DC electricity usage is set to 0.538 Kg CO_2.equivalent /kWh, which is equal to 1.5 E-1MKg CO_2.equivalent /TJ.

Regarding the environmental impact of DCs embedded in the building material, no research to date has particularly conducted for North American countries. Relying on the calculations provided by (Rai et al., 2011) for United Kingdom, 370 kgCO_2 is accounted for each m^2 of a typical distribution center. This impact is accountable for the 25 years life span of the DC building. In accordance with the one-year planning horizon of our study, 1.48 E-5 MkgCO_2/m^2 is taken into account. The CO_2 impact of two major materials of the building, concrete and steel, which account for 80% of building's CO_2 impact (Rai et al., 2011) is almost equal to their CO2.equivalent[4]. Thus, we consider the measure determined above to be in CO2.equivalent unit.

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[1] - http://fpl.bizenergyadvisor.com/warehouses
[2] - Retrieved from: http://www.iea.org/publications/freepublications/publication/jprg_info_paper-1.pdf
[3] - http://www.c2es.org/technology/overview/electricity
[4] - Retrieved from: http://www.winnipeg.ca/finance/findata/matmgt/documents//2012/682-2012//682-2012_Appendix_H-WSTP_South_End_Plant_Process_Selection_Report/Appendix%207.pdf

The summation of the direct GHG emission (obtained from the total energy consumption) and the indirect GHG emission (calculated based on the building area) represents the total GHG emission. Table 5-4 summarizes the DC-induced environmental impact measures to determine the environmental performance of each business.

Table 5-4. Environmental impact measures associated with distribution center building and involved operations

Energy consumption		**GHG emission generation**	
Direct [TJ/kWh]	**Total** [TJ/kWh]	**Direct** [MKgCO_2.equivalent/ TJ]	**Indirect** [MKgCO_2.equivalent/m^2]
3.6 E-6	1.52 E-5	1.5 E-1	1.48 E-5

The energy consumption and direct GHG emission production of PI-enabled open DCs is calculated inspired by the 40% energy savings obtained by automation and efficient material handling in ES3's distribution center (Hambleton and Mannix, 2014). Noteworthy, the indirect GHG emission production remains unchanged for open and conventional DCs. Table 5-5 provides the final measures of Energy consumption and GHG emission calculated for both conventional and PI-enabled open DCs at each configuration.

The final energy consumption and GHG emission production is obtained by summation of DC-induced and transportation-induced measures calculated above.

Table 5-5. Distribution center-induced energy consumption and GHG emission generated for conventional and PI-enabled open DCs

Configuration	**Storage capacity** [Pallets]	**Area** [m^2]	**Conventional DC**		**PI-enabled Open DC**	
			Energy consumption [TJ]	**Total GHG emission** [MKg.CO_2.e]	**Energy consumption** [TJ]	**Total GHG emission** [MKg.CO_2.e]
1	100000	74000	73.85	12.17	44.31	7.74
2	50000	45000	44.91	7.4	26.95	4.71
3	10000	10000	9.98	1.65	5.99	1.05
4	5000	7000	6.99	1.15	4.19	0.73
5	1000	2200	2.20	0.36	1.32	0.23
6	100	300	0.30	0.05	0.18	0.03

5.4 Exploratory investigation

5.4.1 Calculations extension and solver characteristics

Our distribution network design model can be considered an extension of capacitated facility location problems, which are well known to be NP-hard (Gourdin et al. 2000; Mirchandani and Francis, 1990). Hence, our model also belongs to NP-hard class of problems.

In this investigation, overall number of 75 problem instances have been solved using two calculation resources; first, Colosse supercomputer of Laval University managed by Calcul Québec and Compute Canada organization and second, the severs of CIRRELT research center at Laval University. These computers operate with an Intel® Xeon ® CPU X5650 2.67 GHz 2.66 GHz (2 processors), between 18 to 72 GB RAM and were running Windows7 or Windows server 2008 R2 Enterprise operating systems. All problems were solved using IBM ILOG OPL Optimization Studio 12.6.1.

The size of the problem and their solution time varied per business, service level and characteristics of the distribution system. For instance, collaborative web design problems were the most time-consuming among all. We believe that modeling the TL and MTL transportation cost by a piecewise linear function has increased the complexity of the MIP problems. In addition, Table 5-6 shows that the number of non-zero coefficients is very high. This is another reason for the complexity of the problems.

Table 5-6. Characteristics of multiple distribution system-driven MIP problems solved in the investigation

Distribution system	**Dedicated and hyperconnected**		**Collaborative**	
Indicator \ **Problem size**	**Smallest**	**Largest**	**Smallest**	**Largest**
Number of binary variables	66	3623	1454	7124
Number of total variables	187	13100	2896	38687
Number of constraints	125	6656	1610	23996
Number of non-zero coefficients	703	46412	10805	119099

Although the tolerated optimality gap was set to 1% for all problems, the solving time varied from 5 minute to 20 hours. In order to obtain high quality results in reasonably short time, the OPL emphasize parameter was set to optimality. For several problems, the relaxation induced neighborhood search (RINS) heuristic was applied at 100-node interval. Noteworthy, the quality of solution obtained by the latter parameter setting has outperformed the ones by the default settings.

In the following section, first the performance of individual distribution systems and the value of the cross-service level KPIs are presented. Afterwards, the cross-distribution system performance results are presented and discussed.

5.4.2 Cross Service level performance gain

5.4.2.1 Dedicated distribution system performance

A. Economic performance

The economic performance of the dedicated distribution system is summarized in Table 5-7 for each of the three service level requirements sets. This table indicates the collective (all 10 business), the average and the individual business results (for three typical businesses with high, average and low annual throughput).

Table 5-7. Total dedicated distribution cost responding to each service level in [M$/year]

Service Level / Business	Top	Medium	Basic
All 10 Businesses	549	500	489
Average over 10 businesses	55	50	49
High-throughput business sample	142	141	140
Average -throughput business sample	66	60	59
Low-throughput business sample	31	24	22

Table 5-8 highlights the extra cost induced by requiring higher service level when relying on dedicated distribution.

Table 5-8. Economic total distribution cost impact of upgrading service level in dedicated distribution system

$$\rho^{d}_{\tau-\tau'}$$

Service Level / Business	Basic-to-Top	Medium-to-Top	Basic-To-Medium
All 10 Businesses	12%	10%	2%
Average over 10 businesses	12%	10%	2%
High-throughput business sample	1%	1%	1%
Average-throughput business sample	12%	10%	2%
Low-throughput business sample	41%	29%	9%

According to the results provided in Table 5-7, the total distribution cost of responding to the top service level over all 10 businesses sums up to 549 M$/year. For individual firms, this cost varies from 142 to 66 and 31 M$/year for high, average and low annual throughput respectively. Logically, the total distribution cost is expected to increase by responding to higher service levels. Table 5-8 indicates that for this case the increase for all businesses is a slight 2% from basic to medium service, then climbs to 10% from medium to high service, finally, an increase of 12% from basic to high service. In addition, the magnitude of cost increase for high throughput business is smaller as compared to the average and low throughput (1% in contrast to 12% and 41% to offer high service instead of basic service).

It is expected that by responding to lower service levels as compared to the top service level, businesses incur lower DC investment. However, the total transportation cost might not experience steep decline, since by centralizing the distribution on lower number of DCs the total distance traveled in the network would increase. Table 5-9,

Table 5-10 and

Table 5-11 support our presumptions by providing the total distribution center cost and total transportation cost for each service level.

Table 5-9. Number of DCs opened and total annual DC opening and warehousing cost (briefly DC cost) responding to each service level

Service Level	**Top**		**Medium**		**Basic**	
Business	**Number of DC (e1, e2)**	**DC cost** [M$/year]	**Number of DC (e1, e2)**	**DC cost** [M$/year]	**Number of DC (e1, e2)**	**DC cost** [M$/year]
All 10 Businesses	59 (24,35)	182	40 (28,12)	157.46	30 (24,6)	144.04
Average over 10 businesses	6 (2,4)	18	4 (3,1)	16	3 (2,1)	14

Table 5-10. Additional number of DCs and opening and warehousing cost required to respond to higher market service level $\lambda^{d}_{\tau-\tau'}$

Service level	**Basic-to-Top**			**Medium-to-Top**			**Basic-To-Medium**		
Business	**DC to add**	**Additional DC cost** [M$/year]	$\lambda^{d}_{\tau-\tau'}$	**DC to add**	**Additional DC cost** [M$/year]	$\lambda^{d}_{\tau-\tau'}$	**DC to add**	**Additional DC cost** [M$/year]	$\lambda^{d}_{\tau-\tau'}$
All 10 Businesses	29	38	26%	19	24	16%	10	13	9%
Average over 10 businesses	3	4	29%	2	2	13%	1	1	14%

Table 5-11.Transportation cost performance and impact by responding to higher service level

Business	Total transportation cost			Total transportation cost impact		
	Top	Medium	Basic	Basic-to-Top	Medium-to-Top	Basic-To-Medium
All 10 Businesses	313	296	294	6%	6%	1%
Average over 10 businesses	31	30	29	7%	3%	3%

The same finding can be witnessed by comparing Figure 5-3 and Figure 5-4 that depict the optimized distribution networks of an average-throughput business respectively for basic and top service.

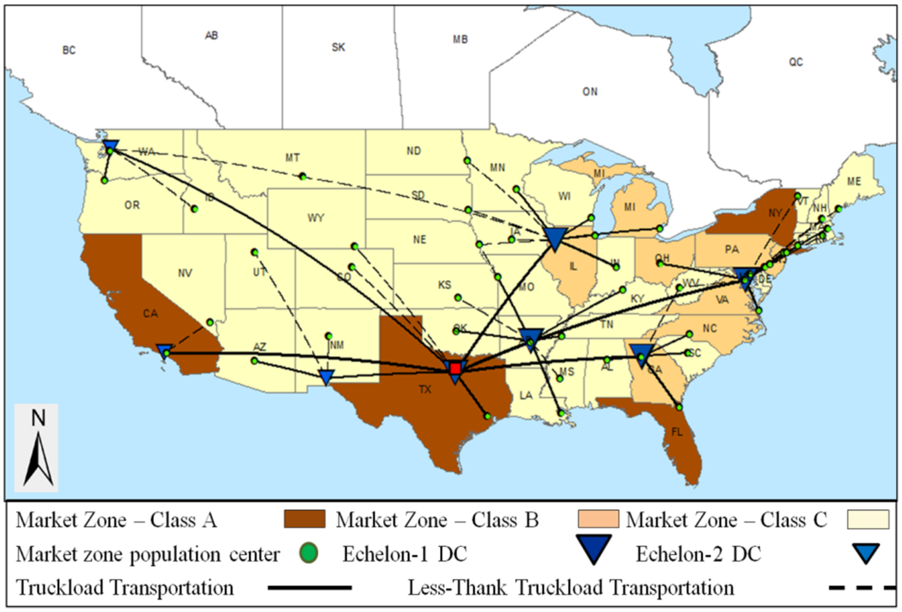

Figure 5-3. Dedicated distribution network of the typical average throughput business responding to the top service level

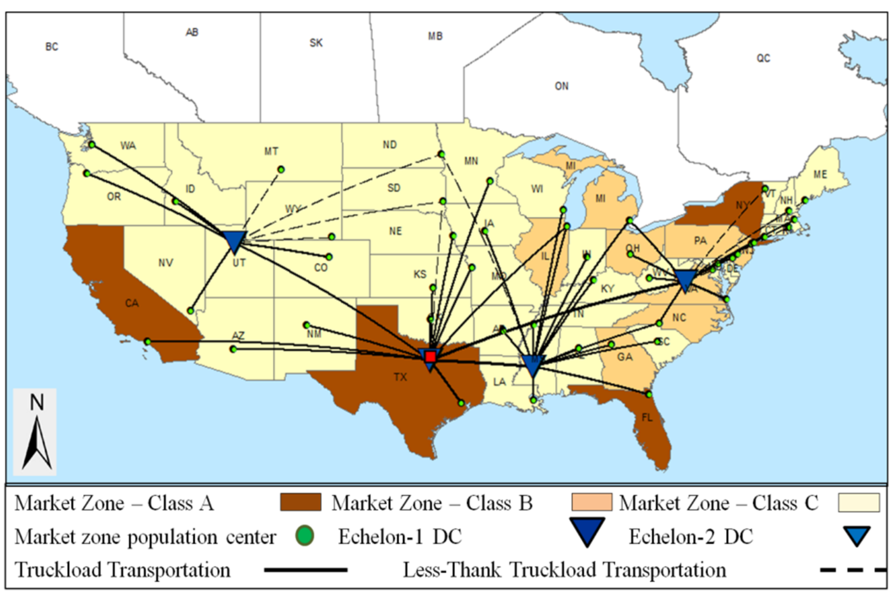

Figure 5-4. Dedicated distribution network of the typical average throughput business responding to the basic service level

B. Environmental performance

The results presented in the previous section, confirm that responding to lower service level, businesses tend to increase the centralization, which translates to opening of lower number of larger DCs and higher truckload shipments. Thus, it is expected to experience a notable decline in the energy consumption and GHG emission. The findings of our investigation presented in Table 5-12 and

Table 5-13,

Table 5-14 and

Table 5-15 support this idea.

Table 5-12. Total energy consumption responding to each service level in [TJ/year]

Business \ Service Level	Top	Medium	Basic
All 10 Businesses	3768	3542	3363
Average over 10 businesses	377	354	336

Table 5-13. Total GHG production responding to each service level in [MKgCO_2.equivalent/year]

Business \ Service Level	Top	Medium	Basic
All 10 Businesses	324	302	287
Average over 10 businesses	32	30	29

Table 5-14. Energy consumption impact of upgrading service level in dedicated distribution system

Business \ Service Level	Basic-to-Top	Medium-to-Top	Basic-To-Medium
All 10 Businesses	12%	6%	5%

Average over 10 businesses	12%	6%	5%

Table 5-15. GHG production impact of upgrading service level in dedicated distribution system

Business \ Service Level	Basic-to-Top	Medium-to-Top	Basic-To-Medium
All 10 Businesses	13%	7%	5%
Average over 10 businesses	10%	7%	3%

According to Table 5-12, the energy consumption over all 10 businesses responding to top service level arrives to 3768 TJ/year. This amount is reduced to 3542 and 3363 TJ/year offering medium and basic service level. This gain represents the impact of consolidation and economies of scale that businesses can benefit from when responding to lower service levels. The total GHG emission generated by 10 businesses is reported by

Table 5-13 equal to 324, 302 and 287 MKgCO2.equivalent/year responding to top, medium and basic. In average, the energy consumption and GHG emission is at least increased by 12% by providing top service level in contrast to the basic, 6% and 5% by providing top service level in contrast to the medium and medium instead of basic respectively.

5.4.2.2 Collaborative distribution performance analysis

A. Economic performance

The economic performance of the collaborative distribution system is summarized in Table 5-16 and Table 5-17 for each service level requirements sets.

Table 5-16. Total collaborative distribution cost responding to each service level [M$/year]

Business \ Service Level	Top	Medium	Basic
All 10 Businesses	502	466	454
Average over 10 businesses	50	47	45
High-throughput business sample	134	134	132
Average-throughput business sample	60	54	54
Low-throughput business sample	25	20	19

Table 5-17. Intra-collaborative distribution system cross-service level economic performance $\rho^{c}_{\tau\tau' jn}$

Business \ Service Level	Basic-to-Top	Medium-to-Top	Basic-To-Medium
All 10 Businesses	11%	8%	3%
Average over 10 businesses	11%	6%	4%
High-throughput business sample	2%	0%	2%
Average-throughput business sample	11%	11%	0%
Low-throughput business sample	32%	25%	5%

According to the results presented in Table 5-16, the collective total collaborative distribution cost responding to the top service level is equal to 502 M$/year. This cost reduces to 466 and 454 M$/year respectively for medium and low service levels. As reported in Table 5-17, the cost of upgrading service to the top level is on average 11% from the basic and 8% from the medium service level. These economic impacts are equivalent of 48 and 36 M$/year.

The following tables specifies the collective total DC cost and transportation cost in the environmental distribution system. Based on the results provided in Table 5-18, surprisingly the number of DCs opened and their incurred costs are increasing by responding to the basic service level. This is due to the large size of the collaborative distribution web design problems particularly by offering the basic service level (higher number of incident links), which makes solving these MIPs more challenging for CPLEX. Thus, while solving these large problems, the solver was stopped at higher optimality gap compared to the rest of problems. This solution challenge indicates one of the limitations of our research and encourages us to apply a strong heuristic approach that is capable of solving large problem instances with an acceptable quality-time compromise for further research.

Table 5-18. Number of DCs opened at each echelon and total annual DC opening and warehousing cost responding to each service level

Service Level	**Top**		**Medium**		**Basic**	
Business	**Number of DC (e1, e2)**	**DC cost** [M$/year]	**Number of DC (e1, e2)**	**DC cost** [M$/year]	**Number of DC (e1, e2)**	**DC opening and warehousing cost** [M$/year]
All 10 Businesses	48(22,26)	157	29(14,15)	129	30(14,16)	135
Average over 10 businesses	5(2,3)	16	3(1,2)	13	3(1,2)	14

Table 5-19. Additional DC opening and warehousing cost required to respond to higher market service level

Service level	**Basic-to-Top**			**Medium-to-Top**			**Basic-To-Medium**		
Indicator	**DC to add**	**Additional DC cost** [M$/year]	**Additional DC cost %**	**DC to add**	**Additional DC cost** [M$/year]	**Additional DC cost %**	**DC to add**	**Additional DC cost** [M$/year]	**Additional DC cost %**
All 10 Businesses	18	23	17%	19	25	19%	-1	-6	-2%
Average over 10 businesses	2	2	14%	2	3	23%	0	-0.6	-7%

Table 5-20. Transportation cost performance and impact by responding to higher service level

Business	Total transportation cost			Total transportation cost impact		
	Top	**Medium**	**Basic**	**Basic-to-Top**	**Medium-to-Top**	**Basic-To-Medium**
All 10 Businesses	289	280	264	9%	3%	6%
Average over 10 businesses	3	3	3	0%	0%	0%

Figure 5-5 and Figure 5-6 show the optimized collaborative distribution web of the sample average throughput business responding to the basic and top service levels. The flow of the partnering business is removed from the maps to ease the comparison of these figures with Figure 5-3 and Figure 5-4.

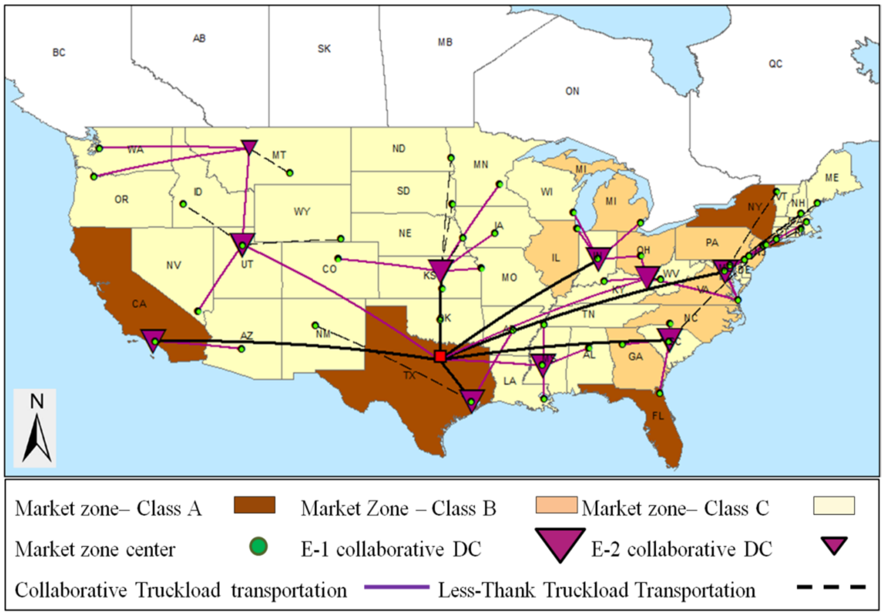

Figure 5-5. Collaborative distribution web of the typical average throughput business responding to the top service level

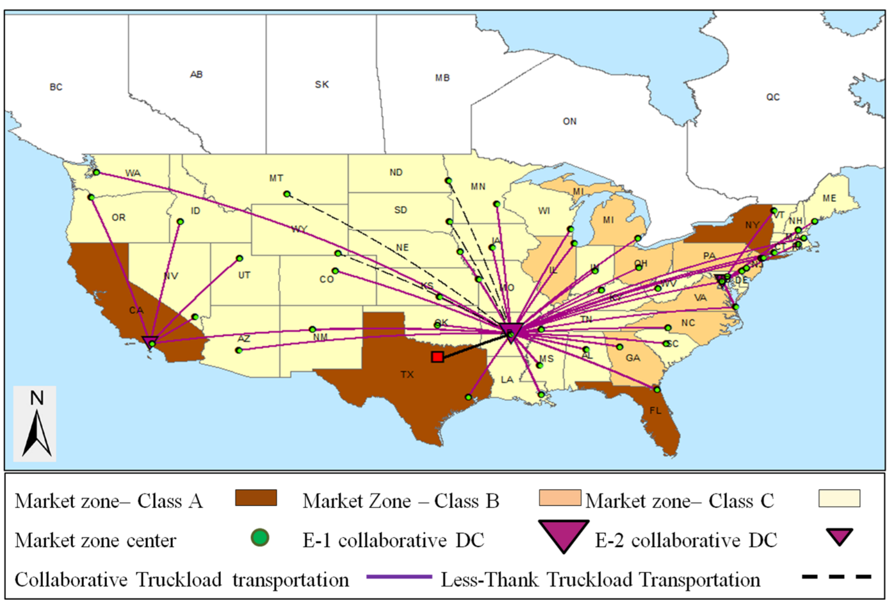

Figure 5-6. Collaborative distribution web of the typical average throughput business responding to the basic service level

B. Environmental performance

Similar to the dedicated distribution system, it is expected to experience a decline in the total environmental impact by offering lower service levels, since partnering companies increase the truck filling rate by consolidation and invest in DCs jointly. Table 5-21, Table 5-22, Table 5-23 and

Table 5-24 support this expectation.

Table 5-21. Energy consumption of the collaborative distribution system responding to each service level

Service Level / Business	Top	Medium	Basic
All 10 Businesses	3720	3516	3439
Average over 10 businesses	372	352	344

Table 5-22. GHG emission production of the collaborative distribution system responding to each service level

Service Level / Business	Top	Medium	Basic
All 10 Businesses	315	290	283
Average over 10 businesses	32	29	28

Table 5-23. Energy consumption impact of upgrading service level in collaborative distribution system $\eta^{c}_{\tau jn}$

Service Level / Business	Basic-to-Top	Medium-to-Top	Basic-To-Medium
All 10 Businesses	8%	6%	2%
Average over 10 businesses	8%	6%	2%

Table 5-24. GHG emission production impact of upgrading service level in collaborative distribution system

$\gamma^{c}_{\tau jn}$

Business \ Service Level	Basic-to-Top	Medium-to-Top	Basic-To-Medium
All 10 Businesses	11%	9%	2%
Average over 10 businesses	14%	10%	4%

By upgrading to the top service level, the collective energy consumption of the collaborative distribution system increases by 8% and 6% by shifting from the basic and medium service level respectively. The value of this energy consumption increase is equivalent of 32 and 25 TJ/year. Similar results are obtained regarding the GHG emission production, while the percentage of impact increase is slightly higher (11% and 9%)

5.4.2.3 Hyperconnected distribution performance analysis

A. Economic performance

The total hyperconnected distribution cost responding to various service levels is presented in Table 5-25 and Table 5-26. The collective TDC offering top service level is 364 M$/year. This value somewhat reduces to 352 M$/year for the basic service level. The individual business total distribution cost varies from 104 to 15 M$/year for high and low throughput businesses responding to the top service level. Similar to the collective performance, by offering top service level, the individual TDC is not strongly impacted (between 0 to 7% according to Table 5-26).

Table 5-25. Total hyperconnected distribution cost responding to each service level in [M$/year]

Business \ Service Level	Top	Medium	Basic
All 10 Businesses	364	359	352
Average over 10 businesses	36	36	35
High-throughput business sample	104	104	104
Average-throughput business sample	43	43	42
Low-throughput business sample	15	15	14

Table 5-26. Intra-hyperconnected distribution cost cross-service level ($\rho^{d}_{\tau\tau' j}$)

Business \ Service Level	Basic-to-Top	Medium-to-Top	Basic-To-Medium
All 10 Businesses	3%	1%	2%
Average over 10 businesses	3%	0%	2%
High-throughput business sample	0%	0%	0%
Average-throughput business sample	2%	0%	2%
Low-throughput business sample	7%	0%	7%

Note that the value of all measures is rounded after conversion to M$/year (or TJ/year and $MKgCO_2$.equivalent/year for environmental KPIs). Hence, some measures experience a slight change from a service level to another. While their rounded value represents zero variation. For instance, the total distribution cost of the high-throughput business indicated as 104 M$/year in table 5-25 is in fact 104 460 746 responding to the top service level and 104 270 011, responding to the basic service level. Hence, the impact is not exactly zero but negligible. Based on such findings, we can argue that offering higher service level in hyperconnected distribution system has lower and even in some cases, almost zero economic impacts. This conclusion can be also witnessed by similarity of the network topology depicted in Figure 5-7and Figure 5-8.

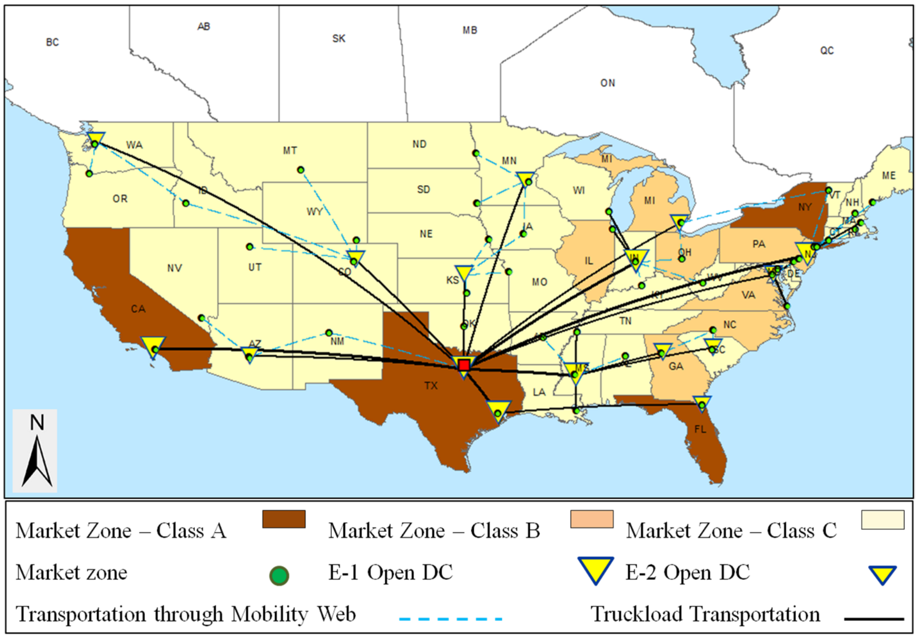

Figure 5-7. Hyperconnected distribution web of the average throughput typical business responding to the top service level

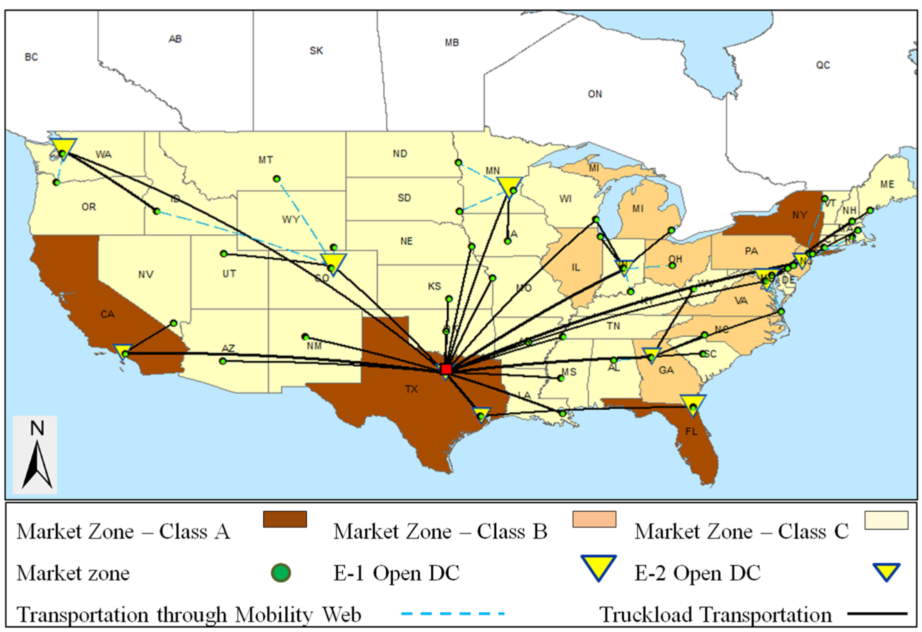

Figure 5-8. Hyperconnected distribution web of the average throughput typical business responding to the basic service level

B. Environmental performance

The energy consumption and GHG emission production of the hyperconnected distribution system cross-service level is presented in Table 5-27 and Table 5-28.

Table 5-27. Energy consumption of the hyperconnected distribution system responding to each service level

Service Level / Business	Basic-to-Top	Average-to-Top	Basic-To-Average
All 10 Businesses	3 321	3 310	3 304
Average over 10 businesses	332	331	330

Table 5-28. GHG emission production of the hyperconnected distribution system responding to each service level

Service Level / Business	Basic-to-Top	Average-to-Top	Basic-To-Average
All 10 Businesses	283	281	281
Average over 10 businesses	28	28	28

The collective energy consumption of the hyperconnected distribution system is 3321 TJ/year. This value is slightly declined to 3304 by responding to the basic service level. Similar to the economic performance of the hyperconnected distribution system, the environmental impact by responding to the higher service level is not increased considerably. Table 5-29 and Table 5-30 present the ratio of the environmental impact in the hyperconnected distribution system.

Table 5-29. Energy consumption impact of upgrading service level in hyperconnected distribution system $\eta^{h}_{j\tau-\tau'}$

Business \ Service Level	Basic-to-Top	Medium-to-Top	Basic-To-Medium
All 10 Businesses	0.5%	0.3%	0.2%
Average over 10 businesses	0.6%	0.3%	0.3%

Table 5-30. GHG emission production impact of upgrading service level in hyperconnected distribution system $\gamma^{h}_{j\tau-\tau'}$

Business \ Service Level	Basic-to-Top	Medium-to-Top	Basic-To-Medium
All 10 Businesses	0.7%	0.7%	0.0%
Average over 10 businesses	0%	0%	0%

5.4.3 Cross distribution system performance gain

In this section the economic and environmental performance of the collective and/or individual set of businesses, responding to each service level is assessed cross the distribution system.

5.4.3.1 Economic impact

According to the results obtained by our investigation, the collective total distribution cost responding to the top service level experiences a 34% decrease from dedicated to hyperconnected distribution system. Almost 27% gain are at stake for shifting from the collaborative distribution system to the hyperconnected, while the impact of shifting to the collaboration from the dedicated is only 9%. These gain percentages represent 185, 138 and 47 M$/year. Figure 5-9 depicts the collective impact of changing the distribution system for multiple service levels defined in this study.

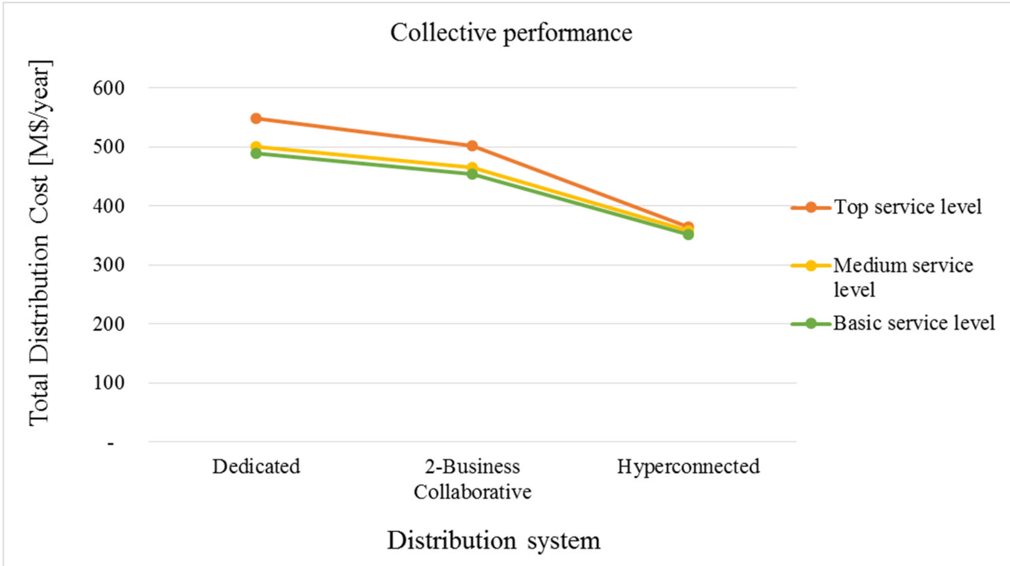

Figure 5-9. Collective economic performance gain in terms of total distribution cost as a function of service level

The individual business economic performance impact by exploiting the hyperconnected distribution system is shown in Figure 5-10, Figure 5-11 and Figure 5-12. It can be observed that the performance of low-throughput business sample experience higher gain ratio in comparison to the high-throughput.

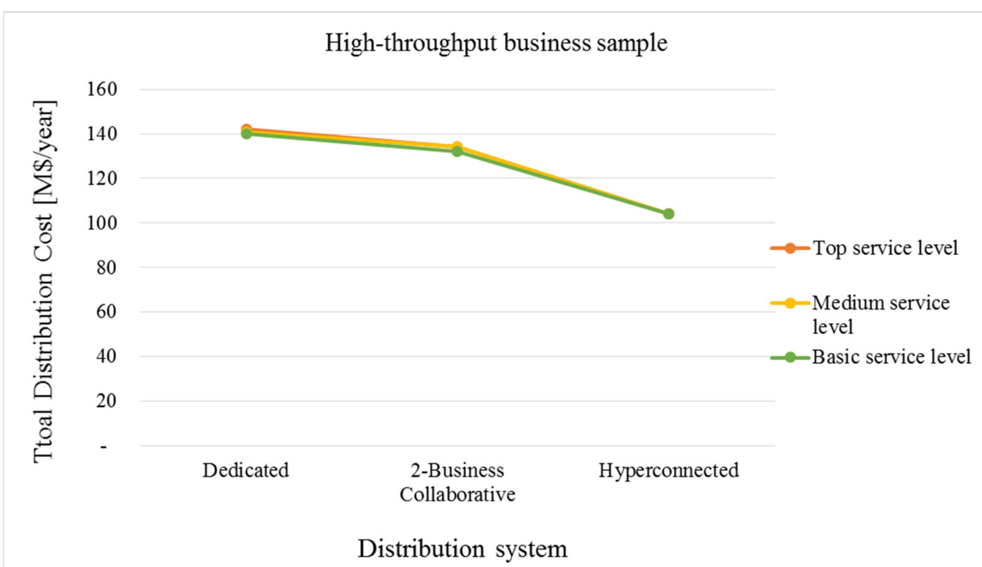

Figure 5-10. High-throughput business sample economic performance gain in terms of total distribution cost as a function of service level

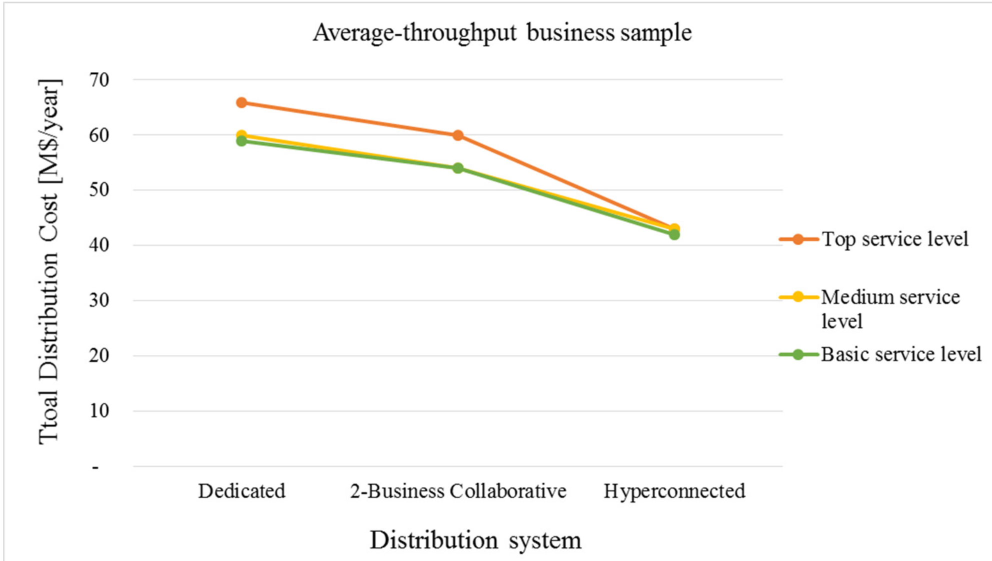

Figure 5-11. Average-throughput business sample economic performance gain in terms of total distribution cost as a function of service level

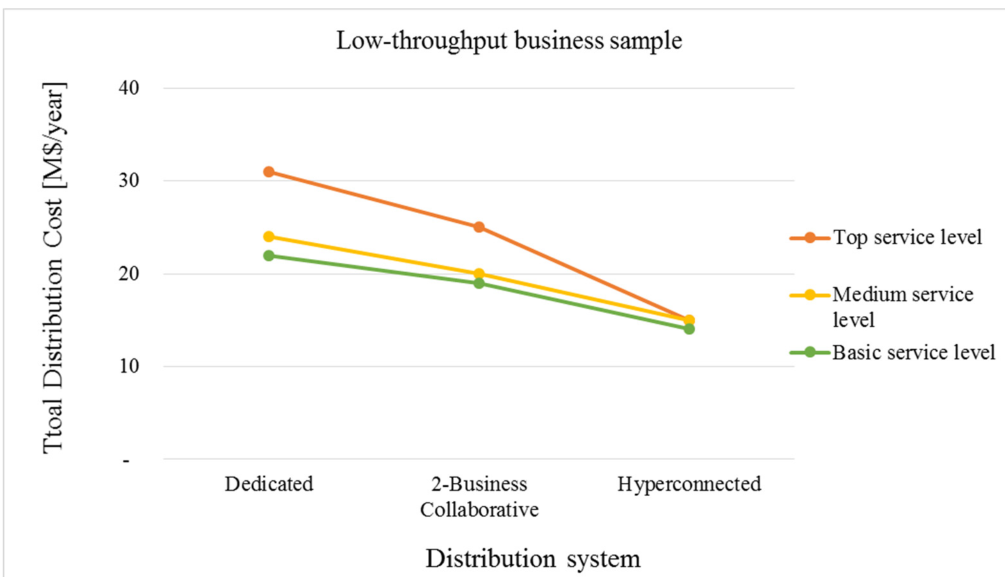

Figure 5-12. Low-throughput business sample economic performance gain in terms of total distribution cost as a function of service level

The collective total distribution center-related cost in the dedicated distribution system is equal to 182 M$/year by responding to the top service level. This value can be reduced to 157 and 61 M$/year by shifting to the collaborative and hyperconnected distribution systems respectively. The gain is between 61-66% by exploiting the hyperconnected distribution system, which is equivalent of 121 and 96 M$/year.

Figure 5-13 shows the collective economic gain in terms of total DC opening and warehousing costs by exploiting the hyperconnected distribution system in comparison to the dedicated and collaborative distribution systems. The total transportation cost in the dedicated distribution system is equal to 313 M$/year. This value can be reduced to 289 and 246 M$/year by shifting to the collaborative and hyperconnected distribution systems respectively. The gain ratio indicates almost 21 and 15% decline by exploiting the hyperconnected distribution system, which is in the line with the findings of Ellis et al. (2013).

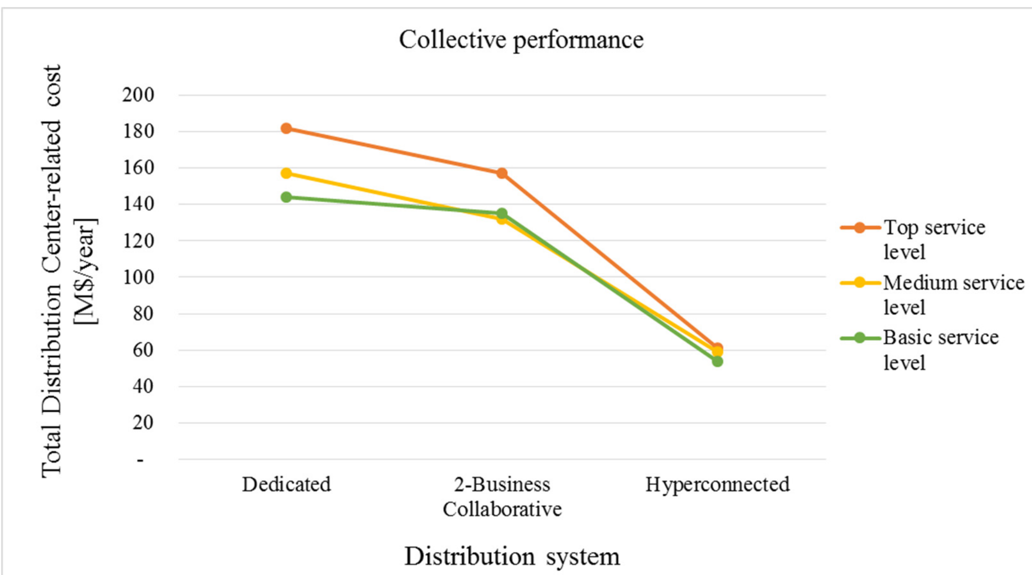

Figure 5-13. Collective economic performance gain in terms of total DC opening and warehousing cost as a function of service level

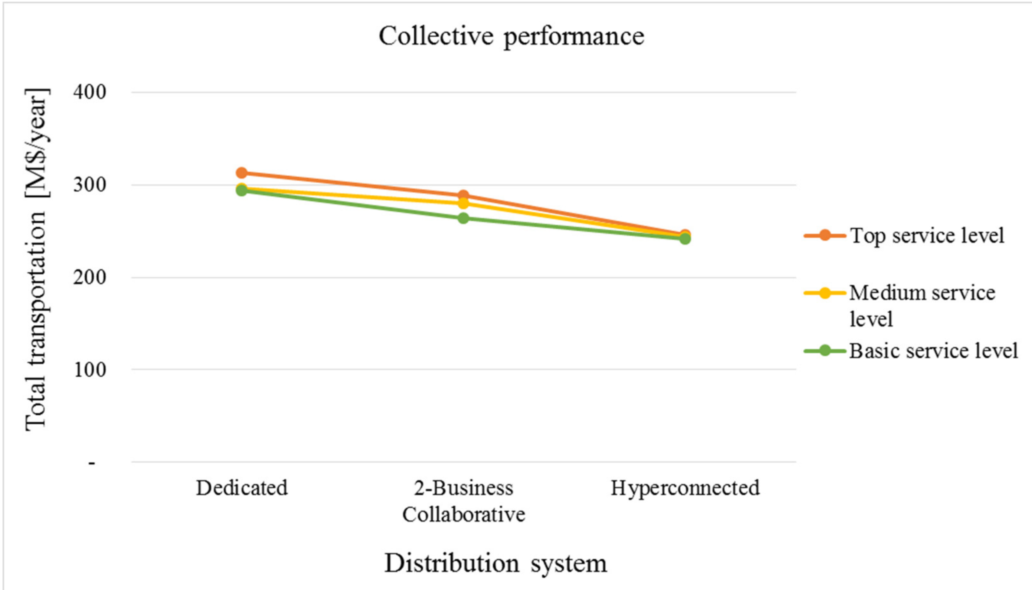

Figure 5-14. Collective economic performance gain in terms of total transportation cost as a function of service level

5.4.3.2 Environmental impact

The collective energy consumption in the dedicated and collaborative distribution system is equal to 3768, 3720 TJ/year by offering the top service level. This amount can be reduced to 3321 TJ/year by exploiting the hyperconnected distribution system and keeping the service level the same. The energy consumption gain by exploiting the hyperconnected distribution system can experience almost 12% improvement. Yet, by offering the medium and basic service levels the gain is smaller (7 and 2% respectively). Figure 5-15 depicts the variation of the energy consumption gain by offering the service levels defined in this research. Figure 5-16 shows the GHG emission production impact by exploiting the hyperconnected distribution system responding to each service level.

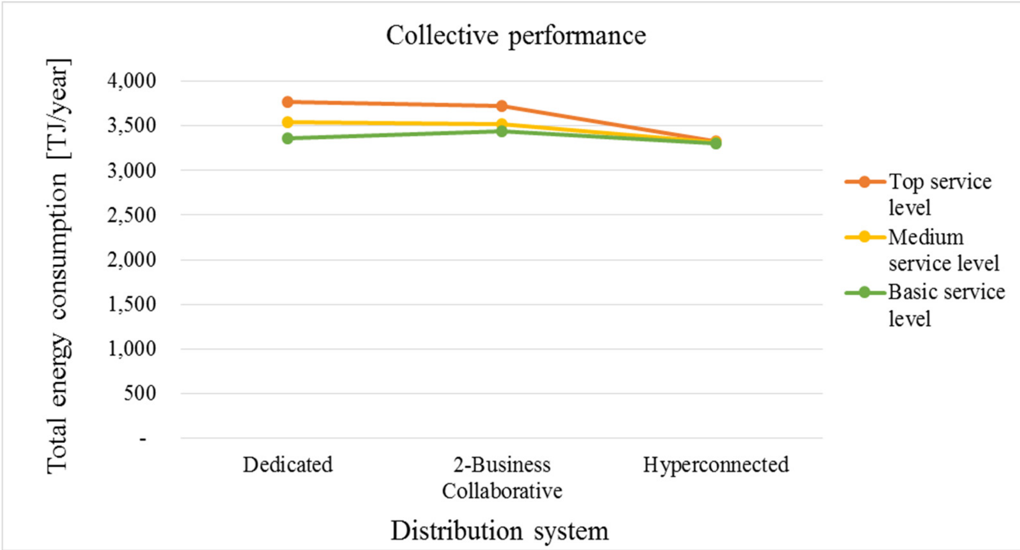

Figure 5-15. Collective environmental performance gain in terms of total GHG emission production as a function of service level

The collective GHG emission production of the hyperconnected distribution system is 283 KgCO$_2$.equivalent/year, which is 13% and 10% lower than the dedicated and collaborative distribution systems.

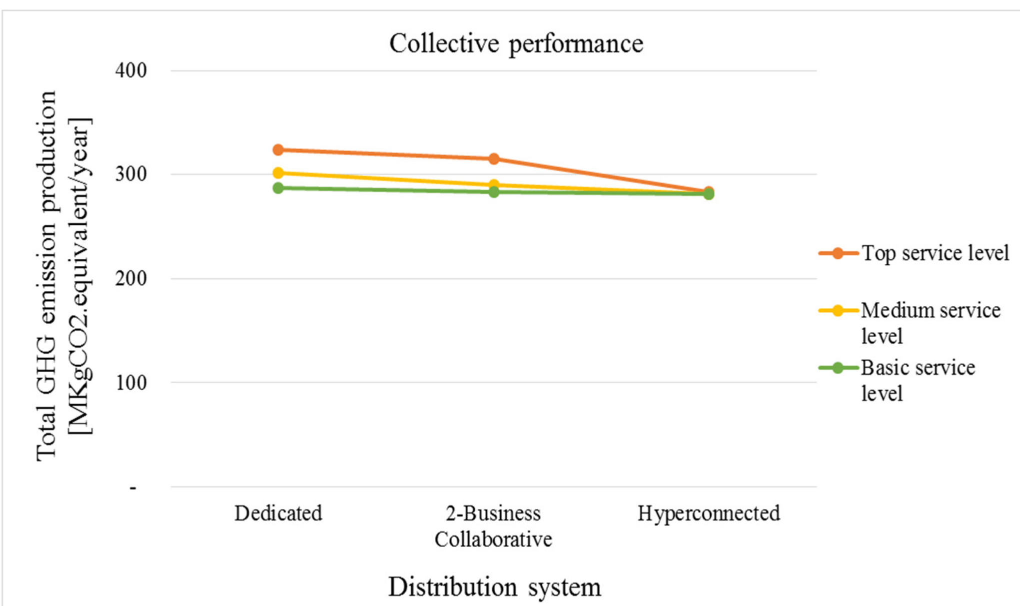

Figure 5-16. Collective environmental performance gain in terms of total energy consumption as a function of service level

5.5 Conclusion

This chapter contrasted the economic and environmental performance of dedicated, collaborative and hyperconnected distribution systems responding to a set of predetermined social performance. The results of the investigation are very promising. There is almost 31 % gain on the collective total distribution cost and 12 % gain on the collective environmental performance (the average between EC and GHG of the average business). These gains are in the line with the similar studies (more focused on the PI-enabled hyperconnected transportation) such as Ballot et al. (2014) and Ellis et al. (2013), which confirms the robustness of our investigation.

Chapter 6

Hyperconnected distribution planning framework

6.1 Introduction

Based on (Montreuil, 2011; Montreuil et al., 2013), in a hyperconnected distribution system business can dynamically deploy their products in large number of open DCs that are owned and operated by other businesses. In the previous chapters, we have investigated the potential performance improvements at stake by hyperconnected distribution. In this chapter, we provide levers to serve two purposes: I) create a platform for future simulation studies to investigate the flexibility and resiliency of hyperconnected distribution webs, II) assist managers in applying hyperconnection practices in real world cases by providing analytical models.

This chapter introduces a Hyperconnected Distribution Planning (HDP) framework structured through four interlaced levels concerned by physical topology, logical topology and operations in a hyperconnected distribution system. Experimentation and application of HDP is subject of our future research. Figure 6-1 underlines this chapter's place in the research approach.

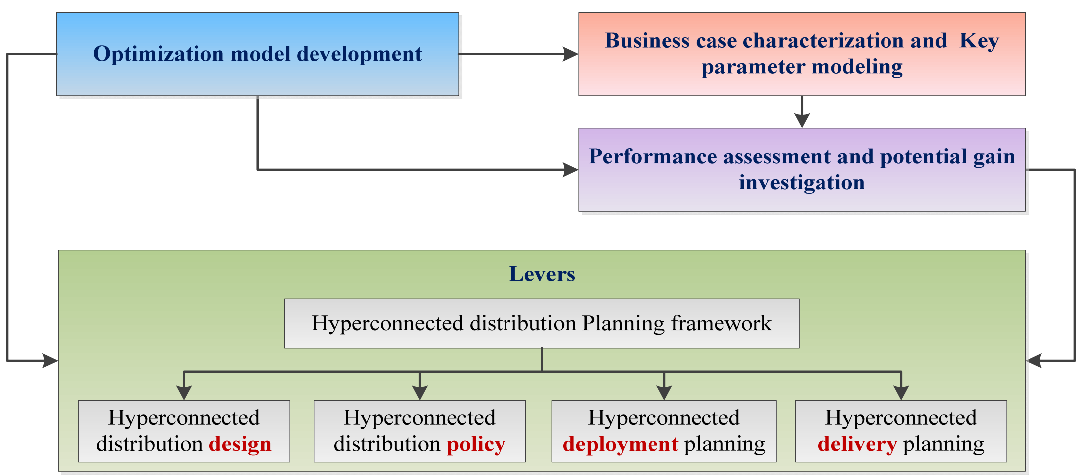

Figure 6-1. Hyperconnected distribution planning framework underlined in the research approach

6.2 Framework structure

In this chapter, we introduce the Hyperconnected Distribution Planning framework including four interlaced planning levels called Hyperconnected Distribution design, Hyperconnected Distribution policy, Hyperconnected Deployment planning and Hyperconnected Delivery planning. Each level involves a planning horizon, a set of input and output parameters and variables, optimization models or heuristics protocols and a set of performance indicators.

The planning horizon duration indicates the time span of forecasts, decisions and activities without implying a fixed planning frequency. For instance, if the planning horizon of a level is three months, it is not meant that this planning should be performed only four times a year. It does rather mean that at any time the revision of this planning level is necessary; the decisions involved are spanned over a planning horizon covering the next three months.

The input parameters and variables are either obtained from the output of the previous level or by the assumptions made in the current level. These values are used in the optimization models and protocols to determine the output of the planning level.

The role of performance indicators is to trigger revision of the previous planning levels. By monitoring the value of these indicators and comparing them to performance norms or targets, managers can evaluate the performance of the distribution system as a whole. It enables them to detect the sources of inefficiency and refresh the previous planning levels if necessary. Noteworthy, at any time that the decisions at a previous level are updated, it entails the revision of the following planning levels.

Figure 6-2. presents the Hyperconnected Distribution Planning framework and depicts the connection between the planning levels.

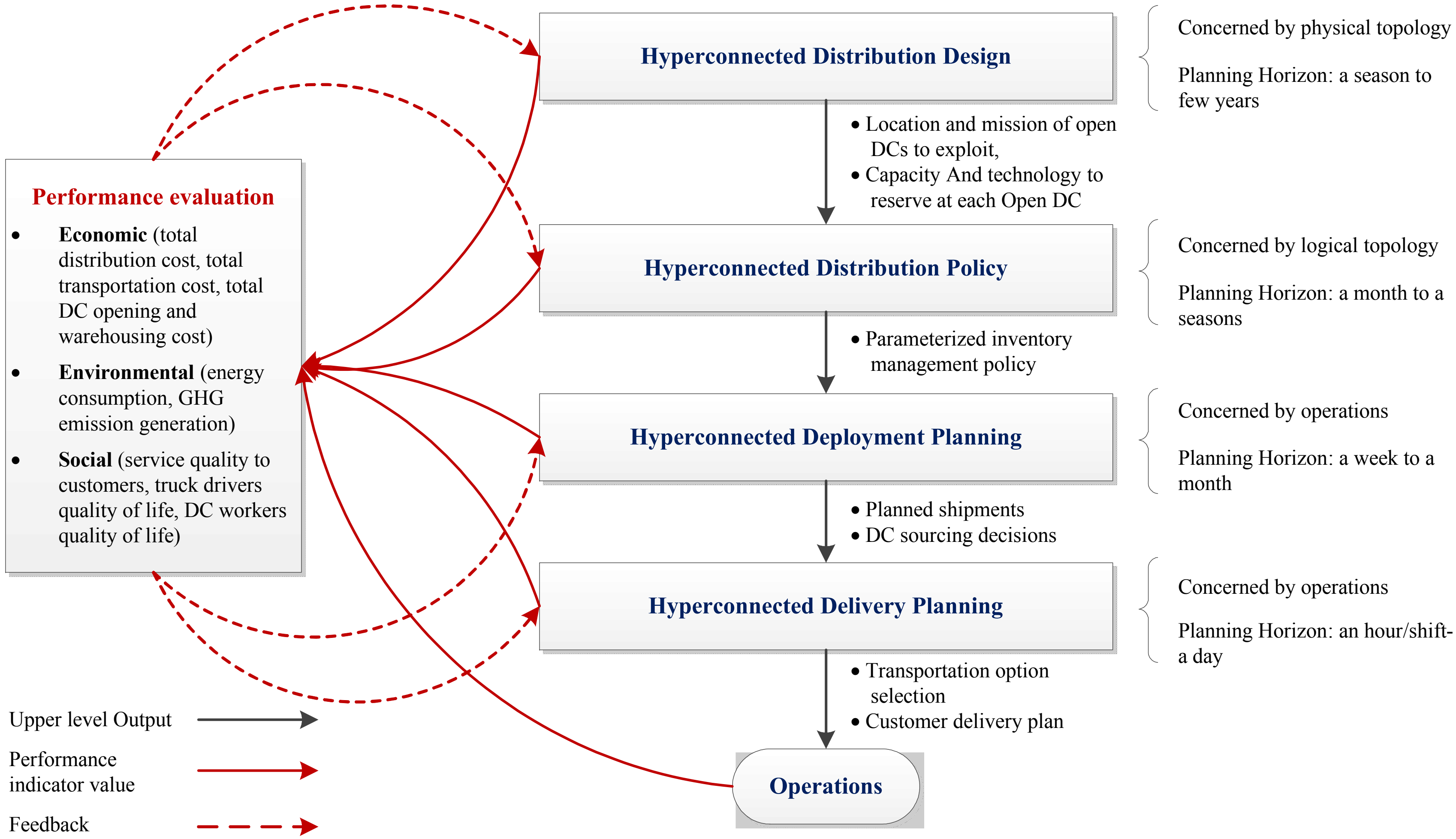

Figure 6-2. The interlaced levels of Hyperconnected Distribution Planning framework

6.3 Hyperconnected Distribution design

The first planning level focuses on the hyperconnected distribution design for a relatively long-term horizon compared to the other hyperconnected planning levels. Exploiting PI enables reengineering of the distribution network more often than existing practices. Depending on the clock speed of the company (Fine, 1998), this horizon may cover several years, a year or a season.

The input data required at this level include the set of potential open DCs, their available capacity and offered cost, the set of markets, their service level and future demand, as well as, production or activity level at plant(s). The goal is to design the hyperconnected distribution web minimizing the total distribution costs.

The output of this level includes a set of open distribution centers to exploit, their missions and required capacity to reserve and the set of markets to cover. The market coverage results obtained here will be used in the following planning levels to ensure a service quality to markets by keeping enough inventory at the right place and right time. However, this does not mean that markets will be always served from a predetermined DC. Influenced by stock availability, this decision can be altered at operational level. The stochastic optimization model presented in the following section is developed to serve the hyperconnected distribution design at this level.

The indicators of this level include open DC capacity utilization rate. The reaction to low capacity utilization a DC might be to close or relocate it. This decision can entail early closing penalty imposed by the open DC owner. The over usage of the capacity demonstrates the need for higher capacity whether in the same open DC or a new one.

By applying the distribution system-driven models proposed in chapter 3, we were able to investigate the potential performance gain by adopting hyperconnected distribution system in chapter 4. While these models were robust enough to enable design and investigation of the distribution network/web of illustrative business cases, some of their fundamental assumptions and modeling features are too simple for the sole purpose of designing hyperconnected distribution webs. For instance, demand is assumed to be known with constant pace. Multi-product and product-dependent costs are neglected. Moreover, the open DCs only differ with conventional DCs in terms of cost.

In this section, we attempt to develop an elaborated distribution network design problem to take into account the dynamism and uncertainty of the business environment, in addition to the characteristics of exploiting PI-enabled Distribution Web. It should be noted that the core modeling approach provides a solid foundation for this stochastic model; several contributions of the deterministic model is employed including transportation flow modeling and cost modeling approaches.

6.3.1 Problem description and planning approach

The hyperconnected distribution strategy described in chapter 5, considers for a single company exploiting the Physical Internet enabled Distribution Web. It is assumed that Physical Internet is fully functional functionality at the decision making time. In other words, a large set of PI-certified hyperconnected DCs and warehouses are available to PI certified users. Moreover, the Mobility Web is assumed fully functional.

A company who wishes to exploit the Distribution Web (*User* hereafter), has to select a set of open DCs and to determine their mission in terms of required capacity, echelon and the subset of markets/DCs to supply. Companies who run the potential open DC (*Owner* hereafter), provide necessary information such as DC's available space and the corresponding costs to all certified Users through a secured PI database. Thus, User has explicit knowledge about the offerings of DW at the time of decision making.

The decisions upon open DC selection and the capacity to occupy at each one should be taken at the beginning of the planning horizon. However, these decisions should be influenced by the operational level decisions such as the transportation, inventory and possible over usage of the capacity. These decisions are influenced by the future business environment, which is unknown at the beginning of the planning horizon. At best, several plausible future environments may possible to anticipate (Klibi et al., 2010).

Several approaches have been proposed in the literature to characterize the future environment, using point forecasting, interval forecasting and sensitivity/risk analysis (Singh, 2009). Montreuil and Laforge (1992) applied a scenario tree approach to model stochastic business environment. Klibi and Martel (2012) developed scenarios using several potential future evolutionary paths to shape the influence of economic and demographic key transitions on the business environment. According to the hyperconnected planning framework presented in chapter 5, the planning horizon of distribution strategy (the planning step which uses the stochastic MIP as a tool), can be as short as a season or maximum one year. Thus, it is reasonable to assume the economic and geo-political forces changing the business environment remain stable during this period. Hence, it is possible to include multiple pessimistic and optimistic scenarios for the purpose of sensitivity analysis.

Figure 6-3 presents our modeling approach incorporating the anticipation of the operational level decisions and associated costs through a set of n scenarios, $\omega \in \Omega$ with probability of occurrence $k(\omega)$.

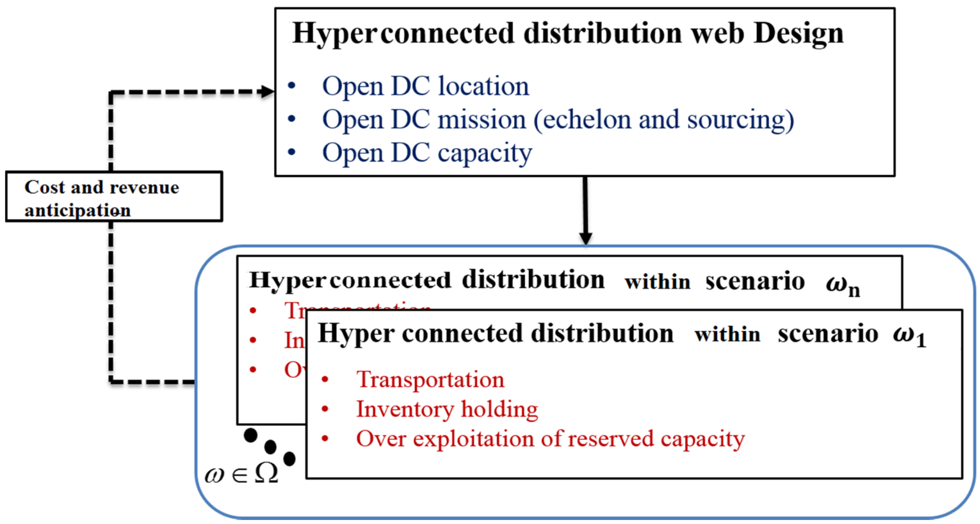

Figure 6-3. Modeling approach (inspired by Klibi et al, 2012b)

The multi-period model presented in this chapter, incorporates two stages; first stage decisions including structure of the web and capacities to acquire are modeled per planning periods noted by $t \in T$. The second stage decisions entail usage of the distribution web during operational periods $\tau \in T'$. The following sections defines decisions and parameters involved in each stage separately.

6.3.2 Modeling first stage problem

Let $l \in L^{\pi}$ be the set of PI-enabled open DCs being offered by independent Owners. The mission of the open distribution centers can take one of the two followings; first echelon DCs (e-1 DC) are supplied by the plant and serve markets and other DCs. Second echelon DCs (e-2 DC) are supplied by e-1 DCs and serve markets (similar network structure as depicted in Figure 3-3).

The maximum available storage capacity (b_{lt}) at each planning period is provided by the owner of the hyperconnected DC. A regular fee, (c_l^o) is incurred by exploiting DC according to the requested capacity (O_{lt}), while over exploitation is permitted up to b_{lt} with a higher cost $c_l^{o^+}$.

The User, produces (or acquires) a set of products $p \in P$ at plant location(s) $v \in V$ with activity level b_{pt}. Status quo storage is modeled at plant location(s); the exploitation cost associated with these DCs are set to zero while they incur inventory holding cost.

Let $m \in M$, be the set of markets. The service level targeted for market *m* is noted by α_m. Here, the quality of service is influenced by the market classification. Past sale records impact the classification and eventually the service provided for each market. The service level is expressed by distance between supplying DC and the market. Hence, a subset of DCs are allowed to serve markets according to the distance between them. Furthermore, it is possible that some markets have particular importance for the User. Thus, the inventory availability to satisfy the demand of these markets becomes crucial. So we define, g_m as the minimum number of DCs to source market *m* (this parameter can be set to zero for less sensitive markets).

Here we define the set of first-stage decision variables:

X_{lt}^{e} : Binary variable equal to one if DC *l* is being exploited in echelon *e* at planning period *t*, and zero otherwise

A_{lmt} : Binary variable equal to one if DC *l* is selected to serve market *m* during planning period *t* and zero otherwise

O_{lt} : Occupied space at open DC *l* during planning period *t*

6.3.3 Modeling second stage problem

The sources of uncertainty include demand, process and supply (Klibi et al., 2010). The scenarios here model only demand's stochastic behavior since it is the most important uncertainty source (Piedro et al., 2009). Furthermore, when User Company decides to design or redesign their hyperconnected distribution web, the supply (in our case available open DC spaces and location) is explicitly known. It should be noted that the PI database will updated frequently and the announced offers can change. However, the information available at specific moments, such as the date and quantity of open space and technologies available at an open DC are definitive. Thus, deterministic decisions regarding their exploitation can be made. Contrary to manufacturing processes, which can involve uncertainty about machine breakage, the stochastic nature of the processes involved in the distribution can be triggered only by demand's behavior. Hence, we define,

$d_{pm\tau}(\omega)$: Product p demand at market m at operational period $\tau \in T^{t}$ under scenario ω

It is possible that market demand cannot be satisfied at operational level. Here, the lost order incurs a cost penalty.

Road transportation by truck is the only transportation mode considered in this study. Let $s \in S$ denote the set of shipment options including Truckload, Multi-drop Truckload, Less than Truckload and exploiting PI-enabled Mobility Web. The transportation flow modeling and transportation cost follow our modeling approach presented in chapter 2. Similar to the core modeling approach, a set of binary decision parameters are applied to select the full truck shipment options on network links.

The following stochastic second-stage decision variables are defined:

$F^{s}_{pvl\tau}(\omega), F^{s}_{pll'\tau}(\omega), F^{s}_{plm\tau}(\omega)$: Product p transportation flow from plant v to DC l , between DCs l,l' and from DC l to market m by shipment option s during the operational period τ under scenario ω respectively

$I_{pl\tau}(\omega)$: Product p inventory level at DC l during the operational period τ under scenario ω

$O^{+}_{l\tau}(\omega)$: DC l over exploitation during the operational period τ under scenario ω

$Y_{pm\tau}(\omega)$: Product p lost order quantity from market m during the operational period τ under scenario ω

$H^{TL}_{vl\tau}(\omega), H^{TL}_{ll'\tau}(\omega), H^{MTL}_{lm\tau}(\omega)$: Binary variable of TL/MTL shipment option selection from plant v to DC l , between DCs l,l' and from DC l to market m during the operational period τ under scenario ω respectively

According to the short planning horizon of this problem, it is assumed that all parameters rather than demand are known and static. Contrary to the core modeling approach, these costs are modeled as a function of the product. For instance, product weight can impact transportation cost, product price can influence the inventory holding and lost order penalty. Let us define,

$c^{f}_{ps}(F^{s}_{pnn'\tau}(\omega), \delta_{nn'})$: Product p transportation flow cost as a function of quantity and distance from a network node n to n' by shipment option s

c^{i}_{pl} : Product p inventory holding cost at DC l

c^{y}_{p} : Product p unitary lost order penalty cost

Figure 6-4 shows the two-stage decision making process adopted in this study.

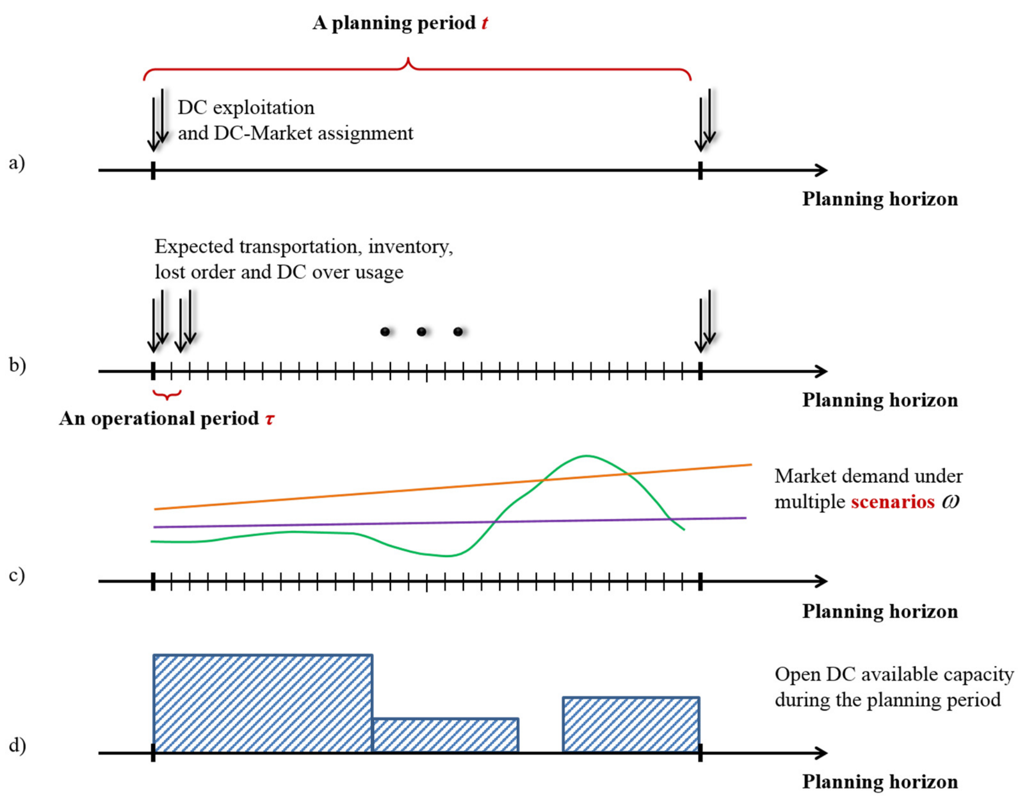

Figure 6-4. The two-stage decision making process along the planning horizon

6.3.4 Problem formulation

Given the set of decisions variables and parameters declared above, the hyperconnected distribution web design problem is modeled as a multi-period multi-product scenario-based two-stage two-echelon MIP problem with complete recourse. The objective function (6.1) minimizes the expected Total Distribution Costs subject to a set of constraints as presented in (6.2-6.22).

It should be noted that several notations are mutual or similar to those employed in the core modeling approach. When descriptions are not provided, the reader can assume similarity to the previous models.

$$E_{\Omega}\left(TDC\right) = Min \sum_{t}\left(\sum_{l} c_l^o O_{lt} + \sum_{\omega \in \Omega} k\left(\omega\right) C_t\left(X,\omega\right)\right) \tag{6.1}$$

Subject to:

Single echelon per DC:

$$\sum_{e} X_{lt}^{e} \leq 1 \qquad \forall\, l, t \tag{6.2}$$

Market can be assigned to exploited DCs respecting service level:

$$A_{lmt} \leq \sum_{e} X_{lt}^{e} \qquad \forall\, l, m \in M_l, t \tag{6.3}$$

Minimum number of DC supplying a market:

$$g_m \leq \sum_{l \in L_m} A_{lmt} \qquad \forall\, m, t \tag{6.4}$$

Available open capacity respect:

$$O_{lt} \leq b_{lt} \qquad \forall\, l, t \tag{6.5}$$

Integrality and non-negativity:

$$X_{lt}^{e}, A_{lmt} \in \{0,1\}, O_{lt} \geq 0 \qquad \forall\, e, l, m, t \tag{6.6}$$

Where for a given planning period $t \in T$:

$$C_t\left(X,\omega\right) = Min \sum_{\tau \in T^t} \sum_{p}$$

$$\left(\sum_{v,l,s} c_{sp}^{f}(F_{pvl\tau}^{s}(\omega), \delta_{vl}) + \sum_{l,\, l' \in \{L-l\}, s} c_{sp}^{f}\ (F_{pll'\tau}^{s}(\omega), \delta_{ll'}) + \sum_{l,\, m \in M_l, s} c_{sp}^{f}\ (F_{plm\tau}^{s}(\omega), \delta_{lm}) + \right.$$

Transportation flow cost

$$\sum_{l} c_{pl}^{i} I_{pl\tau}(\omega) +$$

Inventory holding cost

$$\sum_{l} c_{l}^{o^{+}} O_{l\tau}^{+}(\omega) +$$

Capacity overexploitation penalty cost

$$\left. \sum_{m} c_{p}^{y} Y_{pm\tau}(\omega) \right)$$

Lost order penalty cost

(6.7)

Subject to:

Only first echelon DC is supplied by plant:

$$\sum_{p,v,s,\tau \in T^{t},\omega} F_{pvl\tau}^{s}(\omega) \leq X_{lt}^{1} \qquad \forall\ l, t \quad (6.8)$$

E-2 DC is supplied only by e-1 DC:

$$\sum_{p,l' \in L-\{l\},s,\tau \in T^{t},\omega} F_{pl'l\tau}^{s}(\omega) \leq X_{lt}^{2} \qquad \forall\ l, t \quad (6.9)$$

Only e-1 DC supplies e-2 DC(s):

$$\sum_{p,l' \in L-\{l\},s,\tau \in T^{t},\omega} F_{pll'\tau}^{s}(\omega) \leq X_{lt}^{1} \qquad \forall\ l, t \quad (6.10)$$

DC-Customer assignment:

$$\sum_{p,s,\tau \in T^{t},\omega} F_{plm\tau}^{s}(\omega) \leq NA_{lmt} \qquad \forall\ l, m, t \quad (6.11)$$

Demand and lost order:

$$\sum_{l \in L_m, s} F_{plms\tau}(\omega) + Y_{pm\tau}(\omega) = d_{pm\tau}(\omega) \qquad \forall p, m, \tau, \omega \quad (6.12)$$

Inventory and flow balance:

$$I_{pl\tau}(\omega) = I_{pl(\tau-1)}(\omega) + \sum_{l' \in L-\{l\}, s} F_{pl'ls\tau}(\omega) + \sum_{v,s} F_{pvls\tau}(\omega) - \sum_{l' \in L-\{l\}, s} F_{pll's\tau}(\omega) - \sum_{m,s} F_{plms\tau}(\omega)$$

$$\forall p, l, \tau, \omega \quad (6.13)$$

Initial inventory:

$$I_{pl\tau=0}(\omega) = 0 \qquad \forall p, l, \omega \quad (6.14)$$

Over exploitation quantity:

$$\sum_p I_{pl\tau}(\omega) - O^+_{l\tau}(\omega) \le O_{lt} \qquad \forall l, \tau, \omega \quad (6.15)$$

Over exploitation limit:

$$\sum_p I_{pl\tau}(\omega) + O^+_{l\tau}(\omega) \le b_{lt} \qquad \forall l, \tau, \omega \quad (6.16)$$

Inbound TL shipment option selection:

$$\sum_p F^{TL}_{pvl\tau}(\omega) \le N H^{TL}_{vl\tau}(\omega) \qquad \forall v, l, \tau, \omega \quad (6.17)$$

Inbound TL flow lower bound:

$$q H^{TL}_{vl\tau}(\omega) \le \sum_p F^{TL}_{pvl\tau}(\omega) \qquad \forall l \in L, v \in V, \omega \quad (6.18)$$

DC-DC TL shipment option selection:

$$\sum_{p} F^{TL}_{pll'\tau}(\omega) \leq NH^{TL}_{ll'\tau}(\omega) \qquad \forall l, l', \tau, \omega \quad (6.19)$$

DC-DC TL flow lower bound:

$$qH^{TL}_{ll'\tau}(\omega) \leq \sum_{p} F^{TL}_{pll'\tau}(\omega) \qquad \forall l \in L, l' \in L - \{l\}, \omega \quad (6.20)$$

Outbound MTL shipment option selection:

$$\sum_{p} F^{s}_{plm\tau}(\omega) \leq NH^{MTL}_{lm\tau}(\omega) \qquad \forall l, m, \tau, \omega \quad (6.21)$$

Outbound MTL flow lower bound:

$$qf^{c}_{lm} H^{MTL}_{lm\tau}(\omega) \leq \sum_{p} F^{s}_{plm\tau}(\omega) \qquad \forall l \in L, m \in M_{l}, \omega \quad (6.22)$$

Plant capacity constraints:

$$\sum_{l,s,\tau} F^{s}_{pvl\tau}(\omega) \leq b_{pvt} \qquad \forall p, v, t, \omega \quad (6.23)$$

Integrality and non-negativity constraints:

$$F^{s}_{pvl\tau}(\omega), F^{s}_{pll'\tau}(\omega), F^{s}_{plm\tau}(\omega), I_{pl\tau}(\omega), O^{+}_{l\tau}(\omega), Y_{pm\tau}(\omega) \geq 0 \qquad \forall p, l, m, v, s, \tau, \omega \quad (6.24)$$

Constraints set (6.2) ensure that each DC can be exploited only with one echelon. Constraint set (6.3) guarantee that markets are served by DCs that are being already exploited. These DCs should be located in a predetermined distance to respect desired service level by the customer. Minimum number of DCs to supply each market is respected by constraints (6.4). The capacity to reserve at an open DC cannot exceed the capacity offered by open DC (constraints 6.5).

The second stage objective function (6.7), minimizes the total operational level costs including, transportation, inventory holding, and lost order and over usage penalties. Constraints set (6.8), (6.9) and (6.10) define the network structure by setting the mission of the exploited DCs. Only e-1 DCs are supplied by the plant, only e-2 DCs are sourced by e-1 DCs and only e-1 DCs can supply e-2 DCs.

Constraints set (6.11) ensure that markets are only supplied by DCs that are already assigned to them in the first stage problem. For each scenario, constraints (6.12) set the total flow to each markets equal to their demand or lost order. Constraints set (6.13) balance the flow in and out DCs and determines the value of inventory. The initial inventory is set to zero by constraints (6.14). Constraints set (6.15) determine the overexploitation (if there is any) and constraints set (6.16) limits the overexploitation to the maximum capacity available at DC. Similar to the core modeling approach, constraint sets (6.17-6.22) determine if the full truckload shipment options (TL or MTL) can be used on inbound, DC-DC and outbound links respectively. It should be noted that parameter f_{lm}^{c} , models the consolidation opportunity for outbound shipments. Constraints set (6.23) ensure that the capacity at plant is not overused. Constraints set (6.6) and (6.24) indicate the integrality and non-negativity of decision variables employed in the model.

6.4 Hyperconnected Distribution Policy

The goal of this planning level is to set the inventory policy for a mid-term planning horizon (e.g. season, month) and parameterize it. We do not intend to enforce a specific inventory policy for hyperconnected systems; well-known (s,S) and (s,Q) or predetermined replenishment frequency can be applied based on managerial insights. The major element of this planning level is to parameterize the selected policy for each product (or product family) at each exploited open DC based on the demand of markets assigned to the DC.

The input of this planning level includes the location of open DCs to exploit, their mission and capacity (output of the upper level) and product demand (average and standard deviation, if known). The output involves the parameterized inventory control system for each product at each exploited open DC.

The amount of lost order at operational level (if there is any), that could be potentially served by a DC indicates the accuracy of inventory policy. High lost order triggers a revision on the inventory policy parameterization. For instance, the altered policy might include higher reorder point (s). It can also be a result of selecting the wrong DC, which requires repeating the previous level (design).

6.5 Hyperconnected Deployment Planning

At this level, considering a relatively short-term planning horizon (e.g. month, week) the deployment of products within the set of exploited open DCs is determined. A novel approach, called Dynamic Deployment, is proposed which is capable of dynamically deploying products from multiple sources and redeploying them when required.

The Dynamic Deployment is a Distribution Resource Planning (DRP)-like approach defined to suit the dynamic nature of hyperconnected distribution systems. The most important feature of dynamic deployment in contrast to DRP is that each DC can be supplied by more than one source (whether plant or other DCs). There are similarities between these approaches such as the fact that a rolling horizon planning approach is applied. Yet in dynamic deployment, the refresh pace is flexible, meaning that the frequency of re-planning is not a constant predetermined value but a dynamic variable. For example, anytime the quantity of real demand is known, the forecast error can be calculated and the deployment planning is revised for the next week/month, if the error is significant.

The input of Dynamic Deployment approach include the demand forecast, location of open DCs and their capacity, inventory policy parameterized for each DC and product, available stock at plant(s) at the beginning of the planning horizon and cost functions. The output, involves the shipments planned to and from each DC at each period and the inventories. Table 6-1 shows a sample dynamic deployment planning table. The rows distinguished by different colors, indicate new variables in comparison to the traditional DRP.

Table 6-1. A sample dynamic deployment planning table

DC ID		Day						
		1	2	3	4	5	6	7
Gross requirement $_p$								
Incoming flow $_p$								
Outgoing flow $_p$								
Projected on hand $_p$								
Selected source and lead time								
Planned supply receipt $_p$								
Planned supply order $_p$								

Since in a hyperconnected system a large set of open DCs are exploited, each DC can potentially supply other DCs and be supplied by any other DCs. This is why these two rows should be added to the table. The classic DRP imposes single sourcing. Thus, it is unnecessary to indicate the source and lead time of supplying source inside the DRP table, since it does not change by time. It should be noted that by assumptions made in our core modeling approach (chapter 3), the DC mission has been identified by specific sourcing limitations. For instance, it is assumed that first echelon DCs are only sourced by the plant and the second echelon DCs, only by first echelon DCs. However, such specifications are applied at the design level to determine the most suitable role for each DC. At operational level, these constraints are relaxed.

The goal is to minimize the total deployment cost including transportation and inventory cost while respecting the inventory policy (determined at policy level) and DC capacity (determined at design level). The performance indicators of this planning level include the transportation and inventory costs, in addition to previously defined DC capacity utilization rate.

6.6 Hyperconnected Delivery Planning

The last hyperconnected distribution planning level concentrates on order delivery in a very short-term planning horizon (e.g. day, shift or hour). The goal is to select the source of each delivery among open DCs that are eligible to serve a market (respecting the service level). When the order is available at the closest open DC to the market, selecting the delivery source is simple (*non-constraining inventory*). However, tight inventory (*constraining inventory*) at the closest open DC entails serving the market from another open DC in a way to minimize the total transportation cost and respect the service level. When more than one source to answer market's order is available, a transportation problem can be solved. Noteworthy, if an open DC with available stock within the desired distance from the market does not exist, the order is lost.

6.7 Future experimentation plan

A business case is targeted for the future application of the stochastic hyperconnected distribution network design problem. This business distributes a set of 11 product clusters, which are aggregated group of finished products with almost similar demand behavior per market. A set of hundred market locations, including the top 100 largest populated cities in US and Canada are to be served by this business. Markets are categorized into 3 groups; A, B and C and their service level is influenced by their category. The length of the planning horizon is set to 12 months, with monthly planning periods and daily operational periods. A set of 255 potential open DC site are located with various available open capacity during the planning horizon. Figure 6-5 presents the business market territory and potential open DC location.

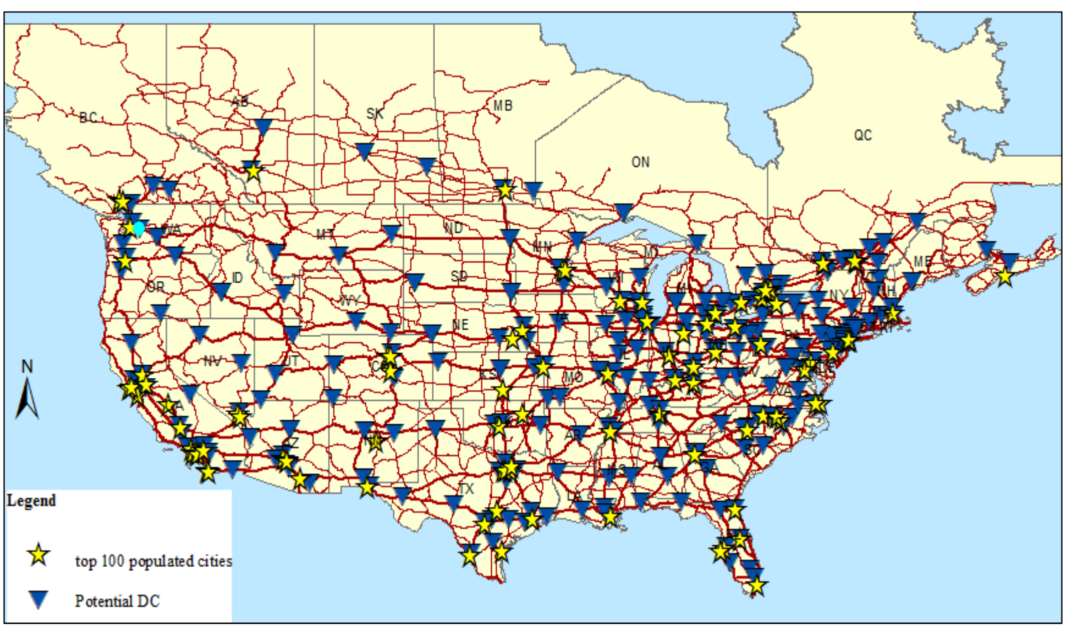

Figure 6-5. Future experimentation geographical area

The extent of the business case considered for this experimentation is very large and necessitates the application of a heuristic approach to solve the stochastic problem with a reasonable quality-time compromise. A solution approach based on the tabu search is under validation to be applied in this experimentation.

6.8 Conclusion

In this chapter, a four-level hyperconnected distribution planning framework is presented. The planning horizon of each level is relatively shorter than in traditional planning frameworks. In addition, monitoring key performance indicators, planning levels can be revised at any time.

Further research is required to elaborate the proposed framework in order to assess the potential of the framework analytically and through simulation. We intend to conceptualize and prototype the decision support systems supporting managers, and to field test the approach in living labs.

Conclusion

The study was set out to investigate the potential economic, environmental and social performance gains by the hyperconnected distribution system. Moreover, it sought to know the characteristics, which influence the magnitude of the gains. The study was also aimed to provide a planning framework regarding the decision making while operating a hyperconnected distribution system.

To this end, several optimization models are developed and applied to design the distribution network of a set of business samples in the dedicated, collaborative and hyperconnected distribution systems. In addition, a number of assessment approaches are created to investigate the collective and business-centric economic, environmental and social performances at each distribution system. Several Key Performance Indicators, including the Total Distribution Cost, Energy Consumption, GHG emission production, Distribution Center investment and Transportation Cost are taken into account.

The explorative findings are summarized in chapter 5: Performance assessment and potential gain investigation. The results indicate that the economic and environmental performance of all business samples are improved in the hyperconnected distribution. However, the magnitude of the gain varies for each key performance measure by the level of market service offered, the annual throughput of the business. It is also influenced by the status-quo distribution system of the business. This section briefly refers to the most important findings.

The collective distribution cost of 10 business samples decreases almost 34% in the hyperconnected distribution system compared to the dedicated system by offering the top service level. These savings are equivalent of 185 M$/year and on average, 19M$/year per business. The value of the collective savings somewhat decreases by responding to the medium and basic service level (141 and 137 M$/year for medium and basic service levels respectively).

The overall energy consumption and GHG emission production responding to the top service level experience 12% and 13% reduction respectively in hyperconnected distribution system compared to the dedicated. These savings represent 447 TJ energy consumption and 41 MKg.CO_2 equivalent GHG emission production per year. The magnitude of the gains decreases to 7% and 2% by responding to the medium and basic service levels.

The costs associated with the DC opening and operations reduces from 182 M$/year in the dedicated system to 61 M$/year in the hyperconnected (66% reduction in the collective measure). The gain reduces to 98 and 90 M$/year for medium and basic service levels. Finally, the transportation cost is reduced 21% in the hyperconnected system compared to the dedicated system responding to the top service level. Similar to the other performance measures, the savings in the transportation cost reduces by offering the medium and basic service levels.

When the status-quo distribution system of businesses involves 2-business collaboration, in general savings become lower than the transition of the dedicated system to the hyperconnected. The collective collaborative-hyperconnected performance gain is estimated at 27% by responding to the top service level (equivalent of 138 M$/year). The savings are reduced to 23 and 22% by responding to the medium and basic service levels. Furthermore, the collaborative-hyperconnected environmental performance gain arrives to 11 and 12%: that represents 399 TJ energy consumption and 32 MKg.CO_2 equivalent GHG emission per year. The collaborative-hyperconnected DC cost and transportation cost reduce 61% and 15% respectively for the top service level. The savings reduce slightly by offering the medium and basic service levels.

The investigation results indicated that businesses with lower annual throughput grasp higher percentage of savings compared to those with high annual throughput. For instance, responding to the top service level, a low-throughput business sample can achieve 52% savings in the total distribution cost, while a high throughput business sample gains 27%. It also revealed that the gains are higher while higher service levels are offered.

Based on the explorative findings of this research, the hyperconnected distribution system can be distinguished as both efficient and sustainable, since it simultaneously reduces the distribution-related costs and does not penalize the environmental and social performances. The decline of energy consumption and GHG emission production and exploitation of open DCs and transportation fleet within the hyperconnected distribution offer a solution to the scarcity of fuel and land. It also provides an alternative to respect the limits indicated by environmental treaties such as Kyoto protocol. Moreover, the results presented in this research distinguish the hyperconnected distribution system to be suitable for the increasingly competitive business environment of today since the highest potential gain is achieved by responding to the top service level. As it is discussed in chapter 2, companies like Amazn.com are re-writing the rules of competition by initiatives like one-day delivery to their top customers and they are planning to offer this service free of charge in the close future.

The conceptual findings of the study are presented in chapter 6: Hyperconnected distribution planning framework. It defines a planning framework including the hyperconnected design, policy, deployment and delivery and indicates the differences of these planning levels in comparison to the current planning practices. This framework stresses the inter-linkage between planning levels in a hyperconnected distribution system. For increasing the flexibility and responsiveness of the distribution system to the changing business environment, the hyperconnected distribution planning framework suggests monitoring some key performance indicators to identify the proper time of revising the decisions taken in a certain planning level.

The optimization models developed in this research expand the field of the network design problem by involving an in-depth anticipation of the operational level and employing non-linear cost functions. Moreover, several novel assessment approaches are developed which are not limited to hyperconnected systems. To name a few, an approach to divide the gains obtained by the synergy of collaborative distribution among partnering businesses and an approach to assess the environmental performance of distribution centers and truck-based transportation operations.

Since the Physical Internet was introduced recently in 2009, the literature on this subject is limited particularly in relation to the distribution. This Ph.D. thesis contributes to the hyperconnected distribution field by answering the two research questions. The promising results obtained by the exploratory investigation are of prominent importance. They can encourage the private and public sectors to invest in the Physical Internet and exploit its offerings. Furthermore, they can encourage other studies in the related fields such as macroeconomics, business models, and strategic enterprise governance for the hyperconnected distribution system. This thesis also provides materials for supplementary research in the distribution and transportation modeling field such as modeling the hybrid distribution systems (dedicated and hyperconnected or collaborative and hyperconnected) and multi-modal hyperconnected delivery.

It should be noted that, our research embraces several limitations. For instance, the investigation is simplified to the single product businesses with known and constant market demand. Moreover, the transportation mode is restricted to the road (truck) and the geographical study area is limited to Canada and the USA. Moreover, using commercial solver CPLEX for few collaborative distribution web design problems, resulted in somewhat low quality solutions. Applying heuristic approach can be an interesting alternative. It can also enable investigating the performance of larger coalitions such as 5-business and 10-business.

Yet the obtained results confirmed the objectives of research, motivating further research related to the hyperconnected distribution system under more comprehensive and realistic scenarios.

The promising future research includes extending the optimization based model and experimentation to include multiple products for each business, using a multi-period rolling horizon and stochastic demand for the same set of business cases created in this thesis. Beyond optimization-based studies as this study, there is a need for agent-based simulations of hyperconnected distribution systems as pioneered by the hyperconnected distribution planning framework presented in chapter 6.

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