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Towards more efficient and resilient supply chain management through interconnection of logistics networks

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Towards more efficient and resilient supply chain management
through interconnection of logistics networks

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Abstract

Irrespective of significant performance achieved, today's logistics networks are overwhelmingly dedicated to an actor and therefore poorly interconnected. This fragmentation exhibits inevitable inefficiency and needs to be changed in respond to today's new arising challenges in efficiency and resilience. To solve this antagonism, an innovative concept - Physical Internet (PI) - has been proposed which is a fully interconnected, open, dynamic logistics system. In such a system, the facilities and means of transportation can be dynamically organized and allocated in the short-term or long-term according to the economic environment. As a result, decisions can be made dynamically, agilely, and thus optimally. This thesis studies the perspectives of the PI to inventory management and transportation regarding the challenges in efficiency and resilience.

As the efficiency of the PI to transportation has been carried out in literature, the first objective of this thesis is to explore the potentials of the PI to inventory management. To this end, we firstly qualitatively examine the new practices brought by the PI and conclude three main characteristics: 1) Distributed stocks near end customers; 2) Transshipment of inventories; and 3) multiple dynamic source options. Corresponding inventory models and solutions are proposed and evaluated with numerical experiments in Fast Moving Consumer Goods (FMCG). This part of study gives a guideline for the vendors applying the PI to make inventory decisions in such an open logistic system.

The second objective is to analyze the resilience of the proposed PI enabled inventory and transportation model confronted to disruptions. The proposed inventory and transportation model are extended with different disruptions at facilities including plants and hubs. Different disruption strategies are developed. Numerical studies in FMCG are carried out.

In a word, this research investigates the inventory management in the PI and the resilience of PI enabled logistics models. It is the first time such a work is done and it should be upfront. From the results of studies, there is no doubt that the PI changes today's supply chains design and improve the performance of supply chain management both in efficiency, effectiveness and resilience.

Keywords: Physical Internet, Inventory management, Supply Chain Resilience, Interconnection of logistics networks, Transportation, Supply Chain Disruptions

Abstract en français

Independent de la performance remarquable accomplie par la logistique d'aujourd'hui, les réseaux actuels sont majoritairement dédiés à un acteur et donc très peu interconnectés. Cette fragmentation conduit une difficulté de mutualisation des flux et dès lors à une efficacité limitée. Ces organisations dédiées et hétérogènes sont de plus en plus déstabilisées par les nouveaux défis en termes d'efficacité, d'efficience et de résilience. Pour répondre à cet antagonisme, un concept logistique innovant - l'Internet Physique (PI) - a été proposé. Dans ce système, les infrastructures et les moyens de transport peuvent être organisés de façon dynamique et attribués à court ou à long terme en fonction des besoins. Par conséquent, les décisions des opérations logistiques peuvent être prises de façon dynamique, agile, et donc de manière plus optimale. Cette thèse aborde les perspectives de PI concernant la gestion de stocks et du transport par rapport aux défis de l'efficacité et de la résilience.

Comme l'étude de l'efficacité de PI par rapport au transport a été déjà effectuée, le premier objectif de cette recherche est d'explorer les potentiels de l'interconnexion des réseaux dans la gestion de stocks, qui n'a pas encore été adressé. À cette fin, nous examinons d'abord les trois nouvelles pratiques apportées par PI : 1) les stocks distribués à proximité des clients finaux; 2) le transbordement de stocks entre les hubs; 3) de multiples options dynamiques de sélection de la source pour chaque commande. Deux modèles de gestion de stocks correspondants sont proposés. Cette étude sert de guide pour des décisions de stockage pour les vendeurs dans un tel système logistique ouvert.

Après l'analyse d'efficacité de PI, la deuxième partie de cette thèse concerne la résilience des modèles de stockage et de transport dans PI confrontés à des interruptions dans la chaîne logistique. On a étendu les modèles de stockage et de transport avec des interruptions imprévisibles dans les infrastructures telles que les usines ou les hubs. Des stratégies différentes sont développées pour atténuer les risques de perturbation des flux. Des études numériques sont effectuées pour évaluer la performance des modèles proposés.

En résumé, cette recherche est la première qui étudie le potentiel de l'Internet Physique pour la gestion des stocks et la résilience de ce système. D'après les résultats, il n'y a aucun doute que PI change la conception de chaîne logistique et améliore la performance de gestion de la logistique de manière significative.

Mots Clés : Internet Physique, Gestion de stock, Résilience, Interconnexion des réseaux logistiques, Transport, Interruptions de chaîne logistique.

Résumé en français

Contexte

Gestion de la chaîne logistique (SCM) est une approche efficace et systématique pour planifier et gérer toutes les activités visant à satisfaire la demande, à partir de l'approvisionnement et de l'ensemble des activités logistiques au sein et entre les entreprises. Elle joue un rôle essentiel dans la performance et la compétitivité des sociétés et des pays, les activités logistiques étant intimement liées à l'économie. Dans les pays développés, la logistique atteint une performance non égalée dans l'histoire. Des exemples probants peuvent être trouvés dans notre vie quotidienne. Par exemple, les clients peuvent être livrés de leurs commandes à un créneau horaire précis de la journée ou dans un délai court après avoir commandé sur un site Internet. En outre, il est beaucoup plus facile et plus pratique pour les consommateurs d'accéder à des produits exotiques d'autres continents à un prix raisonnable.

Indépendamment de la performance remarquable réalisée, les organisations des réseaux logistiques d'aujourd'hui présentent des limites intrinsèques et sont de plus en plus pris en défauts par les nouveaux défis de service d'aujourd'hui. Sous la conception de SCM traditionnelle, les réseaux logistiques sont souvent affectés à l'utilisation d'un acteur, ce qui entraîne des réseaux hiérarchiques, spécifiques et peu interconnectés. Les manques d'information et de coordination conduiraient à des inefficacités mondiales et à l'inefficacité de nombreuses opérations logistiques, telles que des taux de remplissage réduits par les livraisons fréquentes, les détours de transports causés par les expéditions indirectes, des stocks redondants dans un site et les ruptures de stock d'ailleurs en même temps, etc.

De plus, les chaînes logistiques d'aujourd'hui ont été confrontées à un climat économique extrêmement sévère. Plusieurs caractéristiques et tendances peuvent être décrites : les nouveaux canaux de distribution ou de nouveaux acteurs de la distribution et de la logistique, une forte volatilité et l'incertitude de l'environnement économique, la mondialisation des affaires, la tendance à l'externalisation, les cycles de vie plus courts, les attentes élevées des clients tels que la demande de livraison fréquente, et aussi l'importance croissante de la sécurité, gestion de la sécurité et des risques. L'objectif principal du SCM pour améliorer l'efficacité dans le climat d'affaires actuel est un réel défi. A côté, l'adaptation de l'organisation actuelle à ces défis a augmenté la complexité et l'instabilité des chaînes d'approvisionnement, suscitant de nouveaux

défis qui exigent des acteurs de renforcer la résilience de leur chaîne logistique pour atténuer les risques d'interruptions.

Compte tenu des limites des organisations actuelles, pour répondre aux défis élevés, nombre de recherches ont été menées, par exemple en étudiant des modèles d'optimisation, en testant de nouvelles politiques et pratiques pour améliorer l'alignement et la coordination des chaînes d'approvisionnement, en améliorant la collaboration horizontale, ou en appliquant des technologies innovantes telles que les dispositifs RFID et des capteurs. Cependant l'efficacité pour améliorer la performance dans la plupart des recherches est basée sur la conception traditionnelle des SC et des réseaux logistiques hiérarchiques spécialisés.

En supposant que l'organisation hiérarchique spécialisée est une limite inhérente, cette thèse étudie les perspectives d'un concept logistique innovant - Internet physique (PI) par rapport aux défis de SCM. PI est un concept logistique innovant récemment proposé, qui vise à faire évoluer des organisations indépendantes hétérogènes actuelles en un système logistique global interconnecté et ouvert. Le principe de PI est d'améliorer l'intégration, la coordination et le partage des ressources grâce à l'interconnexion des réseaux logistiques indépendants, par des ressources ouvertes, la standardisation des interfaces et des protocoles, des conteneurs standardisés, etc. Plus précisément, cette étude examine ces perspectives de l'Internet Physique pour la gestion des stocks et le transport sur les plans de l'efficacité, de l'efficacité et de la résilience. Comme Sarraj (2013) a déjà étudié l'efficacité du système de transport au PI, cette thèse portera sur l'efficacité et les perspectives de PI pour la gestion des stocks, la résilience des modèles de stockage et de transport dans PI.

Questions de recherche et les objectifs

Plus précisément, cette recherche vise à répondre aux questions de recherche suivantes:

- 1) Quelle est la différence des décisions de stockage dans le PI par rapport à la gestion de stockage traditionnel ? Quels sont les nouvelles pratiques et principes introduits par ce concept innovant ?
- 2) Qu'est-ce qu'un modèle de gestion de stocks correspondant? Avec quelle efficacité ?
- 3) Quelle est la résilience des modèles logistiques de PI, y compris le modèle de stock et de transport de PI proposé confrontés aux interruptions dans la chaîne?

L'objectif de cette recherche peut être conclu en trois parties :

- 1) Examiner les nouvelles pratiques et principes de PI à la gestion des stocks et le transport afin de discuter des potentiels de PI aux défis découlant de l'efficacité, l'efficacit  et la r silience.
- 2) D velopper des mod les de stockage et de transport pour offrir des solutions r alisables possibles pour gestion de stocks et du transport dans un tel syst me logistique ouvert.
- 3) Analyser quantitativement l'efficacit  et l'efficacit  du mod le de stock de PI ainsi la r silience des mod les propos s de stockage et transport aux ruptures d'approvisionnement de la cha ne.

Organisation du m moire de th se

Cette th se se compose de huit chapitres qui peuvent  tre regroup es en quatre parties:

Tout d'abord, le chapitre 1 pr sente le contexte et les enjeux de ce travail. Les facteurs antagonistes affectant le SCM aujourd'hui et les d fis qui en d coulent sont discut s. Des solutions diff rentes dans la litt rature sont pr sent es. Parmi les axes de recherche, cette th se s'int resse aux potentiels de l'interconnexion des r seaux logistiques pour r pondre aux d fis de l'efficacit , de l'efficacit  et de la r silience. Pr cis ment, on prend l'Internet Physique comme approche d'interconnexion des r seaux logistiques. On se concentre sur les perspectives de PI pour les activit s de stockage et de transport dans le but d'am liorer l'efficacit  et la r silience de cha ne logistique.

Apr s le chapitre introductif, la deuxi me partie de cette th se explore les perspectives de la PI pour la gestion de stocks, qui est compos  des chapitres 2, 3 et 4.

- Le chapitre 2 donne une revue de la litt rature des probl mes de gestion des stocks. Une analyse qualitative est men e pour identifier les diff rences des probl mes de politiques de gestion de stock dans PI ainsi que de nouvelles pratiques permises par ce nouveau concept.
- Le chapitre 3 d veloppe un mod le de simulation de stockage pour fournir une d cision de gestion de stock possible dans PI et pour quantitativement explorer les perspectives de PI dans la gestion des stocks en ce qui concerne l'efficacit  et l'efficacit .
- Le chapitre 4 continue cette partie de la recherche en proposant un mod le d'optimisation de gestion de la strat gie de gestion de stock dans PI pour les

fournisseurs. Cette partie de l'étude répond aux questions suivantes : comment les décisions optimales sont prises pour des problèmes de gestion de stock dans un réseau ouvert ? Quels sont les avantages économiques possibles ? Quelle est la sensibilité des paramètres de coût des prestations telles que les valeurs de produits ou la variabilité de la consommation ?

Ensuite, on continue cette recherche afin d'étudier la résilience des modèles de gestion de stock et de transport de PI proposés lorsqu'ils sont confrontés à des risques d'interruptions.

Le chapitre 5 examine la littérature des interruptions de chaînes d'approvisionnements et de résilience, dans l'objectif de définir les problèmes de résilience dans PI et les avantages potentiels apportés par PI.

Le chapitre 6 étudie la résilience des modèles de gestion de stock de PI du chapitre 4. Différentes interruptions imprévisibles sont supposées dans les usines des fournisseurs et les hubs. L'objectif de cette étude est de savoir si l'application de PI peut aider les entreprises à atténuer les risques d'interruptions de service et donc d'améliorer leur résilience.

Le chapitre 7 analyse la résilience du système de transport confronté à des interruptions dans les hubs. Ce travail vise à donner une définition de la résilience de l'Internet Physique, à élaborer des protocoles de transport implantés avec des régimes d'interruption, et d'analyser leurs performances lorsqu'ils sont soumis à différents profils d'interruptions.

Enfin, le chapitre 8 conclut cette thèse, en indique les limites des contributions présentées, et propose des perspectives pour de nouvelles recherches.

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General Introduction

Research Context

Supply chain management (SCM) is an effective and systematic approach to plan and manage all activities to fulfill demand including sourcing and procurement, conversion and all logistics activities within and across companies. It plays a vital backbone to organizations' business performance as SCM activities are intimately tied to economic expenses and benefits. Nowadays, the SCM has reached a significant performance than ever in developed countries. Convincing examples can be found all around our daily life. For example, the customers can be delivered for their orders within a precise window in a short time just after few clicks of ordering on the Internet. Besides, it is much easier and more convenient for consumers to access exotic products from other continents with a reasonable price.

Irrespective of remarkable performance achieved, today's supply chain organizations exhibits inevitable limits and have been challenged more and more by today's new SCM practices. Under traditional SCM design, the logistics networks are often assigned to the use of one company, resulting in current hierarchical specific logistics networks barely horizontally interconnected. The lack of information and coordination of current organizations would lead to global inefficiencies and ineffectiveness in logistics operations such as poor fill rates of transportation means by frequent delivery, transport detour caused by indirect shipment, large redundant inventories, stock outs, and etc.

On the other hand, today's supply chains have been experiencing an extremely severe business climate. Several characteristics and trends can be outlined such as new multiple distribution channels and new players of logistics, high volatility and uncertainty of economic environment, globalization of business, outsourcing trend, shorter product life-cycles, high customer expectations such as demand of frequent delivery, and also the increasing importance on safety, security and risk management. The premium goal of SCM to improve the efficiency and effectiveness under current business climate becomes quite complicated. Beside, adapting current organization to these challenges increased supply chain complexity and instability, arousing new challenge required companies to build resilient supply chains to supply chain disruptions risks.

Considering the limits of current organizations, to respond to the arising SCM challenges, dramatic numbers of research have been carried out, e.g. by studying optimization models, by testing new policies and practices to enhance the alignment and coordination of supply chains, by enhancing the horizontal collaboration such as pooling, or by applying innovative technologies such as RFID and sensor devices. Nevertheless the demonstrated efficiency and effectiveness to improve the performance of current SCM, most of the research are based on traditional SCM design and current hierarchical heterogeneous logistics networks.

Assuming that current hierarchical heterogeneous logistics organization is an inherent limit, this thesis studies the perspectives of innovative logistic concept – Physical Internet (PI) to the arising SCM challenges. The PI is a recently proposed innovative logistic concept which aims to integrate current heterogeneous independent organizations into an open global interconnected logistic system. The principle of the PI is to enhance the integration, coordination and sharing of resources through interconnection of independent logistic networks by open resourcing, standardization of interfaces and protocols, smart containers, etc. More specifically, we strengthen our study on two major activities of SCM: inventory management and transportation. Hence, this study will examine the potentials and perspectives of the Physical Internet to the arising SCM challenges in efficiency, effectiveness, and resilience regarding inventory management and transportation. As Sarraj (2013) has already studies the efficiency and effectiveness of PI transportation system, this thesis will address the efficiency and effectiveness perspectives of the PI to inventory management and the resilience of PI enabled logistic models.

Research Questions

More precisely, this research aims to answer the following research questions:

- 1) What is the difference of inventory decisions making in the PI compared to traditional SCM design and what's the new practices and principles brought by these innovative concept?
- 2) What is a corresponding inventory control model? With which efficiency and effectiveness?
- 3) What is the resilience of PI enabled logistic models including the proposed inventory model and PI transportation system to supply chain disruptions?

The objective of this research can be concluded into three folds:

- 1) Examine the new practices and principles enabled by the PI to inventory management and transportation in order to discuss the potentials of the PI to the arising challenges in efficiency, effectiveness and resilience.
- 2) Develop corresponding inventory and transportation model to offer possible feasible solutions for inventory and transportation control in PI.
- 3) Quantitatively analyse the efficiency and effectiveness of the proposed PI enabled inventory model as well the resilience of the PI enabled inventory and transportation model confronted to supply chain disruptions.

Work organisation

In order to answer the proposed research questions, we have adopted a classic research methodology as follows.

Firstly, we presented an introduction to describe the research context and the scope of this thesis.

- a) To this aim, we firstly conducted a literature review of SCM as to identify the major activities, antagonistic factors affection today's SCM performance, as well as arising challenges in today's serve business climate. We restrict our study in two major logistics activities: inventory management and transportation. Increasing challenges to improve efficiency, effectiveness and resilience of current SCs were outlined in today's ever changing and competitive economic environment.
- b) Then, a discussion followed to outline main research streams within the existing literature to overcome the limits of current SCM and to respond to the arising challenges. Among the organization principles of SC networks, we chose the recently proposed innovative concept of interconnection of logistics networks – Physical Internet as our research context.
- c) Then our literature review search was oriented to the literature related to the Physical Internet as to identify potentials of the PI to inventory management and transportation regarding efficiency, effectiveness and resilience. This is done also to position our study in the research about this open logistic system. From the literature, we found that the

research of efficiency and effectiveness of PI transportation system has been already taken out. Therefore, this thesis analyses the perspectives of the PI to inventory management regarding efficiency and effectiveness and the potentials of the PI to improve supply chain resilience.

Second, to examine the perspectives of the PI to inventory management, we took out three steps of study. In this part, firstly we took out a study to discuss inventory problems and models in literature. This part of study was done as to identify the antagonistic factors affecting today's inventory systems, difference in inventory problems in the PI compared to classic inventory models as well as establishing major assumptions. Then we continued our study by developing a rule-based simulation inventory model to explore how the PI affects the inventory control policies. After, in order to quantitatively analyse the new practices and perspectives, a simulation-based optimisation inventory control model was proposed and studied. For the proposed models, numerical experiments in FMCG sector have been taken out. Results of the models were validated by a simulation work. Different performance indicators were studied and compared.

After the analysis of efficiency and effectiveness, the resilience of the PI enabled logistics models including inventory and transportation model were studied. In this part, the proposed PI enabled inventory models and transportation system were extended with disruptions at hubs or/and plants. The facility disrupted will become unserviceable until the disruptions ends. Different disruption profiles were studied. Numerical experiment were taken out in FMCG. A simulation was followed to validate the models.

All details about the methodology applied is given in each chapter.

Structure of the Thesis

The dissertation is composed of eight chapters which can be grouped into four parts:

Firstly, Chapter 1 introduces the research context and scope of this thesis. The antagonistic factors affecting today's SCM and arising challenges are discussed. Different existing methodologies in literature are presented. Among the research streams, this thesis interests in the Physical Internet and a discussion is given about the potentials of PI to arising challenges in efficiency, effectiveness and resilience. The scope of this research is defined as to analyze the

perspectives of the PI to inventory management regarding efficiency and effectiveness and the potentials of the PI to improve supply chain resilience.

Then, the second part of this thesis explores the perspectives of the PI to inventory management which is composed of Chapter 2, 3 and 4.

- Chapter 2 gives a literature review to inventory problems and inventory management in literature. A qualitatively analysis of differences in inventory problems in the PI as well as new practices enabled by the PI is carried out in this chapter.
- Chapter 3 develops a rule-based simulation inventory model to provide a feasible inventory decision for inventory problems in the PI and quantitatively explore the perspectives of the PI to inventory management regarding efficiency and effectiveness.
- Chapter 4 continues this part of research by proposing an optimization inventory control model for the vendor managed inventory strategy in the PI. This part of study answers the following questions: How the optimal decisions are made for inventory problems in an open network? What are the most possible cost benefits? What is the sensitivity of parameters to cost benefits such as products' values?

Next, our study researches on the resilience of the proposed PI enabled inventory and transportation models confronted to supply chain disruptions risks.

- ❖ Chapter 5 examines the literature of supply chain disruptions and resilience as to find disruptions and resilience problems in the PI and potential benefits brought by the PI.
- ❖ Chapter 6 studies the resilience of the proposed PI inventory models in Chapter 4. Different unpredictable disruptions are assumed in the plants of suppliers and the PI hubs. The objective of this study is to find out whether applying the PI can help companies to mitigate disruptions risks and therefore improve their resilience.
- ❖ Chapter 7 analyses the resilience of Physical Internet enabled transportation system confronted to disruptions at hubs. This work aims to provide a definition of resilience of the Physical Internet, develop corresponding transportation protocols

implanted with disruptions protocols and analyse their performance to different disruptions profiles.

Finally, Chapter 8 concludes this dissertation, indicates the limits of the works presented, and proposes perspectives for further research

Chapter 1. Towards more efficient and resilient supply chain management through interconnection of logistics networks

1.1 Supply chain management (SCM)	19
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1.1 Supply chain management (SCM)

1.1.1 Concept and definition

1.1.1.1 Supply Chain

The concept of supply chain origins from issues related to physical distribution of materials (Shaw 1915). Since 1990s, research on supply chain has showed an exponential rise in popularity. However, until now, there exist no universal definition for the concept. Christopher (1992) defines a supply chain as “... *a network of organizations that are interconnected, through upstream and downstream links, in the different business processes and activities that produce value in the shape of products and services to clients*”. Lee and Billington (1993) emphasize that the functions of a supply chain includes the procurement of materials, transformation of material to intermediate and finished products, and distribution of finished products to customers. Mentzer et al. (2001) propose that a supply chain is a set of three or more entities (organizations or individuals) directly involved in the upstream and downstream flows of products, services, finances, and/or information from a source to a customer. This definition is widely used in the literature afterwards and adapted in this thesis.

From the organizational scope, according to degree of complexity, Mentzer et al. (2001) classify the supply chain in three types: direct supply chain, extended supply chain, and ultimate supply chain, shown in Figure 1. A direct supply chain encapsulates a focal company and its direct suppliers and customers. An extended supply chain not only includes the focal company and its direct suppliers and customers but also the suppliers’ suppliers and the clients of customers. An ultimate supply chain demonstrates a global version and includes all the organizations concerned with all the upstream and downstream flows of materials, services, finances, and information from the ultimate supplier to end customers.

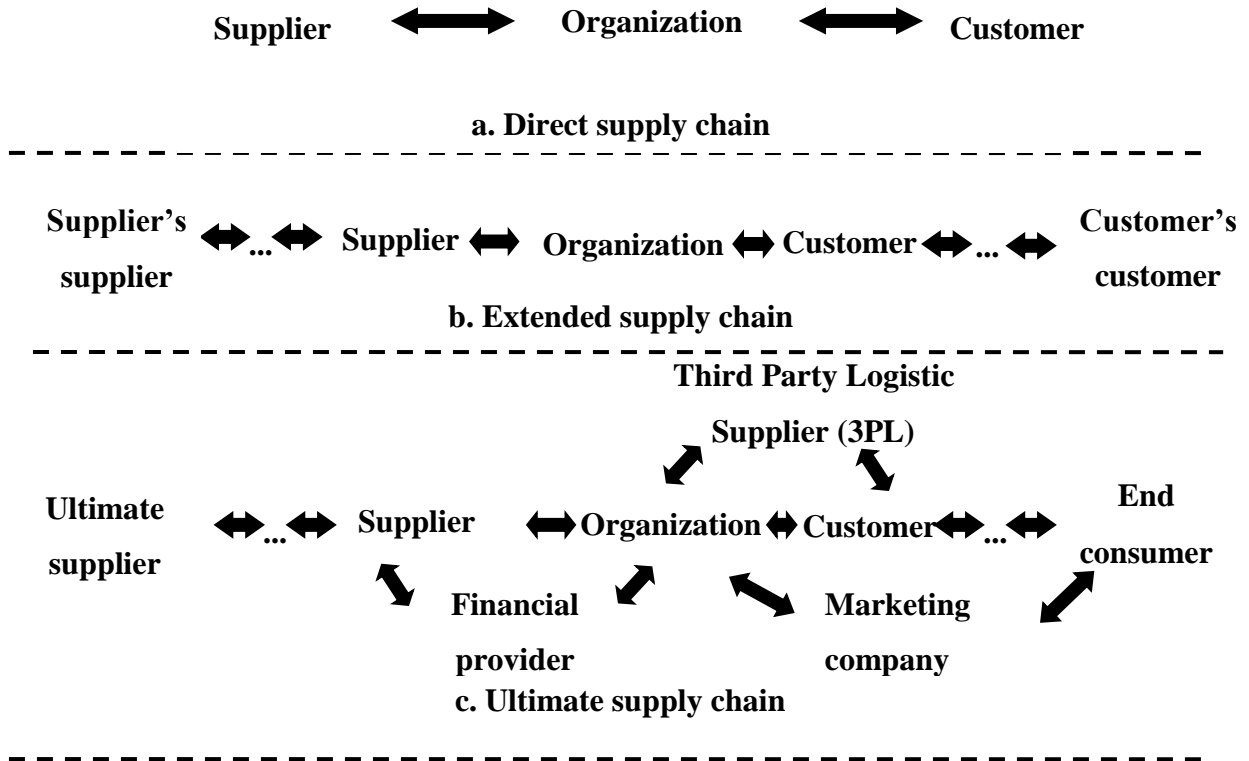


Figure 1. Organisational classification of supply chains *Source : (Mentzer et al. 2001)*

Instead of the linear structure as a supply “chain”, Lambert and Cooper (2000) describe the organization of supply chain as a hierarchical multi-echelon network from initial suppliers to end-consumers in Figure 2. They underline that the supply network of different actors may inter-crossed as they may have same suppliers/customers. In addition, organizations can be grouped according to the number of degrees of separation from the focal company, i.e. “Tier 3”, “Tier 2”, and etc.

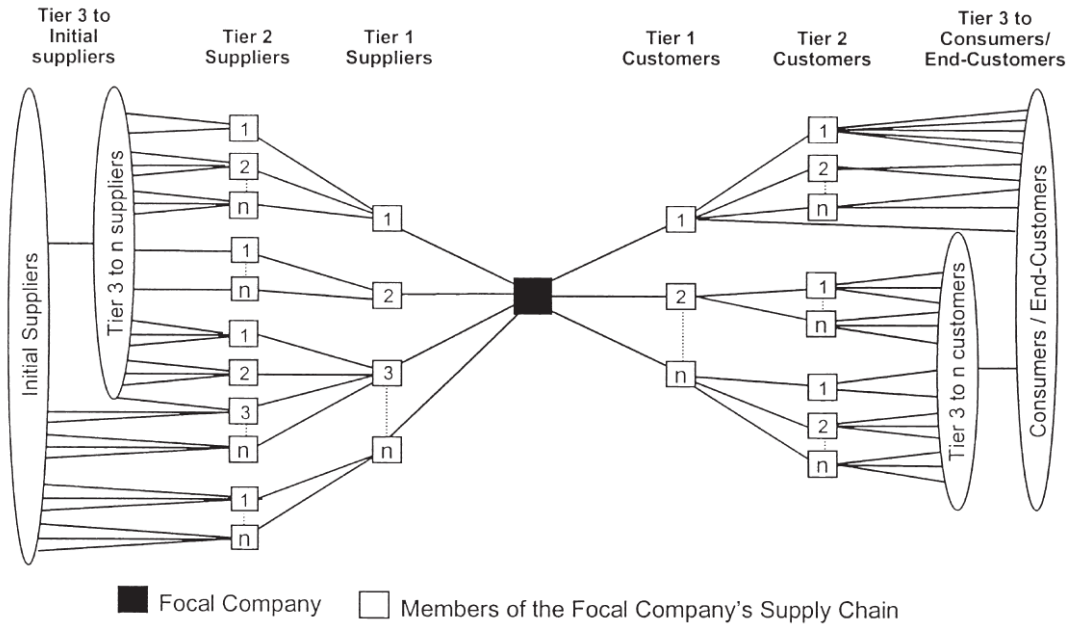


Figure 2. Example of structure of Supply Chain Network (Lambert and Cooper 2000)

1.1.1.2 Supply chain management

The term SCM was firstly introduced by consultants in the early 1980s (Oliver and Webber 1982). Similar as the term “supply chain”, the existing definitions and concept for SCM are often adapted to perspectives of different actors. Nevertheless, the Council of Supply Chain Management Professionals¹ in the US, which is the first professional leader in this field, gives the following definition:

“Supply chain management encompasses the planning and management of all activities involved in sourcing and procurement, conversion, and all logistics management activities. Importantly, it also includes coordination and collaboration with channel partners, which can be suppliers, intermediaries, third party service providers, and customers. In essence, supply chain management integrates supply and demand management within and across companies.”

(CSCMP, 2010)

¹ <http://cscmp.org/aboutcscmp/definitions.asp>

Here the logistics management refers to planning, implementing and controlling the efficient, effective forward and reverse flow and storage of goods, services and related information between the point of origin and the point of consumption in order to meet customers' requirements. An example of a supply chain is described in Figure 3.

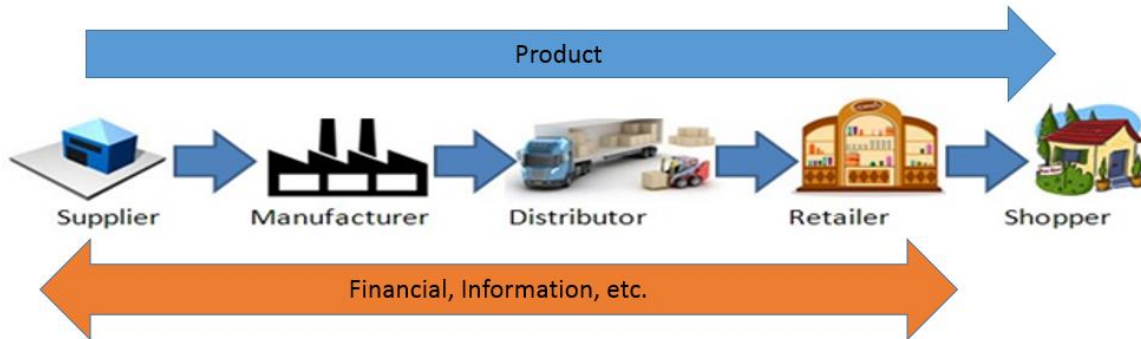
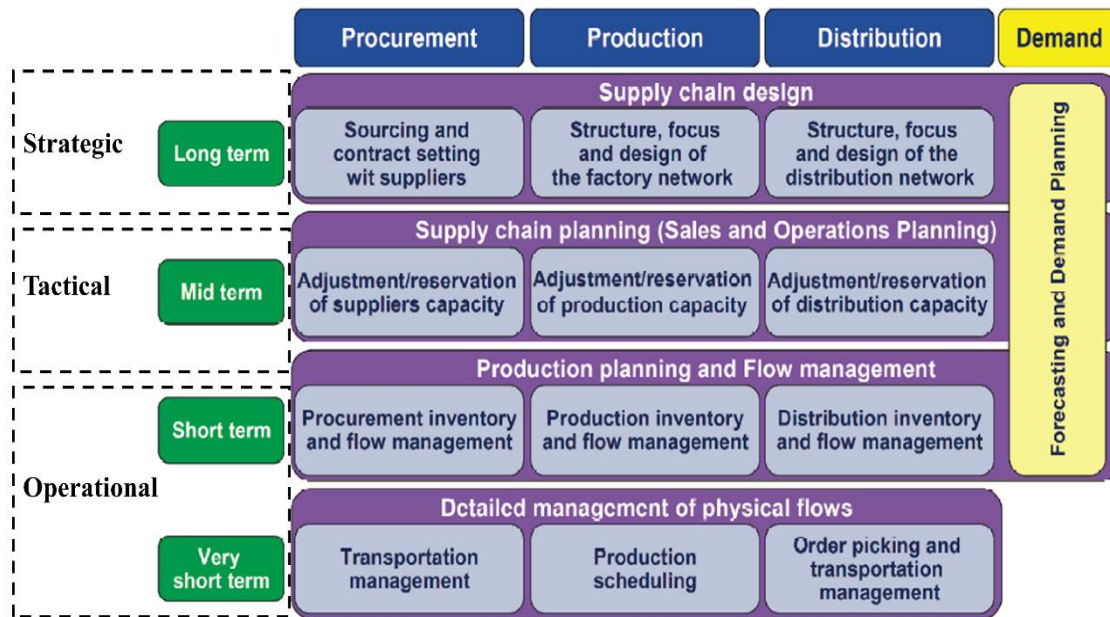


Figure 3. Example of *SCM*

From the definition, we can see that *SCM* begins with procuring the materials or services needed to create end products, and continues until the finished goods in the customers' hands. Figure 4 gives a map of key supply chain activities. The *SCM* decisions involved can be categorized into three levels: strategic, tactical, and operational. As an essential part of *SCM*, the strategic level decisions design the supply chain network including prescribing facility locations, production technologies and plant capacities. The tactical level prescribes material flow management policies, including production levels at plants, assembly policy, and etc. Finally the operational level schedules operations to assure in-time delivery of finished goods to customers including inventory control policies and distribution planning.



Source: Dallery (2000)

Figure 4. Key activities of SCM

Our research strengthens on inventory management and transportation as they are two of major activities in SCM and account for a large proportion of a company’s logistics costs. For example, according to report by ASLOG (Logistic association in France)², the transportation and storage cost averagely corresponds to 80% of the total logistics cost which is at least 12% of net sales of companies. In 2012, the transportation of goods and warehousing cost has reached up to 144.6 billion € in France³. Waller, Williams, and Tokar (2008) point out that business logistics cost as a percentage of US gross domestic product has grown to 9.5 percent, and of the over \$1 trillion spent on logistics, approximately 33% can be attributed to the cost of holding inventory. Thus well managing inventory and transportation activities is quite critical to the economic performance and competitiveness both for companies and their country.

²http://www.aslog.org/fr/315-l-etude-benchmark-aslog-20082009---l-etat-de-l-art-de-la-logistique-globale-des-entreprises-en-franc.html?input2=&input1=&mots=&nb_res=0&niv2=25

³ Source : Commission des comptes des transports de la Nation (CCTN), 2014.

1.1.2 Limits of current organisation and challenges ahead

SCM has shown an increasing importance in the past decades and achieved remarkable performance than ever. Convincing facts can be found all around us for our daily life. For example, it is possible to get products from another continent with a reasonable cost within 2 days or even 24 hours, to have a parcel delivered just by several clicks on the Internet, to order fast-moving consumer goods (FMCG) and be shipped free regardless of the quantity within two hours, and etc.

Regardless of remarkable services achieved, current supply chain systems still present an appearance of simplicity: moving goods from one point to another, aggregating, disaggregating, stocking (Ballot, Montreuil, and Meller 2014). This simplicity is applied in order to simplify logistics operations as to offer an affordable efficient service. However, this appearance is misleading because of complex nature of logistics operations as well as the vulnerability in SC. It exhibits inevitable limits leading to inefficiencies in transportation, inventory control and other logistic operations and also has been challenged more and more by today's arising practices.

Firstly, traditional SCM assigns logistic networks mostly to the use of one company, which results in current heterogeneous independent logistics networks barely horizontally interconnected. As a result, each operator is limited in its options of service offerings, resulting in global inefficiency. For example, the arising customer expectation for short frequent delivery and small shipments per supplier and per product results in quick small shipments which makes difficult to fill the mode of transportation. European statistic show that trucks over 3.5 t are on average filled to between 50 and 60 % of their maximum weight capacity. Besides, as the networks are often hierarchical with multiple echelons as shown in Figure 2, this organization would lead to large redundancy of inventories caused by Bullwhip effect and increased volatility of end customer demand. The Bullwhip effect refers to the phenomenon where the variance of orders to the supplier is largely amplified than sales in retailers and the distortion propagates upstream in an amplified form (Lee, Padmanabhan, and Whang 2004). Because of some degree of centralization, current logistic organisation will inevitably cause indirect travels. Irrespective of the size of the company, it is generally impossible to serve all of its customers directly, resulting in indirect and unnecessary transit. This indirect transit may lead to more days, or even weeks, resulting in excess inventories in certain sites and sometimes poor customer services.

In addition to the limits of current organisation, the challenge to improve the efficiency and effectiveness of SCM is extremely severe in today's business climate which has been characterized by high uncertainty, globalization of business, outsourcing, shorter product life-cycles, high customer expectations reflected in the importance of narrow delivery time windows and pressure on increasing delivery frequency, and also the growing importance on safety, security and risk management (Stefanovic, Stefanovic, and Radenkovic 2009; Angel et al. 2006). Efficiency and effectiveness have been basic criteria of performance evaluation as the premium goal of SCM is to build cost-efficient supply chains as to improve companies economic performance (Shepherd and Günter 2010; Fugate, Mentzer, and Stank 2010). Efficiency refers to the relationship between efforts and resources involved in the operation and the actual utility value as a result of the action. It is usually related to the achievement of objectives at lower cost. Effectiveness refers to the satisfaction with the results such as customer service level.

Furthermore, adapting current organisations to these challenges increased supply chain complexity and aroused new challenge – building resilience in SCs to increasing disruptions risks. The increased complexity caused more instability and unpredictability in today's SCM, leading to the negative consequences such as supply chain disruptions (Stefanovic, Stefanovic, and Radenkovic 2009; Ghadge, Dani, and Kalawsky 2012). For example, significant supply chain disruptions reduce the share price of affected companies by as much as seven percent on average⁴. Therefore, the design of supply chains that are efficient and effective while resilient to disruptions has been becoming an emergent issue for today's SC challenges (Sheffi 2005b; Kamalahmadi and Parast 2016; Christopher and Peck 2004; Ponomarov and Holcomb 2009). Here the resilience of supply chain refers to the capacity of the system impacted by the disruptions to return to its original state.

1.2 Effective solutions in face of SCM challenges

To overcome the limits of today's organisation and respond to the challenges, a significant number of work have been done. Here we conclude research streams into four categories: 1)

⁴<http://www.forbes.com/sites/steveculp/2013/02/15/supply-chain-disruption-a-major-threat-to-business/#71b420d77572>

Alignment and integration; 2) Horizontal collaboration; 3) Applying innovative technology; 4) Interconnection of logistics networks. As we focus on the inventory and transportation activities in SCM, the innovative solutions in these two activities will be discussed.

First of all, many studies address the ideas related to alignment and integration (Frohlich and Westbrook 2001; Flynn, Huo, and Zhao 2010; van der Vaart and van Donk 2008). The alignment and integration often refer to the vertical coordination and cooperation within the same or between logistic operators in different stages, hence internal and external integration. Integrated planning is often used for the internal integration to bond internal process, e.g. sales and operations planning (S&OP) to overcome the disintegration in the planning and operational decision-making process thus improve the efficiency (Oliva and Watson 2011; Umble, Haft, and Umble 2003). External integration, often concerning supply chain strategy design, addresses the integration between many vertical entities. Innovative strategies under external vertical integration can be found such as variants of Vendor Managed Inventory (VMI) (Disney and Towill 2003; Waller, Johnson, and Davis 1999a), Collaborative Planning, Forecasting and Replenishment (CPFR) (Seifert 2003; Aviv 2001), supplier development (Spekman 1988; Chan and Kumar 2007), efficient consumer response (ECR) (Corsten and Kumar 2005; Kurnia and Johnston 2001), and Collaborative Transportation Management (CTM) (Esper and Williams 2003; Doukidis et al. 2007).

Another important research stream in face of challenges concerns the horizontal collaboration (Barratt 2004; Simatupang and Sridharan 2002; Cruijssen, Cools, and Dullaert 2007). It refers to collaboration between actors of the same level in a supply network. Bahinipati, Kanda, and Deshmukh (2009) conclude main benefits of Horizontal collaboration in logistics as the following aspects: lower prices by aggregation of purchasing quantities, reduced supply risk, reduction of administration cost due to centralized purchasing activities, reduced inventory and transportation costs by consolidation, and etc. Important methodologies under horizontal collaboration refer to such as inventory pooling (Corbett and Rajaram 2006; Wong, Van Oudheusden, and Cattrysse 2007), lateral transshipment (Paterson et al. 2011; Axsäter 1990), Freight consolidation through pooling SCs (Pan 2010; Pan, Ballot, and Fontane 2013; Tyan, Wang, and Du 2003), Collaborative Transportation Management (CTM) (Esper and Williams 2003; Doukidis et al. 2007), and etc.

In addition, researchers and practitioners also work on applying innovative technology to improve the performance of SCM. For example, applying the Internet of Things (IoT), Radio-Frequency Identification (RFID) and wireless, mobile sensor devices to enhance the visibility and virtualisation of supply chain by offering real time information through resources connected to the Internet (Tajima 2007; Asif 2005; Verdouw et al. 2016). It makes the supply chain considerably more precise and improves the efficiency and reliability of the entire chain. Recent example can also be found in the application of Data Science to SCM such as Big Data to support decision-making with great data accuracy (Zhong et al. 2016; Waller and Fawcett 2013).

Last but not least, recently, an innovative concept about the interconnection of logistics networks, which can be seen an extension of horizontal collaboration, has been proposed by (Ballot, Montreuil, and Meller 2014). It is called as Physical Internet (PI) which is based on the universal interconnection of logistics services. The objective of PI is to create a global open interconnected logistic system that is economically, environmentally and socially efficient and sustainable. Our research interests in the potentials and perspectives of this innovative concept to SCM. The following section gives a detail description of the PI and discusses the potentials and perspective of the PI to the challenges.

1.3 Physical Internet: an innovative concept to improve SCM through interconnection of logistics networks

1.3.1 Metaphor and Definition

The terms “Physical Internet” was firstly introduced by Benoit Montreuil and inspired by the title of an article⁵ in the Magazine *The Economist*. The concept of PI arose from the metaphor of Digital Internet (Ballot, Montreuil, and Meller 2014). Despite of the appearance of nowadays global interconnected Digital Internet of computer networks, the computer networks used to be fragmented and barely interconnected due to diverse and incompatible technologies. Each network operator need to construct specific interfaces as to communicate with another network, resulting in relatively costly, slow and capacity restrictive data communicating across systems and companies.

⁵ <http://www.economist.com/node/7032165>

Then since the late 1970, the International Organization for Standardization (ISO) and International Telegraph and Telephone Consultative Committee (CCITT) took out projects to evaluate these specialized interfaces into standardized interfaces and protocols, in order to integrate multiple separate networks into a single network of networks (Leiner et al. 2009). These documents were lately merged together to form a standard called The Basic Reference Model for Open Systems Interconnection (OSI model).

With standardized interconnection model, a set of networks can be interconnected which is called as Internetwork. The Internet is the largest internetwork which is a global system of interconnected computer networks that using the Internet protocols suite (TCP/IP) to link billions of devices worldwide⁶. By using the common Internet through standardized protocols and interfaces, computer network operators share the same global network of networks. The speed and volume of data flows grew exponentially. In addition, the evolution of Internet has led to the transformation of network uses as broad as the economy and society, with the creation of email application, peer to peer communications, and etc. People have been highly interconnected through email and social networks. Due to the effectiveness of Digital Internet, we can send emails from a network user in one continent to another network user just by several clicks in seconds. Thanks to the hyper effectiveness, the users barely pay attention to the invisible data stream in the Digital Internet. In fact, the data of messages and addresses are embedded in digital data packets through standardized universal codes and protocols. With all the information in the digital data packet as well as the protocols in Internet servers and routers, the digital data packet routes automatically and independently of infrastructure among the interconnected servers / routers in the Internet until it reaches its destination.

Inspired by this metaphor, the objective of Physical Internet aims to integrate current specialized logistics networks into an open global logistic system through a standardized set of collaboration protocols, modular containers and smart interfaces for increased efficiency and sustainability (Montreuil, Meller, and Ballot 2013). An example of this global system is shown in Figure 5. b inspired by the Digital Internet in Figure 9.a.

⁶ https://en.wikipedia.org/wiki/Internet#cite_note-21

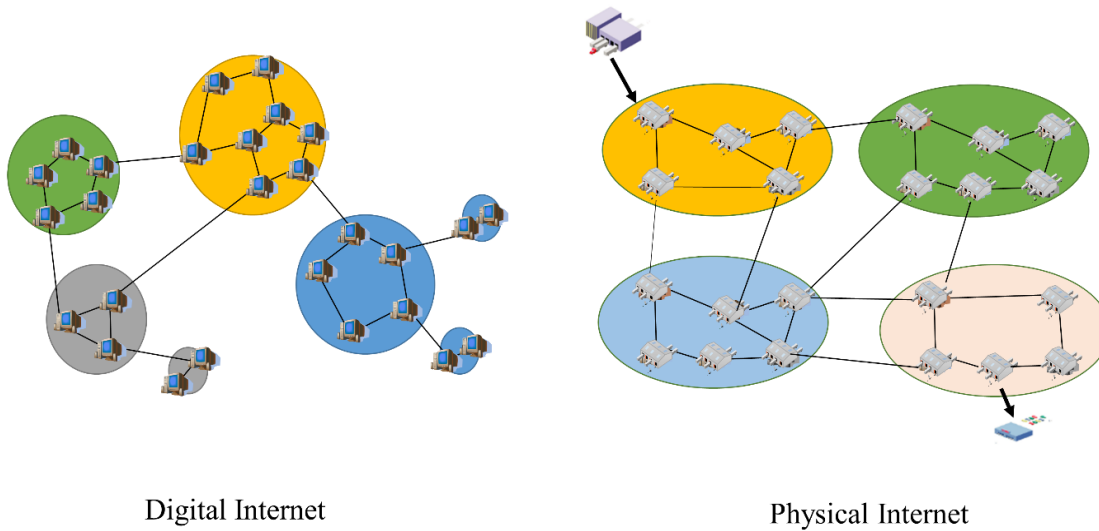


Figure 5. From Digital Internet to Physical Internet (*Sarraaj 2013*)

In other words, the PI is a common open global logistic system which is composed of PI hubs operated by different services providers as long as they are interconnected through standardized interfaces, protocols and modular PI containers. Just like data packets and servers in Digital Internet, the goods in the PI are encapsulated in smart modular PI containers which route among PI hubs. In the PI, the containers may pass several PI hubs with several transportation modes by different operators. By this way, all users including suppliers, shippers, and consignees can share this same logistic system, which enables full horizontal and vertical coordination in logistics. Besides, instead of owning and specializing the resources like in traditional supply chain design, the users of PI pay and use the logistics services as what we do for the use of Digital Internet, such as warehousing and distribution.

1.3.2 Perspectives of PI to SCM challenges

With utilization of the PI, we conclude the following possible perspectives of benefits:

- a) The transport need is reduced thanks to the removal of the systematic transit through central warehouses as discussed in 1.2.2. This transit averagely adds up to 20% of detours to reach consumers.

- b) Open logistics facilities and transportation means enabled by the PI will facilitate collaboration of different actors, thus with possible improved efficiency and effectiveness through sharing.
- c) More storage and transportation options will be possible for both suppliers and retailers as they can store their goods not only in their own warehouses but also in all open logistic facilities through encapsulation in PI containers.
- d) More source and delivery options will be possible for the customers, thus with possible improved effectiveness.
- e) Smart PI containers will enhance the visibility and virtualisation of the entire supply chain system.
- f) Adaption to market or other changes such as disruptions becomes quicker as it is a case of defining a new route within an existing global system instead of creating a new ad hoc network in current SCs, hence with possible improved robustness and resilience.

1.4 Map of research in the PI and scope of our work

Though the concept of PI shares similarities with the Digital Internet, there exist fundamental differences. Montreuil (2011) points out two key differences: 1) every single move or sojourn of a modular PI container and every single physical operation on it is costly; 2) every move and operation take time opposite to instant data transition in Digital Internet.

Therefore, as an innovative concept in logistics, numbers of studies have been carried out. Here we cite several references to give out some examples. In Europe, the Alliance for Logistics Innovation through Collaboration (ALICE), supported by the European Commission in 2013, has adopted the concept and developed a roadmap towards a real-world Physical Internet by 2050⁷, seen in Figure 6. Further studies about the concept of the network are carried out by (Ballot, Montreuil, and Fontane 2011; Ballot, Montreuil, and Meller 2014; Montreuil 2011; Mervis 2014). (Lin et al. 2014; Ballot, Gobet, and Montreuil 2012; Sallez, Montreuil, and Ballot 2015; Pan and Ballot 2015) are taken out to study PI container, PI facility design and engineering. (Zhong, Huang,

⁷ <http://www.etp-logistics.eu/>

and Lan 2014) interests in the impact of new technologies to the PI. (Sarraj 2013; Sarraj et al. 2014) study the transportation performance of PI network in terms of FMCG cases in France and assess the new organization can reduce up to 35% of actual transportation cost through the optimization of full truckload and integration of different transportation means.

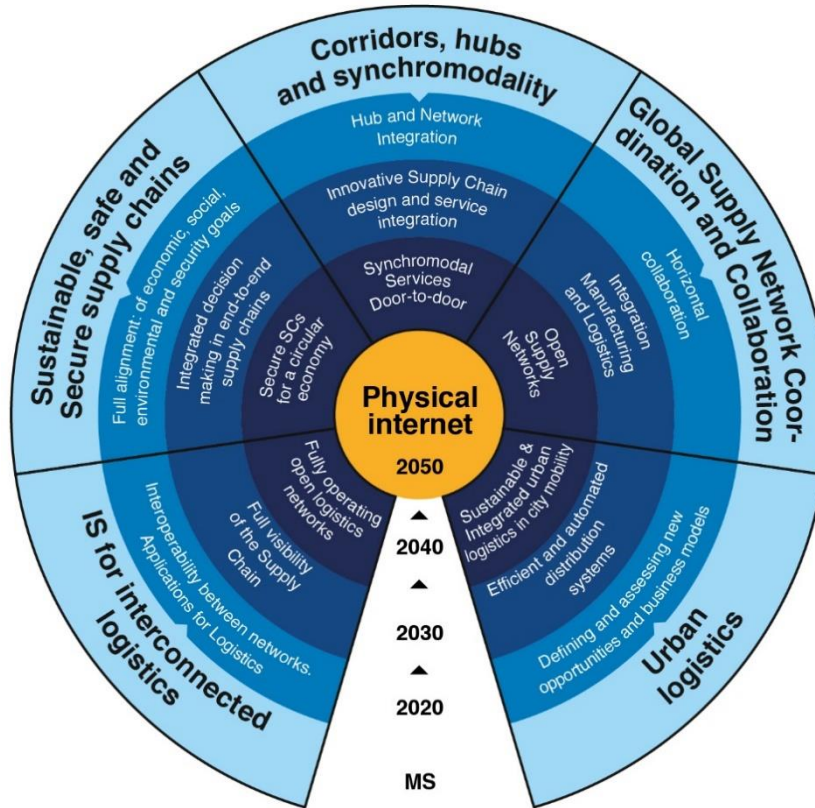


Figure 6. Roadmap towards Physical Internet by 2050 by ALICE

Following the research stream, this thesis concentrates on the potentials and perspectives of this global open hyper interconnected logistic system to the arising SCM challenges in efficiency, effectiveness and resilience. Besides, we stress our study on two major logistics activities: inventory management and transportation. As Sarraj (2013) has already addressed the efficiency and effectiveness of PI transportation system, this thesis tries to answer the following questions: 1) What's the perspectives and potentials of the PI to inventory management regarding efficiency and effectiveness? ; 2) What's the resilience of PI enabled logistic systems?. A description of studies addressed is found in Table 1.

	Efficiency	Effectiveness	Resilience
Inventory management	Chapter 2, 3	Chapter 2, 3	Chapter 4, 5
Transportation	<i>(Sarraj 2013)</i>	<i>(Sarraj 2013)</i>	

Table 1. Scope of this thesis

The rest of this thesis is organized as follows. Part I including Chapter 2, 3 and 4 will examines the perspectives of the PI to inventory management. Part II including Chapter 5, 6 and 8 will discuss the resilience of PI enabled models. In the beginning of each part, we will give an introduction to present the problematic in each part of research, as in Chapter 2 and Chapter 5. Finally, Chapter 8 concludes the study and provides some perspectives for future research.

Part I. EFFICIENCY AND EFFECTIVENESS OF PI ENABLED INVENTORY MODELS

To examine the efficiency of inventory models applying Physical Internet approach, we carry out three parts of research:

- 1) Firstly we take out a study to discuss inventory problems and models both in literature. This part of study is done as to answer the question: what are the main differences between the classic supply networks and the PI enabled supply network in terms of inventory management?
- 2) Then we continue our study by developing a rule-based simulation inventory model to analyse how the PI affects the inventory control policies. This part of study aims to answer the following questions: First, what inventory control model could be used to the PI? Second, do the new models always make the PI reducing the inventory costs? This part of results has been published in Pan et al. (2015).
- 3) After, in order to quantitatively analyse the new practices and perspectives brought by the PI, we will propose a simulation-based optimisation inventory control model. This part of study tries to answer the following questions: How the optimal decisions are made for inventory problems in an open network? What are the most possible cost benefits? What is the sensitivity of parameters to cost benefits such as products' values? This part of results has been published in Yang, Pan, and Ballot (2015) and submitted in YANG, PAN, and BALLOT (2016b).

Therefore, the rest of this section is organized according to these three parts.

Chapter 2. Introduction of inventory problems in the Physical Internet

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The objective of this chapter is to provide an introduction of inventory problems in the Physical Internet (PI). To this end, we firstly give a general brief review of inventory management in literature, which is followed by a discussion of the need of the PI in this domain. Then a qualitative study follows to analyse inventory problems in the PI and the new practices brought by this open interconnected logistic system. Finally, a discussion of related practices in the literature will be given.

2.1 Inventory management

Inventories exist throughout the supply chain in various forms for various reasons, i.e. uncertainties both from the customers and suppliers. Inventory system takes a large proportion of a company's supply chain management cost and helps company to maintain competitive advantages. Thus, efficiently managing inventory systems becomes quite crucial to improve a company's business performance.

2.1.1 Definition and basic inventory control policies

Inventory or stock refers to the goods or materials that a business holds for certain purposes. There are three basic reasons to keep inventories:

- 1) Time lags in the supply chain, also called as the lead time, refer to certain amount of time to maintain stocks.
- 2) Uncertainties in the demand, supply and also the movements of goods. In this issue, the inventories are used as buffers to meet these uncertainties.
- 3) Economies of scale. Producing or purchasing in large lots allows a stage of the supply chain to exploit economies of scale and lower cost, (Chopra and Meindl 2007). The presence of fixed costs associated with ordering and transportation, quantity discounts in product pricing, and short-term discounts or trade promotions encourages different stages of a supply chain to exploit economies of scale by ordering in large lots.

Inventory management is a science primarily about specifying the shape and percentage of stocked goods with certain constraints to particular objectives. Recent comprehensive review about inventory management can be found in Silver (2008) . He concludes the main possible objectives and constraints as follows.

Possible objectives of inventory management:

- i. Cost minimization
- ii. Service level maximization
- iii. Profit maximization
- iv. Determination of a feasible solution
- v. Maximization of rate of return on stock investment
- vi. Ensuring flexibility to cope with an uncertain future

And etc.

Three categories of possible constraints:

- A. Supplier constraints – minimum order sizes, restrictions to certain pack sizes, restrictions on lead times, and etc.
- B. Marketing constraints – minimum tolerable customer service levels, and etc.
- C. Internal constraints – storage space limitations, maximum workload, and etc.

In detail, we can conclude that inventory management is a science which attempts to answer the following questions for certain objectives with respect to certain constraints:

- a) How often should the inventory status be determined – what is the review interval?
- b) When should a replenishment order be placed?
- c) How large should be the replenishment order?

To respond to these questions, there are two major ordering disciplines: continuous review policies – (s, Q) and periodic review policies – (T, S) . In case of continuous review, the inventory level is revised continuously and an order of quantity of Q will be placed immediately after the inventory level drops below a reorder point – s , an example as shown in Figure 7. This policy is the optimal for a single location inventory system with constant set-up costs, linear holding cost and penalty cost, fixed replenishment lead time and which allows for backordering of unsatisfied demands. Scarf (1959) demonstrate the optimality under a finite horizon and Iglehart (1963) in an infinite horizon.



Figure 7. Continuous inventory review policy – (s, Q)

In the case of periodic review, the inventory level is inspected under every T periods and an order of quantity of $Q = S - \text{current inventory level}$ ($S - \text{replenishment level}$) will be generated only at the review moments and if current inventory level is lower than reorder point s , an example as shown in Figure 8.

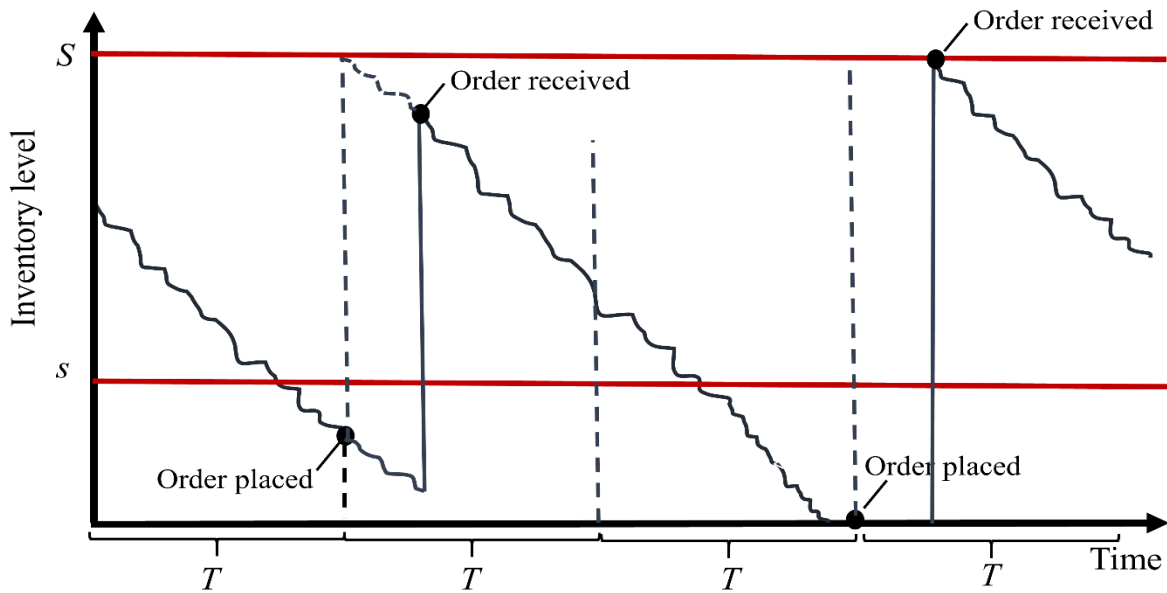


Figure 8. Periodic inventory review policy – (T, s, S)

2.1.2 Field of study: inventory control models in FMCGs

As the supply chain strategy varies for different products, our research concentrates on supply chain management strategies and inventory control policies for Fast Moving Consumer Goods (FMCG). FMCG refer to products that are sold quickly and at relatively low cost with mass distribution, such as beverage, fresh foods, over-the counter drugs and etc. The term FMCG also refer to the mass distribution/consummation or the grand distribution/consummation.

According to the ranking of Cabinet Deloitte for the LSA magazine and the calculations of *DGCCRF* (Direction générale de la concurrence, de la consommation et de la repression des fraudes) in France, the first 10 consumer goods distribution companies in the worldwide have created a grand value of 1.258 trillion US dollars in the global economy in 2013⁸. *Carrefour* is the only one French distribution company in this list with a turnover of 75 billion euros, equivalent to 99 billion US dollars. The group manages more than 10 800 stores in different formats in worldwide, consisting 1421 hypermarkets, 2917 supermarkets and almost 6000 outlets (stores, cash & carry, etc.). In addition, the Carrefour Group is the second largest of the private employers in France with more than 116 000 employees⁹.

The supply chain management for FMCG sector has been much developed in nowadays and the Figure 9 summarizes the today's organization in this sector. Generally, logistic sites in this sector can be classified into two levels:

- 1) Upstream stage, where there are various suppliers with different sizes in charge of production, as well as centralized or integrated central purchasing centers which manages supplies.
- 2) Downstream stage, where the sale to end consumers is done through distributors.

⁸http://www.economie.gouv.fr/files/files/directions_services/dgccrf/documentation/dgccrf_eco/DGCCRF_eco32.pdf

⁹ http://www.carrefour.com/sites/default/files/DDR_2014_FR.pdf

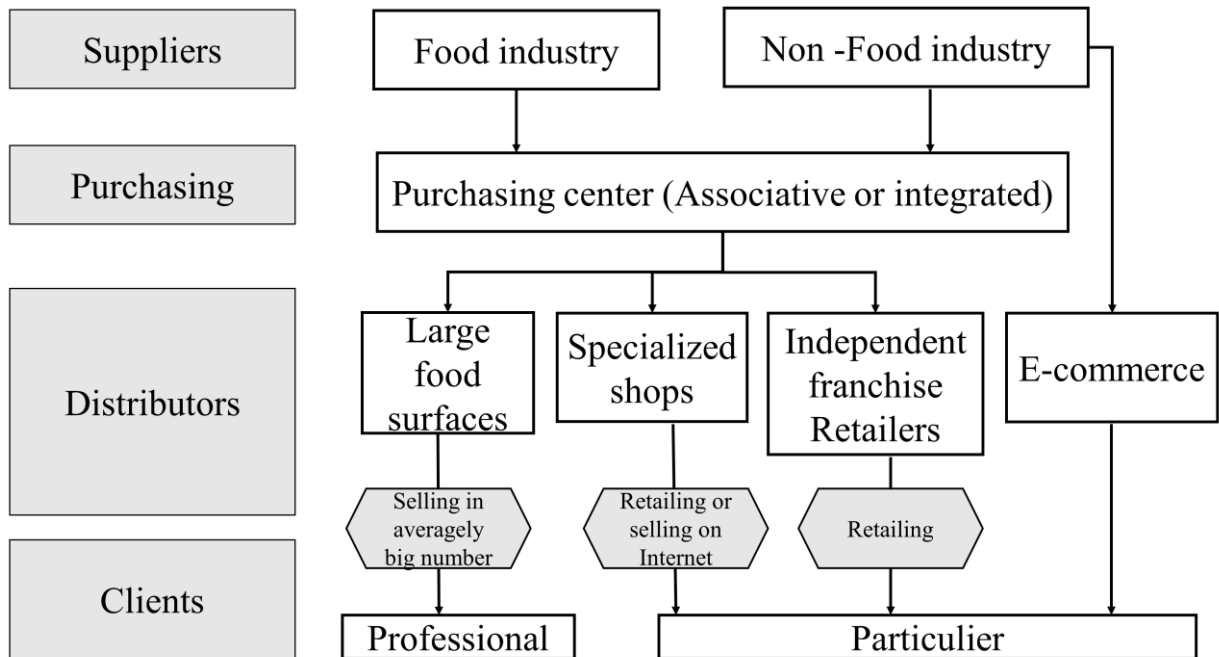


Figure 9. Supply chain organization of FMCG sector (Synopsis 2007)

To better illustrate the organization structure, we use the example by Ballot and Fontane (2010), as shown in Figure 10. The majority of logistics sites for FMCG is distributed throughout the national territory. Generally, the supply chain network for FMCG possess three echelons:

- 1) The plants produce and deliver their finished products to warehouses (in actual FMCG sector, the supplier usually owns only one or few national warehouses).
- 2) The warehouse receives and stores products from different factories of the supplier. Then they group these products and deliver to distribution centers according to customer orders. The warehouses can be provided and managed by external logistic service providers.
- 3) Then the large quantity of products will be distributed to distribution centers owned by different distributor companies, such as Carrefour. A distributor company may have several regional distribution centers to serve local points of sales.

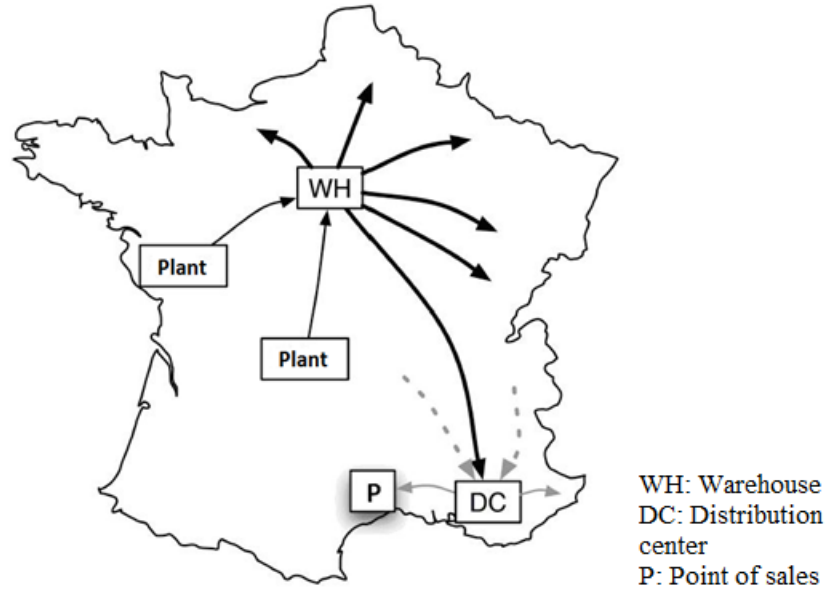


Figure 10. Supply Chain structure in food industry in France by Ballot and Fontane (2010)

This distribution structure is not the only existing structure for FMCG sector however it is most dominant one. It is called as “long circuit” as opposed to “short circuit” where the products are delivered by producers directly to stores, representing in 2008, about 75% of the flow of food in “long circuit” against 25% in “short circuit”. Thus in our research, we consider this distribution structure as the current supply chain frameworks for FMCG sector.

Concerned to inventory management in this sector, as the supply network is hierarchical and fixed once it is defined, the inventory management problems consist of when and how much to order while considering numbers of constraints to certain objectives. Besides, companies’ quests for efficacy in their logistic networks often leads to centralized storage and sorting organizations that allow products from plants and suppliers to be grouped before being redistributed. This trend can also be explained by the disappearance of small regional warehouses and the increased number of big distribution centers. DORNIER (1997) use the example of *Yoplait* to illustrate this trend in upstream logistic parties and focus on the benefits of centralization of stocks especially for suppliers. Later Harrison and van Hoek (2005) explain the need of centralization of stocks in downstream parties for distributors by the example of supply chain organizational evolution of *Nike* in Europe. At the very beginning, the company use decentralized supply chain decision framework with local distribution partners in each country in Europe. Due to the growth of the

different markets and the lack of coordination among different distributors, serious problems emerged, such as a type of product that in one country is gravely in shortage and often in excess stocks in the warehouse of another country, and vice versa. Thus, in the early 1990, *Nike* consolidated its 22 national warehouses in Europe in one European distribution center in Laakdal Belgium.

2.1.3 Effective current inventory control strategies

In face of the arising challenges and the limits for current organisations, numerous strategies based on current hierarchical specialized system are proposed and new technologies are adapted to enhance its efficiency. From strategic and operational aspect, we conclude the literature on improving the performance and service quality into two groups:

- I. through collaborative inventory policies such as Collaborative Planning, Forecasting and Replenishment (CPFR) in (Fliedner 2003) and (Holweg et al. 2005), vendor-managed inventory (VMI) in (Waller, Johnson, and Davis 1999a) and (Yao, Evers, and Dresner 2007);
- II. and through improving the current organization's agility and flexibility, such as adding new practices by lateral transshipments and substitutions in inventory systems proposed in (Paterson et al. 2011), inventory pooling studied in (Corbett and Rajaram 2006) and joint inventory studied in (Çapar 2013), multi-sourcing strategy in (Thomas and Tyworth 2006), as well as the Inventory Routing Problem (IRP), which combines the vehicle routing planning and inventory control problem (Bertazzi and Speranza 2012).

Despite the efforts and contributions of the research works, inventory costs are still representing a very important part in the total logistics costs. The reason is that, on one hand, most of the models in the literature rely on hierarchical and independent supply chains to store and distribute products for customers over a given geographical area; on the other hand, these models are more and more challenged by the higher volatility of economic climate and the incomplete visibility and accuracy of the global inventory level. Recently, some research works have proven that the interconnection of logistics networks, i.e., logistics pooling or the Physical Internet, may improve the efficiency of transportation, see (Pan, Ballot, and Fontane 2013; Pan et al. 2014; Sarraj et al. 2013). But the inventory management issues are not yet well addressed in this context,

especially new inventory control models. Hence we will explore the perspectives of this innovative concept to inventory management.

2.2 Inventory Problems and new practices in the Physical Internet

This part describes differences in decision-making between PI and traditional supply network designs in inventory management. To illustrate the differences, we take a general example of current distribution system in FMCG and the distribution system in PI, shown in Figure 11.

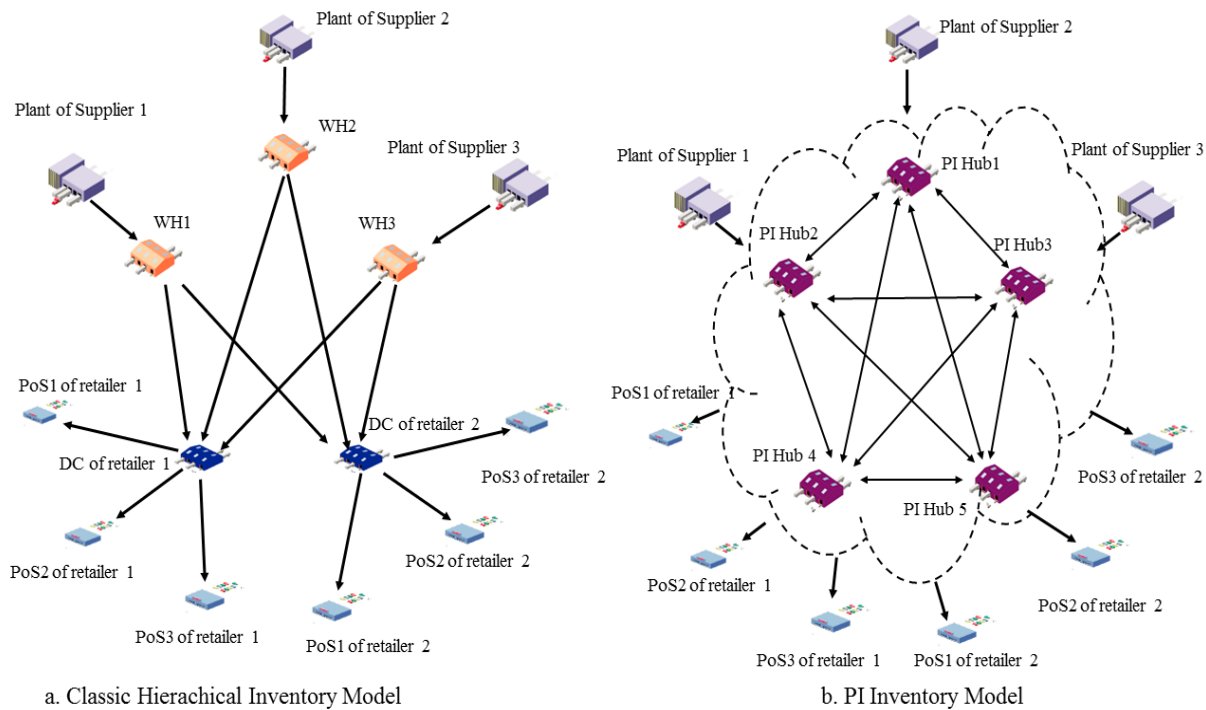


Figure 11. Current dominant distribution system in FMCG vs. PI

Figure 11.a presents the most dominant logistics system structure in the FMCG sector based on traditional SC network design. About 75% of the flow of food is distributed through what are called “long circuit” compared with 25% via “short circuit” where the products are delivered directly to stores (Sétra 2008a). Thus, in this chapter, we consider “long circuit” as the general logistic system structure for FMCG. As seen in Figure 11.a, the current logistics network is a multi-echelon hierarchical structure composed of upstream sites controlled by suppliers (plants and warehouses) and downstream sites (distribution centres and points of sale) controlled by retailers.

Each company defines and optimizes its own part of the logistics network. Once the network has been defined, the storage locations and replenishing schemes (source-destination pairs) are also determined for the long term. Inventory control decisions under this scheme concern how much and when to order to satisfy customer demand.

Instead of a pre-determined hierarchical structure, the distribution and storage network in PI is transformed into an open interconnected network of PI-hubs through standard interfaces and shared by users, as depicted in Figure 11.b. One or several Logistics Service Providers (LSP) manage PI-hubs as long as they are interconnected. The goods are encapsulated and distributed in modularized, traceable shipping units called PI containers. They can be routed in the distribution network, taking into account their physical nature, in the same way data packets transit in the Digital Internet. It is even possible for different users of the PI to share a same PI container according to needs. Thus, under PI, the storage and distribution system offers shippers and consignees many more options. The PI allows users to place stocks all around the system if needed by using on-demand warehousing service within PI¹⁰. Besides, the source options for orders including replenishment orders and customer orders can be dynamically determined according to the real status of the network, which result in open multiple dynamic sourcing options. As a result, these new practices would lead to potential reduced total logistic costs and improved customer service, hence improved efficiency and effectiveness. For example, the PoS1 of retailer 1 can be served by PI-hub2 if it is more profitable at a given time. In this respect, Figure 11 is a logical description not a reflection of potential geographical synergies that are partly unreachable in Figure 11.a. Thus, under this scheme, the network, as well as the logistics services, becomes completely interconnected. And three main characteristics of PI enabled inventory models were outlined: 1) Possibility of distributed stocks in hubs near end customers; 2) Transshipment and full pooling of inventories among hubs; and 3) multiple dynamic source options for each order.

As a result, under this structure, as the sourcing points for retailers or hubs are no longer fixed, inventory replenishment questions concern not only how much and when but also where to satisfy each order. Certainly there are also other numerous questions associated to this organization: handover of the goods property, traceability, security, etc. They are not addressed here as we focus

¹⁰ It exists already such as Flexe.com, Amazon.com, and etc.

only on inventory replenishment policies, of which the objective is to find the best compromises of effectiveness such as customer service level, and efficiency such as total logistic cost.

2.3 Relevant work in literature

Considering the new practices brought by PI to inventory management, within the existing literature, we find the following four categories of related research: 1) Inventory models with lateral transshipment rebalancing inventories among retailers within a company; 2) Inventory models with multiple source supplier options allowing a buyer's order satisfied by multiple suppliers; 3) Inventory routing problems combining vehicle routing and inventory control problems where a supplier decides when to visit its customers, how much to deliver to each of them and how to combine distribution flows with vehicle routes; 4) Integrated location-inventory models which consider intermediate facility allocation decisions and inventory decisions simultaneously.

Differing from product flows, we have classified the literature of lateral transshipment into the following two groups: 1) horizontal lateral transshipment (HLT) depicted in

Figure 12.a, which redistributes inventories among retailers within a company (Gross 1963; Diks and de Kok 1996; Archibald, Black, and Glazebrook 2009); 2) vertical lateral transshipment (VLT) shown in Figure 12.b that redirects an incoming customer demand to pooling members of the same echelon (Axsäter 1990; Dada 1992; Seidscher and Minner 2013).

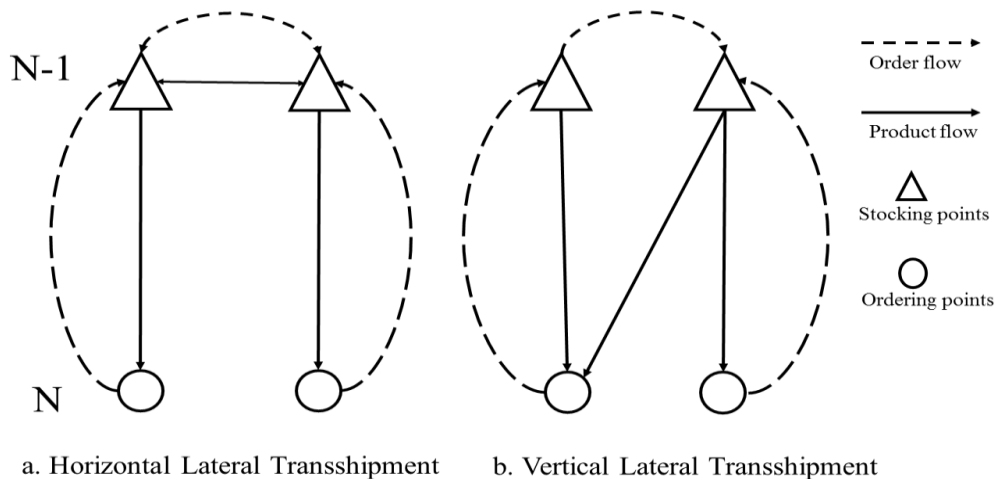


Figure 12. Lateral transshipment flows

Recent comprehensive overviews are provided in (Paterson et al. 2011) for papers published before 2011. Here, we discuss several publications after 2011 to give an insight of research problems in lateral transshipment. (Çapar, Eksioğlu, and Geunes 2011) study a two-echelon inventory model with two distribution centers and two identical retailers with positive lead times. They compare the overall supply chain performance of four sourcing strategies: current sourcing strategy OP_{cur} with fixed supplier, reactive transshipment OP_{NLC1} redirecting customer demands when facing a stockout, ordering policy OP_{NLC2} based on the earliest delivery time, and ordering policy OP_{new} based on the expected total cost including the fixed ordering and transportation cost associated with all outstanding orders. (Paterson, Teunter, and Glazebrook 2012) propose an enhanced transshipment policy for a single echelon N location system under continuous review. The enhanced transshipment enables a preventive redistribution of stock among the pooling members to prevent the future stock-out in addition to emergency transshipment corresponding to the stock-out state. Results show average costs are reduced by between 11% and 17% in comparison with no transshipment. In a word, the literature has shown that transshipment is quite profitable for retailers with long replenishment lead times from suppliers and who are located closer to one another or who have significant shortage penalty cost. In spite of horizontal inventory sharing in both transshipment and PI inventory models, the distribution network in PI is fully interconnected and shared by all users. In addition, the source is selected dynamically whereas in lateral transshipment the source is pre-assigned within one company and the transshipments are used as lateral support for regular replenishment orders.

According to whether an order can be split into sub-quantities and met by several source supply points, two groups of inventory models with multiple suppliers can be identified: i) without order splitting which focus on a source substitution method (Ng, Li, and Chakhlevitch 2001; Çapar, Eksioğlu, and Geunes 2011; Veeraraghavan and Scheller-Wolf 2008); ii) with order splitting which focuses on an inventory allocation method in addition to source substitution (Sculli and Wu 1981; Ryu and Lee 2003; Song, Dong, and Xu 2014). For example, (Ng, Li, and Chakhlevitch 2001) consider a two-echelon inventory model with two identical warehouses and two identical retailers under a continuous (Q, R) replenishment review. Delivery times are constant and unmet orders are backordered. Two sourcing strategies are compared with the traditional sourcing modes where the retailers are pre-assigned to specific warehouses: 1) emergency transshipment redirecting the

incoming retailer demand to the other bases when the pre-assigned base faces a stock-out; 2) designate the incoming retailer demands to the first base with stock on hand when both bases are out of stock. A simulation is developed to determine the best Q and R parameters for each supply chain entity to minimize total system cost including average total cost both at warehouses and retailers. (Veeraraghavan and Scheller-Wolf 2008) examine a periodically reviewed single-stage inventory system with dual sourcing through a regular fixed lead time channel and a smaller lead time premium channel. A simulation-based optimization procedure is developed to determine the order-up-to level parameters for each channel minimizing the infinite-horizon average holding, penalty, and ordering cost. In conclusion, the existing work shows that multi-sourcing can reduce the mean and variance of the effective lead time and a split order model always has lower stock levels than the equivalent non-split model. However, the multi-sourcing options in current multi-sourcing models are only restricted between the upper level storage points and their successive demand points. Storage points on the same echelon are independent and no product flows are allowed between these storage points. Thus, it differs from the PI inventory model.

Similarities can also be found in inventory-routing problems (IRPs). Differing in the decision space, two types of inventory routing problems are often addressed: 1) decisions over time only where the routes are given, which refers to Single Link Shipping problems and Direct Shipping problems (Speranza and Ukovich 1994; Bertazzi, Paletta, and Speranza 2005); 2) decisions over time and space where the timing of the deliveries and the routes to be travelled need to be decided simultaneously (Coelho, Cordeau, and Laporte 2012; Solyalı and Süral 2012). The pioneer contribution of IRPs can be date back to 1980s (Bell et al. 1983) where inventory management of industrial gases at customer locations is integrated with vehicle scheduling and dispatching problems. They dealt with the case with stochastic demand to minimize the transportation cost with required customer inventory levels. The following decisions have to be made simultaneously by the supplier: when to serve a given customer, how much to deliver to this customer and how to combine the vehicle routes of the distribution to different customers.

The existing literature on IRPs demonstrates that this strategy can improve SC performance through savings in distribution and production costs for suppliers by coordinating shipments to different customers. Despite the fact that vehicle routing optimization may exist in both models, PI inventory models differ mainly from IRPs in the following two ways: 1) transportation sharing in

PI is achieved by modularized and standardized containers and routing protocols including vehicle routing optimization, interconnection of multi-modal transport, etc.; 2) PI can rebalance stocks among PI-hubs to satisfy replenishment orders from retailers while stock rebalancing among different retail companies is not addressed in IRPs.

To sum up, the authors can't find corresponding inventory control model within the existing literature to the new practices brought by the Physical Internet. It is therefore a new research issue and a new topic in inventory management. In the rest of Part I: Chapter 3 proposes and discusses a rule-based PI inventory model through a simulation as to provide a feasible inventory solution in the PI; Chapter 4 investigates how optimal decisions could be made in such an open network.

Chapter 3. Perspectives of new inventory control models in Physical Internet: a simulation study

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This chapter aims firstly to find new research questions related to inventory management in Physical Internet, and secondly to provide a view of how the PI network affects traditional inventory control policies. The results of this part have been published by Pan et al. (2015).

3.1 Introduction

Classical supply chain design relies on a hierarchical organization to store and distribute products over a given geographical area. Within this framework a stock shortage affects the entire downstream section of the supply chain regardless of the stocks kept in other locations. With the implementation of the Physical Internet approach of which the aim is to integrate logistics networks into a universal system of interconnected, inventories can be divided among shared hubs that serve the market and source substitution is allowed. This chapter measures the impact of such an organization on inventory levels and then costs with service level set as a constraint. The analysis focuses on the resource levels (transportation and inventory) required by the current supply model and by the Physical Internet system in order to serve a market with a (Q, R) stock policy. The (Q, R) policy is used here as it is reported as the most commonly used inventory review policy (Waller, Williams, and Tokar 2008). Besides, in the PI, Q could be a container size.

Starting with two supply models and with the definition of cost models as well as inventory policy, the work of this chapter is based on computer simulation. The analysis tested 3 different categories of criteria in order to allow dynamic source selection when an order is placed: Source Substitution, Minimum Ratio and Minimum Sum. Source substitution, one of the simplest criteria, was found to be the most efficient and stable according to different scenarios. The main intent of this chapter is to discuss the new research question related to inventory management in Physical Internet, and secondly to provide a view of how the PI network affects traditional inventory control policies.

The rest of chapter is structured as follow. Part 2 provides a solution to the inventory problem in the PI by defining some replenishment strategies based on two factors: shipment distance and inventory level. Then in part 3 the strategies will be assessed using simulation studies driven by the objective of minimizing the total cost generated by transportation and inventory and the results will be discussed. In Part 4 we explore the generalization of the results obtained in Part

3 to more complex networks. Part 5 summarizes the findings of this chapter and highlights perspectives for future work.

3.2 Define replenishment policies in the Physical Internet

Due to the complexity of the problem, the main research objective of this chapter is to define and assess rules to choose replenishment in the PI with (Q, R) inventory policy and no backlog. In Chapter 2 we have discussed the modality of the distributed inventory in the PI, which allows the possibility of multi-source replenishment and thus the unpredictability of the source point for every order. Hence it is necessary to set up replenishment policies to select the best source point for each order, while determining the optimum reorder point and lot size for orders in the distribution network of PI.

A simulation approach is adapted to assess the performance of strategies compared to the classical supply model. In order to compare the results of the simulation, we use the same input data for all scenarios, such as demand (mean value and variation), lead time, etc. However, we should recall that our main objective here is to study the performance of distributed inventory in the PI, but not to determine the best replenishment strategy in such a system. Actually it may be the case that the best strategy will be determined specifically with respect to actual cases with different constraints and demands. This is not the intention of this chapter. Furthermore, as the first step of our research, we only analyze cycle inventory in this chapter. The impact of the new strategies on safety stock will be studied in the next step.

3.2.1 Classical supply network

The classical supply network serves as the benchmark for considered as reference to the PI scenarios. As shown in Figure 11.a, in the classical supply model source-destination pairs are fixed, e.g. Retailer₁ supplied by DC₁ which is supplied by WH₁, and so on. To simplify the problem, we assume that the deterministic lead times are not subject to change over the simulation period and that retailers use (Q,R) and discrete continuous review policy for inventory control (for example each day at 00:00 the retailer checks the inventory level in the simulation model)

3.2.2 Alternative strategies in the PI

On the other hand, in the PI every order can be filled by different source points according to the real-time status of the potential sources and the criteria of selection. For example the order from Retailer₁ could be shipped from any hub, and a hub could be delivered from another hub or directly from the plant depending on the selection criteria. The two most important factors taken into account are: distance between source and ordering point; and the inventory level at the source. Accordingly 3 categories of criteria are defined to select the source point in the PI and assess performance: Source Substitution, Minimum Ratio and Minimum Sum.

3.2.2.1 Source Substitution

Intuitively the logical source point would be one closest to the destination, for lead time and transportation cost reasons. But in this case replenishment would not be dynamic if distance is the only criterion. If one takes inventory level into account, the Source Substitution strategy is based on a very intuitive criterion, which is as follows: the source of replenishment is the closest (in terms of km) source with sufficient available inventory to fill the order. In other words, the criterion is Distance First - Inventory Second. This rule will be simulated in Part 3.3.

3.2.2.2 Criterion of the Minimum Ratio

Furthermore, we can consider the importance of transportation and inventory to be on the same level. The system is driven simultaneously both by minimum distance and by local inventory level. The aim is to achieve a more uniform distribution of inventory across the network, thereby decreasing the overall lead time of replenishment and total handling costs. Here we employ two common expressions to formulate the interaction: ratio or sum.

3.2.2.2.1 Minimum Ratio

The idea of the minimum ratio criterion is to reduce the global amount of inventory through the more uniform distribution of inventory in the system. At the same time it is necessary to find a trade-off between this objective and the cost of transportation. Therefore the network flows are driven by the following criterion. Whenever a retailer or a hub needs to be replenished, the source of shipping is the one that minimizes the ratio of the distance to its current inventory of inventory:

$$\min (\text{Ratio}_i = \frac{D_i}{S_i}; i \forall \text{candidate sources}) \quad (1)$$

Where D_i is the distance from a candidate source i to the destination point; S_i is the inventory level at candidate source i ; and candidate source i should have sufficient inventory to fill the order.

Obviously for each order the minimum ratio criterion promotes the sourcing point which has shorter distance to destination, but which also has a higher level of inventory. To simulate the strategy investigated here, we suppose that each ordering point of the network (either retailer or hub) calculates the minimum ratio of its sourcing points, in order to find the most convenient source (hub or manufacturing facility). For instance, every time Retailer 1 needs to be replenished, it calculates the above-defined ratio for each hub, and sends an order to the hub where the ratio is the lowest. The replenishment of Retailer 2 takes place similarly. In particular, hub replenishment can occur between hubs which means a hub can place its order with a plant as usual, or with its adjacent hubs. This is the potential benefit provided by the interconnected network under PI.

3.2.2.2.2 Minimum Ratio modified with coefficients

The above-defined ratio is the primitive way to investigate the strategy simultaneously taking into account distance and inventory level. However it can be expanded to different forms, for example modified with the following power coefficient. The candidate source that minimizes this ratio is chosen for replenishment:

$$\min (\text{Ratio}_i = \frac{D_i^\gamma}{S_i^\phi}; i \forall \text{candidate sources}) \quad (2)$$

With D_i and S_i having same definition as in Equation (1); γ , ϕ are coefficients to calculate the Ratio of each candidate source i .

The value of γ and ϕ will be determined via simulation study, by changing their value within a set range in order to determine the optimum source yielding the lowest total cost. This approach will be discussed further in the simulation and result parts. Obviously Equation (1) is a specific form of (2) when γ and $\phi=1$.

3.2.2.3 Criteria of the Minimum sum

It is also possible to implement another common mathematical expression to interpret the interaction of distance and inventory level, which is to sum the importance of these two factors. Here we study the formulation with monomial expression or exponential expression.

3.2.2.3.1 Minimum sum of Monomials

The minimum sum of monomials is based on the same logic that the candidate source having the lowest value $f(D_i, S_i)$ will be selected as a replenishing point. The value of $f(D_i, S_i)$ will be formulated in minimal expression as follows:

$$\min (f(D_i, S_i) = \alpha D_i^\gamma + \beta S_i^\delta; \quad i \forall \text{candidate sources}) \quad (3)$$

With D_i and S_i having same definition as in Equation (1); α , β , γ , δ are coefficients to calculate the value $f(D_i, S_i)$ of each candidate source i .

Obliviously the value of the coefficients in the Equation (3) is very sensitive to the final decision. Another role of the coefficients is to differentiate the impact of transportation and inventory on the decision. In a given simulation case such as in Part 4, we can test different values of the coefficients to determine the best one hereafter taken as parameters of the simulation model.

3.2.2.3.2 Minimum sum of Exponentials

Based on the same logic, another criterion proposed here is the minimum sum of exponentials, as presented in Equation (4):

$$\min (f(D_i, S_i) = \alpha^{D_i} + \beta^{S_i}; \quad i \forall \text{candidate sources}) \quad (4)$$

D_i and S_i having same definition as in Equation (1); α and β are coefficients to calculate the value $f(D_i, S_i)$ of each candidate source i .

The intention of the sum of exponential expression is to strengthen the sensitivity of distance and inventory level, the factors which are in exponential position, to the selection of the replenishing point. The value of the coefficients will be determined in the same way presented above.

Until now we have demonstrated the four categories of replenishing point selection strategies. They are: the classical model with fixed path, source substitution, minimum ratio of distance to inventory level, and the minimum of sum, and also their models expanded to the PI. In the next part we test their performance via simulation studies.

3.3 Simulation study and numerical results

This part discusses the simulation models and results of evaluating the performance of the replenishment policies as defined above. Before introducing the simulation process, we will explain how to model the inventory holding and of transportation cost functions, which are the functions considered in the simulation model.

3.3.1 Cost functions

The cost elements are communicated by our research partners. Only the two most important elements are taken into account as mentioned above: inventory and transportation. Basically the inventory holding cost model is linear as function of storage time for a volume of a cubic meter (m^3). For instance at the Warehouse, distribution center and hub level the cost is 0.11 Euro/(day· m^3), while at the Retailer's the cost is given by a 3/2 ratio, which is equal to 0.165 Euro/(day· m^3), as shown in Figure 13. This represents more expensive inventory in a shop.

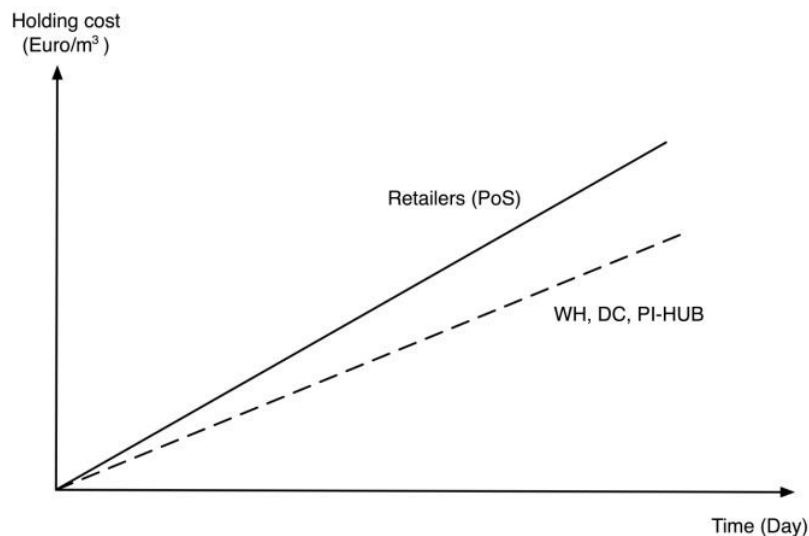


Figure 13. Cost function of inventory holding

The function for the transportation activity is a step function (non-continuous), whereas the transportation is only by road in our case. The function chosen models full truckload operations as it is usually the case in the FMCG supply chain. As shown in Figure 14, each segment stands for the cost of using a truck, which is 1.4 Euro/km. Unlike other research papers which feature a purely linear cost function for transportation, the piecewise linear function results in an optimized transportation scheme which minimizes the total transportation cost by minimizing the number of trucks. This issue has also been discussed in (Meuffels et al. 2010; Pan, Ballot, and Fontane 2013). However, to accord with the reality, only the price for full-truck-load is considered. That is why all segments in Figure 14 are flat.

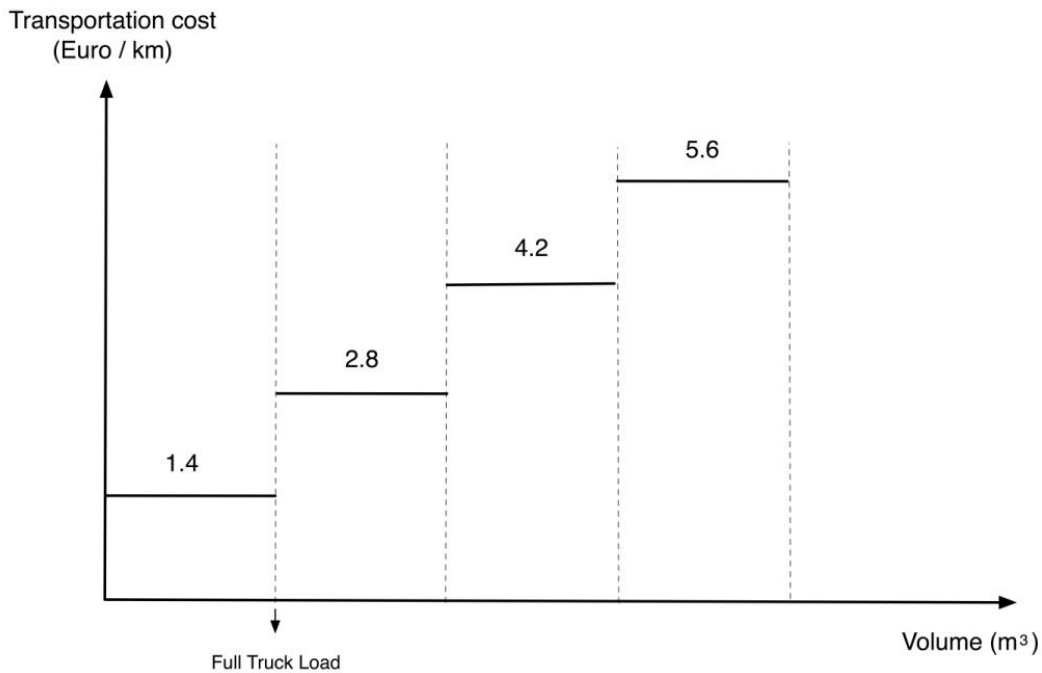


Figure 14. Cost function of road transportation

3.3.2 Simulation models

To test the different strategies defined above, we developed a model in AnyLogic which is a multi-method simulation modeling software developed by XJ Technologies (www.anylogic.com). It is a multi-agents based simulation model (Macal and North 2010). Without giving all details,

this part summarizes the features and assumptions of the simulation model as follow, to help readers understand the operation of the model.

- a) Usage of discrete event simulation model;
- b) Time of simulation is 1000 days (all the order processes take place once a day). Nevertheless, to wipe off the impact of initial inventory level on the results, only the 730 days (two years) in-between the period are used for data analysis.
- c) Daily demand submits to Normal distribution (mean values and standard deviation values are defined and presented in Table 2).
- d) Network pattern is fixed (number of plants, WHs, DCs, Retailers and hub, as well as their location, distance and lead time);
- e) Simulation is driven by the minimization of total cost of the supply network (transportation cost plus inventory holding cost);
- f) Experiment designed to minimize the total cost according to inventory parameters of Lot size (Q) and Reorder point (ROP), and to determine the coefficient for the equations (2)-(4), which were defined in the replenishment criteria.
- g) Service rate is a precondition for the analysis: total shortage should be less than 100 units at the end of the simulation (global service level $\geq 99,96\%$); If the simulation returns a lower service level, it means that the running combination of parameters (Q',R') does not fulfill the above-mentioned precondition. Therefore this combination will not be considered as a possible solution of the system.
- h) Unmet demands are considered as lost sales and they are not considered as part of total cost.
- i) Direct shipments from plant to retailers are not allowed.
- j) All plants considered as unlimited production sources (without regard to inventory cost and production cost)

In order to compare the results obtained via experimentation, all scenarios have the same input data. The difference is only the replenishment strategies in different supply networks.

3.3.2.1 Scenario of classical supply network

The classical supply network scenario is the benchmark for the other scenarios of PI scenarios. A simple supply network is designed as the field of the simulation studies, as shown in

Figure 15. As mentioned above, network pattern is fixed, as well as the distance or lead time for all scenarios.

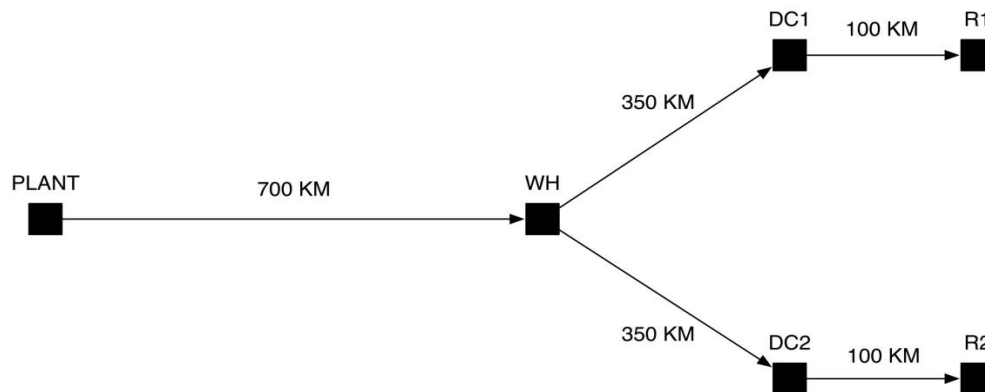


Figure 15. Classical supply network designed for simulation

In addition to the designed network, we took a sampling of flows from a database of FMCG companies. To simplify the problem, only one product is considered in the model. We analyzed the flow of this product over the course of one year in two regions modeled as Retailer 1 and Retailer 2 in Figure 15. We can further calculate the mean value and standard deviation (S.D.) of daily demand, the lead-time, lot size etc., being the essential input data for the simulation. The product unit is measured in full pallet (which is 1.73 m³). Parameters are shown in Table 2.

No	Parameters	Unit	Type	Value	Step
1	Daily Demand R1	[units/day]	Stochastic	Mean=20, S.D.=4	-
2	Daily Demand R2	[units/day]	Stochastic	Mean=35, S.D.=7	-
3	Lead time DC to R	[Days]	Fixed	7	-
4	Lead time WH to DC	[Days]	Fixed	10	-
5	Lead time Plant to WH	[Days]	Fixed	14	-
6	Lot Size Retailer 1	[units]	Fixed	76	-
7	Lot Size Retailer 2	[units]	Fixed	90	-
8	ROP Retailer 1	[units]	Fixed	27	-
9	ROP Retailer 2	[units]	Fixed	47	-
10	Lot Size WH to DC 1	[units]	Discrete	25 (min) 800 (max)	25
11	Lot Size WH to DC 2	[units]	Discrete	25 (min) 800 (max)	25
12	Lot Size Plant to WH	[units]	Discrete	100 (min) 1000 (max)	50
13	ROP DC 1	[units]	Discrete	20 (min) 800 (max)	20
14	ROP DC 2	[units]	Discrete	20 (min) 800 (max)	20
15	ROP WH	[units]	Discrete	100 (min) 1000 (max)	20
16	Production Lot to plant	[units]	Fixed	1200	-

Table 2. Parameters of experimental simulation of classical model

Parameters 1 to 9, and 16 are fixed in all simulation scenarios, since they are known data related to the demand at the retailer level and the network pattern. Parameters 10 to 15, which are unknown from the database, are variables to be determined by experimental simulation. We increase parameter value in step from min to max value; and each combination of parameters is replicated ten times (a set of ten simulations for each combination of parameters). Then we compare the results (minimizing total cost) to determine the optimum configuration. The lower and upper thresholds are approximately calculated according to the mean demand of retailers and lead time. In addition, the simulation results also validate that it is unnecessary to test the higher value of lot size and reorder point than the upper thresholds. Besides, the step value plays a crucial role for the accuracy of the model and results. The chosen values show good compromise of accuracy and the number of simulation. Eventually the method can be improved in the next steps. In this chapter we focus only on the qualitative analysis and the method used has limited impact on the results.

The method is applied in the same way to the following scenarios but under different algorithm. We present here the algorithm of simulation for the scenario of classical supply network; and the optimum value of parameters 10 to 15 will be presented later.

Inventory Control algorithm in classical supply network:

1). *Initialization (time = 0 days) : assign 1200 units at plant inventory, assign to all the other nodes a stock level equal to (SS + lot size);*

2). *i-th day:*

a. *Demand erodes a part of retailer's stock: if shortage occurs, sales unfulfilled are simply lost.*

b. *control on every i-th node: Stock Level < ROP, if yes an order is sent at the upper level, and placed in the order list, processed by the "delay unit" in function of the lead time assigned and finally shipped during the (LT + i)-th day.*

c. *Control unit: if the upper level does not have enough the order is back-logged until stock availability at the source.*

d. *In the graph only the available stock are showed (once the order is placed at the node x, the stock available will be decreased of the order-quantity even though they might be still physically located in the inventory).*

3). End of the simulation (time =1000 days) :

- a. data are written on an Excel file, for each node of the network;
- b. cumulative level of shortage, number total order placed is shown.

3.3.2.2 Scenarios of PI

Compared to Figure 15, the pattern of the PI supply is the same. However, since the DC1, DC2 and WH are now considered to be open HUB 1 to 3 respectively, several new replenishment paths are possible, e.g. shipment from plant to HUB2 or HUB3, from HUB1 to R1 or R2 and particularly the interconnection between hubs. Figure 16 shows the new paths with distance in addition to the paths presented in Figure 15.

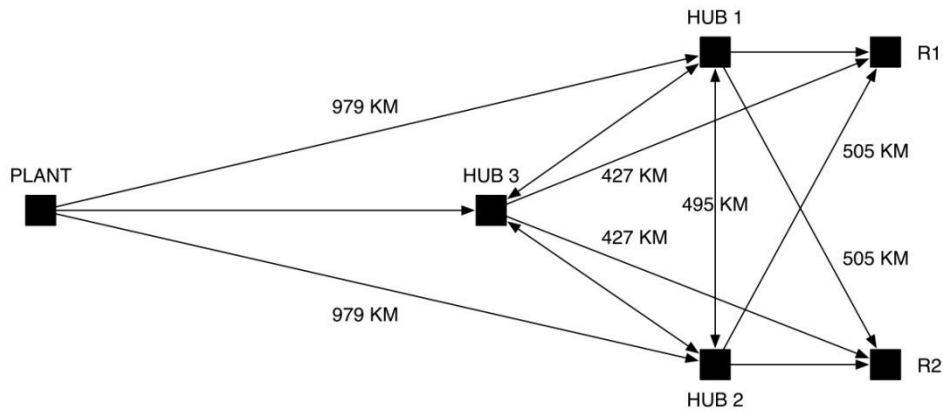


Figure 16. Physical Internet supply network used in simulation

Parameters 1 to 9, and 16 are maintained in the PI simulation scenarios. Note that the lead times between WH and DCs are now the lead times between Hubs; and the lead time to the new paths is proportional to the distance. Parameters 10 to 15 are no longer suitable in the PI models and they are replaced by parameters 17 to 21 in Table 3. In the same way their optimum value will be determined via simulation experiments.

No	Parameters	Unit	Type	Value		
				Min	Max	Step
17	Lot Size HUB to HUB	[units]	Discrete	20	800	20
18	Lot Size Plant to HUB	[units]	Discrete	20	1000	20
19	ROP HUB1	[units]	Discrete	20	800	10
20	ROP HUB2	[units]	Discrete	20	800	10
21	ROP HUB3	[units]	Discrete	20	800	10

Table 3. Modification of parameters in PI models

It should be recalled that another particularity of the PI models is the criterion for selecting the suitable replenishing points with some of them have coefficients to be determined as well. Once the value of lot size and reorder point are set in the PI, the next step is to determine the value of the coefficients in Equations (2) to (4). In the same way, the value of each coefficients ranges from -100 to +100 in 0.25 step. Every combination is tested (ten times) in a number of simulation experiments to find the optimum value in each equation. The algorithm of simulation for Physical Internet scenarios are as follow; and the outcome is presented in the next part.

Inventory Control Algorithm in Physical Internet:

1). *Initialization (time = 0 days): assign 1200 units at plant inventory, assign to all the other nodes a stock level equal to (SS + lot size);*

2). *i-th day:*

a. *Demand erodes a part of retailer's stock: if shortage occurs, sales unfulfilled are simply lost.*

b. *control on every i-th node: Stock Level < ROP, if yes an order is sent at the upper level, and placed in the order list, processed by the "delay unit" in function of the lead time assigned and finally shipped during the (LT + i)-th day. The Replenishment source is chosen by the criteria described in section 2.3.2 "Determination of replenishment source".*

c. *control unit: if the upper level does not have enough stock, it does not appear as a potential candi-date as replenishment source.*

d. *In the graph only the available stock are showed (once the order is placed at the node x, the stock available will be decreased of the order-quantity even though they might be still physically located in the inventory).*

e. *Swapping-avoid cycle: No recurrent lot swapping is allowed (if the hub x receives a certain order quantity for the hub y, the latter cannot accept orders from the former for a certain period, until that order has not been sent to a retailer, this is to avoid perpetual circulation of order within the π -network.*

3). *End of the simulation (time =1000 days) :*

a. *data are written on an Excel file, for each node of the network;*

b. *cumulative level of shortage, number total order placed is shown.*

3.3.3 Numerical results and discussion

A number of simulation experiments have been executed but only the final results are presented in this part. In all, we have defined 6 simulation scenarios and they are listed as shown in Table 4.

Sc No.	Model	Selection criteria of replenishing point
S1	Classical network	Fixed
S2	PI	Source Substitution
S3	PI	Minimum Ratio
S4	PI	Minimum Ratio modified with coefficients
S5	PI	Minimum sum of Monomial
S6	PI	Minimum sum of Exponential

Table 4. Simulation study scenarios

S1- Classical model				
Source	Destination	Q	R	Mean Shipment Frequency
DC 1	Retailer 1	76	27	39,1
DC 2	Retailer 2	90	47	58.4
WH	DC 1	200	100	14.5
WH	DC 2	275	100	18.7
Plant	WH	600	220	12
S2 - Source Substitution				
Source	Destination	Q	R	Mean Shipment Frequency
HUB 1	Retailer 1	76	27	19.5
HUB 1	Retailer 2	90	47	22.2
HUB 1	HUB 2	160	150	3
HUB 1	HUB 3	160	100	0
HUB 2	Retailer 1	76	27	10.3
HUB 2	Retailer 2	90	47	31.8
HUB 2	HUB 1	160	150	2
HUB 2	HUB 3	160	100	0
HUB 3	Retailer 1	76	27	10.4
HUB 3	Retailer 2	90	47	3
HUB 3	HUB 1	160	150	4.5
HUB 3	HUB 2	160	150	3.3
Plant	HUB 1	200	150	26.4
Plant	HUB 2	200	150	25
Plant	HUB 3	200	100	10

Table 5. Optimal lot size Q and reorder point R in classical network and in PI

The results of optimal lot size and reorder point in the classical and the PI determined by simulation is presented in Table 5. The criterion to select replenishing points in the PI is Source Substitution, i.e. Scenario 2. We can see that the PI allows replenishment between hubs and the optimal lot size of each hub is the same. Remember that these values are set according the demand at the retailer level, in other words only for this case. Changed input data certainly results in different outcomes. Knowing that the results of the other scenarios are very close to S2, the lot size value and reorder point of S2 are therefore maintained in the other scenarios in order to simplify the simulation process. Further, according to the mean values of shipment frequency (of ten times simulation) shown in the table, we can easily observe the new replenishment paths allowed in PI. For example the retailers can now place orders with all HUBs including the HUB3 that was the WH in the classical. The lateral transshipment between HUBs is also allowed.

Figure 17 compares the global inventory level of the current network and the PI with Source Substitution criterion in function of time. As demonstrated by the linear trend line, the mean global level is very stable for both of the two networks, but the PI has obviously a lower level. Furthermore, as discussed in (Kleijnen 1995; Sargent 2013), Figure 17 argues also the verification and validation of the simulation model from two angles, on one hand the fact of stable mean inventory level in line with the stochastic demands submitting to Normal distribution; and on the other hand the inventory level of the current network correspond to the real-world situation.

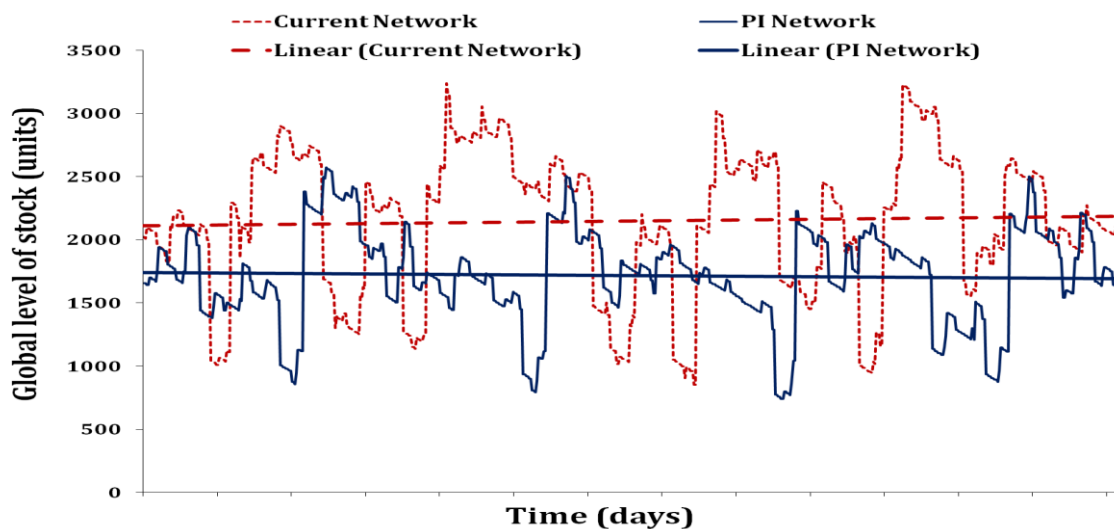


Figure 17. Global inventory level in the classical and the PI (with Source Substitution) in function of time

Once the lot size and reorder point have been set in the PI, the next interesting question is to analyze the impact of the criteria of replenishing point selection on total cost. By changing the value of the coefficients equations 2 to 4, we have identified two main findings from the results. First, some equations are more sensitive to the coefficient value, i.e. the equation of minimum sum with monomials. The optimum coefficient values in each equation, for which the total cost is the minimum in each scenario, are presented in Table 5. Second, different criteria have very different impact on total cost, as shown in Figure 18. Obviously S2 with the source substitution criterion in the PI shows the best performance in this case, economizing 9.16% of the cost of the classical model. On the other hand, the S5 with the Minimum Sum of Monomials criterion is not favorable. But, again, criteria performance can be very different depending on input data and the configuration of the network. In addition, their impact on safety stock should also be studied in the next step, and considered as a part of the total cost.

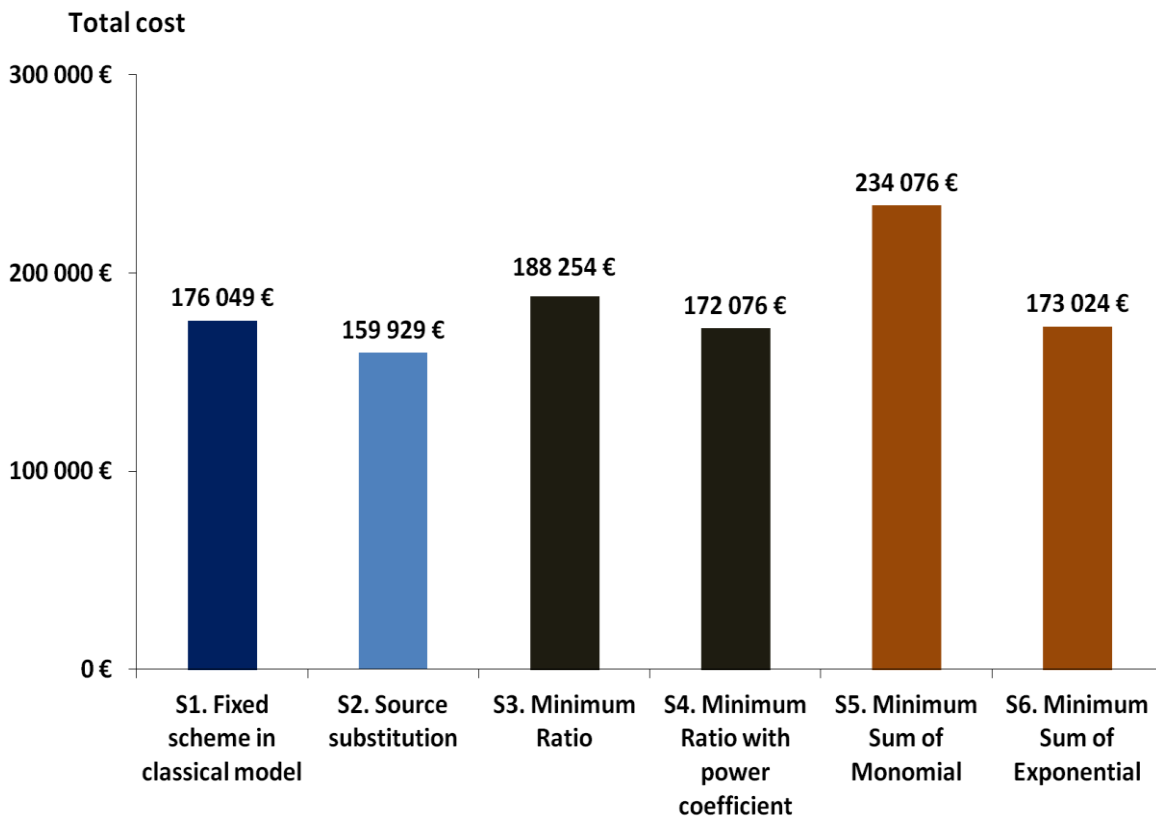


Figure 18. Total cost of simulation scenarios

In this part we have defined new replenishment strategies in a distributed inventory system through a PI. The strategies have been simulated in a number of experiments in a simple network having one product (one plant and one WH) and two DCs and retailers. The results show that performance in terms of total cost of the studied strategies is very different.

3.4 Generalization to extended networks

The results obtained in the previous part were based on the simulation of a simplified supply network. This part aims to observe the performance of the criteria in more complex and more realistic networks along with the sensitivity. To this end, we have studied several scenarios with changes to the input data, for example changing site location to change distance, variation of demand, and the possibility to spilt orders etc. Here, not all scenarios are presented as we prefer to focus on two very interesting cases: one the sensitivity of coefficients' optimum value in extended networks, and another the performance of the criteria (Source Substitution as an example) in different networks when the number of retailers increases.

3.4.1 Analysis of value of coefficients in extended networks

In addition to the simple network studied above (hereinafter Network A), we define two more complex networks, B and C, as follows to assess the criteria:

Network A: 1 manufacturing facility, 1 warehouse, 2 distribution centers and 2 retailers
(3 open hubs in PI)

Network B: 2 manufacturing facilities, 2 warehouses, 2 distribution centers and 2 retailers
(4 open hubs in PI)

Network C: 3 manufacturing facilities, 2 warehouses, 3 distribution centers and 3 retailers
(5 open hubs in PI)

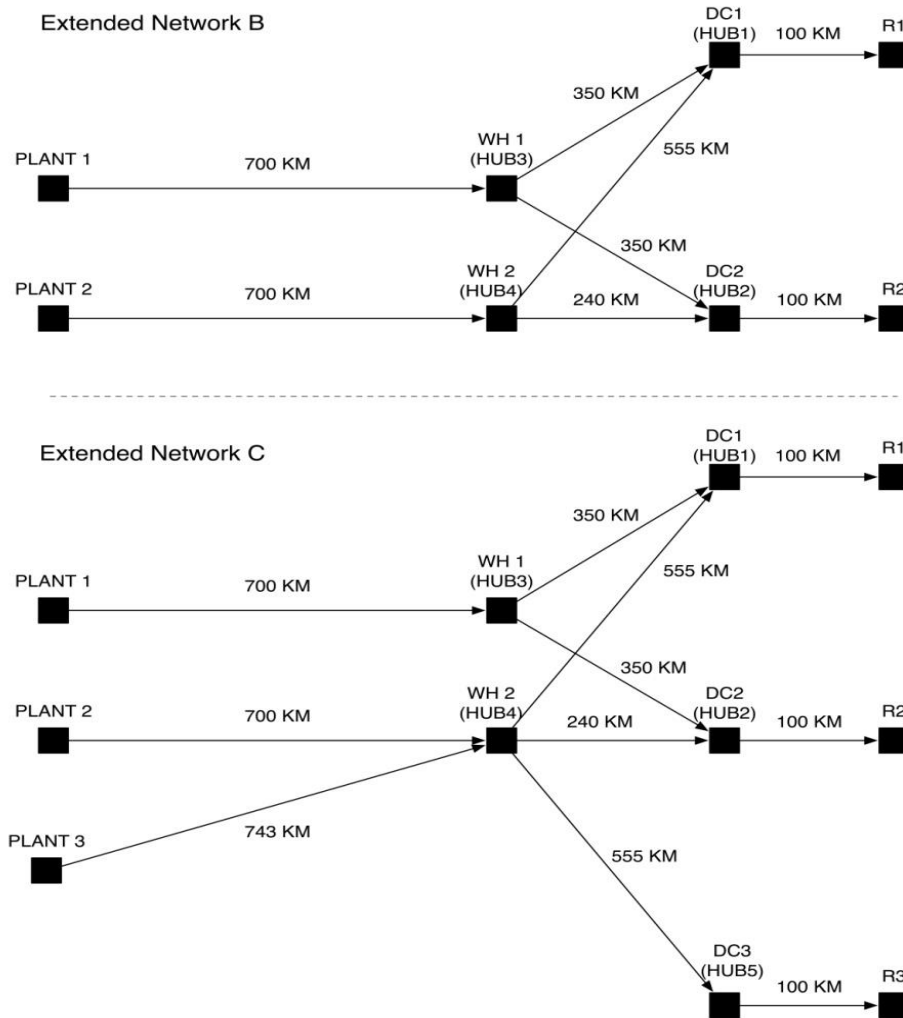


Figure 19. Extended networks B and C

As illustrated in Figure 19, the patterns of Network B and C are defined similarly to A. Not all the details, such as site location and distance between sites etc., are given here. Though the B and C analysis is still far from some practical complex cases, it aims to provide a better insight into how the criteria perform in gradually complete networks without losing sight of generalization. The extension of the study was stopped at Network C to avoid complexity issue.

Table 6 illustrates the optimum value of the coefficients when the networks expand gradually. As we can see, the value of exponential coefficients is roughly steady from Network A to C, which means the determination of their value is insensitive to the complexity of network.

However the variation of the other linear coefficients is more significant. The outcome is very important for further research.

Parameter	Minimum ratio				Minimum sum					
	$\frac{D_i}{S_i}$		$\frac{D_i^\gamma}{S_i^\varphi}$		$\alpha D_i^\gamma + \beta S_i^\varphi$				$\alpha^{D_i} + \beta^{S_i}$	
	γ	φ	γ	φ	γ	φ	α	β	α	β
Network A	1	1	15.25	8	20	-35.5	45	9.5	1.5	2
Network B	1	1	13.5	10.75	23	-44	32.5	18	2	2.5
Network C	1	1	14	13.5	21.5	-41.5	27	23	-3.5	6

Table 6. Sensibility of coefficients' optimal value in extended networks

With regard to the performance of criteria, the result of Networks B and C is very similar to that of network A presented in Figure 16: again the Source Substitution criterion drives Network B and C to their best performance.

3.4.2 Variation of the number of retailers

Another scenario involves changing the number of retailers in the networks while using the same supply network (plants and hubs). The idea is to study the performance of the PI faced with market areas with different retailer densities (we assume that all retailers in the same market area are shipped by the PI). Actually it is an equivalent assumption of increasing the final demands and the number of trips to the points of sales. Since the Source Substitution criterion is the simplest but leads to the best result, only this criterion is simulated in the model as an example to compute the savings against the classical supply network. We changed the number of retailers from one to six and each time we computed the total cost of transportation and inventory holding. Figure 20 demonstrates the savings in terms of total cost as a function of the quantity of retailers.

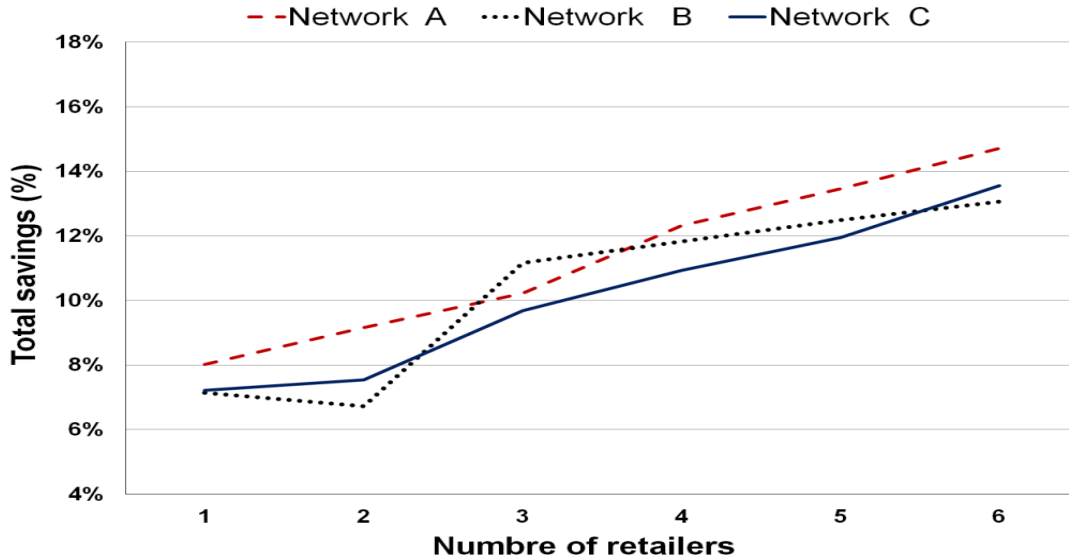


Figure 20. Total savings by the PI in terms of total number of retailers (under Source Substitution criterion)

The trend in savings is highlighted in Figure 20: the overall savings tend to increase as the number of retailers increases. Furthermore, when comparing the curves of Network A and C, we can see that the relative increment is roughly independent of the number of suppliers (but slightly disturbed in Network B). These are important results as in reality we have dozens of retailers for a single firm in the same market area (e.g. in the Ile-de-France), and in general they have a very different populations of suppliers.

3.5 Conclusion

In this chapter we proposed a first approach based on simulation to select a supply source in a PI with distributed inventories. (Q, R) inventory policy without backlog was used as our inventory management system. The objective was to test different criteria to select the best source anytime supply is requested. Within our framework and before more in-depth research, source substitution was found to constitute the most efficient rule of selection in the numerical study. Minimum ratio with power coefficients and Minimum sum of exponential coefficients were also found to be better than the classical model. More interestingly, the model suggests that the benefit

of the PI increases with the size of the distribution network where it can be benefit more from economies of scale. An in-depth study related to this observation is necessary and interesting.

This chapter does not aim to provide the best replenishment policy for a PI, but to give an initial insight into the potential performance of different criteria in such an open supply network. The results obtained are encouraging but are limited to the geometry of the network, to the simulation model and to the rules and constraints applied. The results need further investigation to demonstrate the robustness of the source substitution criterion and the performance of the PI vs. classical supply chain organizations.

As the first contribution, this chapter exploits a research field of inventory management in Physical Internet. Many research questions related to the field could be further identified and studied. For example, the first question of interest is to study how optimal decisions could be made for inventory problems in such an open network considering that this work is based on a simulation model. Besides, further investigation should be carried out to quantitatively study the new practices of the PI as to outline advantages to inventory management. Last but not least, a sensitivity study is necessary in order to find out the most possible costs benefits.

Chapter 4. Innovative vendor managed inventory strategy taking advantage of interconnected logistics services in the Physical Internet

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The previous chapter took an initial insight into the potential performance of a rule-based inventory model in Physical Internet. Continuing the research stream, this chapter investigates how optimal decisions are made for inventory problems in an open network, what are the most possible cost benefits and what is the sensitivity of parameters to cost benefits such as products' values. This part has been published by Yang, Pan, and Ballot (2015) and submitted in YANG, PAN, and BALLOT (2016b).

4.1 Introduction

Yet, the existing extensions are based mainly on traditional supply chain (SC) network designs in which each firm defines its own logistics network. Once the network has been defined, the storage points (warehouses) as well as the replenishing schemes are fixed and dedicated, resulting in the current predetermined hierarchical multi-echelon inventory systems. Even though flexibility within a company's logistics network such as multi-sourcing may exist in the literature, logistics operations are always quite restrictive and specialized within their own predetermined network. Therefore, a more open design with more degrees of freedom for inventory and distribution systems is appealing. Assuming that the hypothesis of a predetermined dedicated hierarchical inventory structure is an inherent limit of current inventory models, we are interested here in studying innovative models that are more open, flexible and horizontally collaborative.

More specifically, this chapter continues researching on inventory control models applying the Physical Internet (PI). Concerning inventory problems, the distribution and storage system in PI is transformed into a common, open, interconnected logistics service of PI-hubs shared by many companies. The PI allows users to place stocks all around the system and open multiple sourcing options for orders, by using on-demand warehousing service within PI, see FLEXE.COM as an example. Hence, the inventory decisions in the PI become very complex. The inventory in the PI can be managed by either vendor or buyer.

This chapter investigates the situation where vendors manage the inventories in the PI. It is therefore a PI enabled vendor managed inventory (VMI) problem. The VMI is related where the vendors access inventory information of retailers and manage inventories in the distribution network (Waller, Johnson, and Davis 1999b; Diabat 2014). However, the proposed innovative VMI enabled by PI differs from the classic VMI in that the vendor can demand storage capacity

dynamically at any hub and rebalance stocks between hubs if needed, while rebalancing inventories among DCs of different retailers is impossible with classic VMI. In other words, the VMI in PI is extended to several retailers thanks to interconnected logistics services. Under PI, vendor inventory management framework decisions lie on: 1) how to respond to each retailer replenishment order with required constraints; 2) how to efficiently move inventories in the PI-network to satisfy these orders with certain objectives. Chapter 3 firstly proposed a rule-based simulation model to investigate the potential of inventory models applying PI compared with classic inventory models. However, this work is based on a simple rule-based simulation and an optimization model needs to be developed in order to quantitatively study the problem better. This chapter aims to fill this gap.

The objective of this chapter is twofold: firstly, to provide an optimization model for inventory decision-making in PI, which is new to the literature, and secondly, to quantitatively study the performance and characteristics of inventory models applying PI, and to analyse logistics network configurations favourable to PI. In other words, this chapter concerns a quantitative study that aims to answer the following questions: How are optimal decisions made for inventory problems in an open network? What are the most possible cost benefits? What is the sensitivity of parameters to cost benefits such as products' values? To achieve this, an inventory problem of a single FMCG product under stochastic demand is studied. A simulation-based optimization model is proposed to determine optimal inventory decisions to minimize the annual logistics cost according to a targeted level of service. Finally, a sensitivity study is conducted to analyse the impact of the network configuration and product features on the performance of the proposed optimization model.

The remainder of this chapter is organized as follows. In Section 2, the simulation-based optimization model is proposed for the PI inventory problem of the vendors, followed by a solution approach in Section 3. Then, in Section 4, the optimization model is implemented in FMCG studies. A number of scenarios are proposed and studied in order to validate the model and study its pertinence in different network configurations. Finally, Section 5 concludes the study and provides some prospects for future research.

4.2 Simulation-based optimization model

This work deals with a single-product inventory problem in a typical FMCG network with a plant (a vendor) serving a group of N_r retailers via a network of M intermediate storage points (hubs or DCs or WH). Two types of networks are taken into account: the current most dominant supply network in FMCG and the PI, as discussed in Chapter 2. The inventory decisions in the distribution network are assumed made by the vendor. The retailers face real demand data from the FMCG industrial sector and the optimal inventory decisions of each retailer are computed locally based the model of Giard (2005). The results are considered as the inputs of the optimization model for the vendor. The objective is to find optimal inventory control decisions for intermediate storage points and source selection decisions to minimize the annual total logistics costs while satisfying demands from retailers.

As replenishment decisions in PI are highly dynamic, i.e., sourcing point, order size, and reorder point are dynamic, a non-linear simulation-based optimization model is proposed. This is a well-established approach in literature where the objective function and constraints are evaluated through simulation (Jalali and Nieuwenhuys 2015). A metaheuristic using simulated annealing is applied to have optimized inventory decisions. To validate the proposed model and its pertinence, different cost components and demand settings in a typical network are analysed. A simulation study with different logistics network settings is then conducted using the optimization results to quantitatively investigate the performance and impacts of PI compared to the classic inventory model. An illustration of the methodology is depicted in Figure 21.

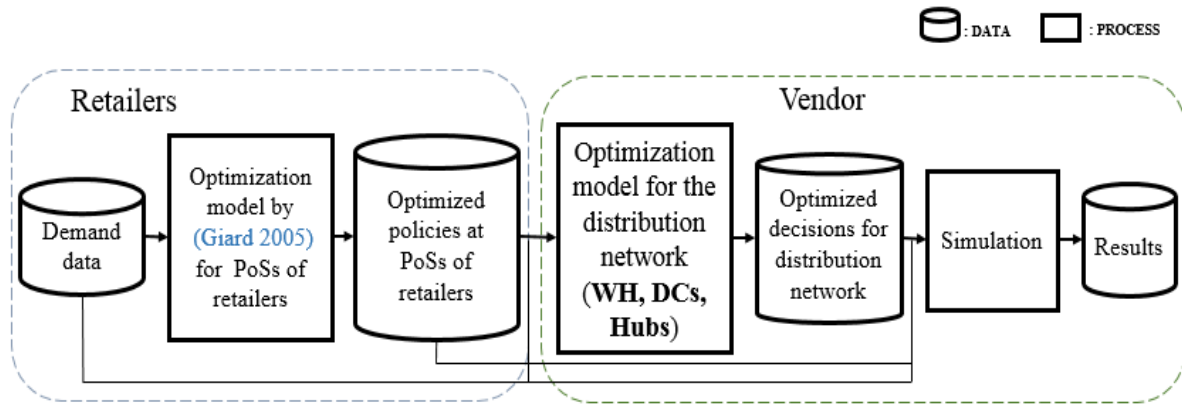


Figure 21. Methodology depiction

4.2.1 Assumptions

The following common assumptions are adopted for all the scenarios. a) The storage facility applies a (R, Q) continuous review policy where a replenishment order Q is placed when the inventory level drops below a reorder point R . This policy is reported as the most commonly used inventory review policy (Waller, Williams, and Tokar 2008). b) The plant is assumed to always have adequate stocks to meet demands and there is no capacity constraint for hubs. c) Penalty costs are incurred if replenishment orders from retailers are not met immediately and end customer demands unsatisfied at retailers. d) The lead times among all the interconnected facilities are given and assumed to be constant. e) The orders are served on a first-come-first-served basis. f) No partial delivery is allowed. g) End customer demands at retailers are uncertain and subject to normal distribution. h) The vendor makes all source selections to supply the retailers. i) The optimal replenishment policies for retailers are determined by the algorithm proposed by Giard (2005). j) Locations of all sites remain the same in all scenarios.

Five logistics costs are considered: inventory holding cost, transportation cost, fixed ordering cost, penalty costs, and handling cost. Holding costs are charged for each unit in stock per unit time at hubs, DCs or WH. The transportation cost for each delivery of goods is considered and includes three parts: upstream transportation costs from plants to hubs or WH, upstream transportation costs between hubs or to DCs, and downstream transportation costs to retailers. Each

replenishment order placed incurs a fixed ordering cost. Penalty costs are charged for orders placed by retailers that are not immediately satisfied and are assumed to be proportional to the product value. Finally, handling costs are considered for each movement of stocks when they enter and leave hubs, DCs or WH.

4.2.2 Notations and Model Formulation

From the analysis, we can see that the inventory problems in the PI differ from traditional inventory optimization problems as the source decision for each order is dynamically determined. Because of this openness, a simulation-based optimization modelling method is applied, which is a well-established approach in literature where the objective function and constraints are evaluated through simulation (Jalali and Nieuwenhuys 2015). To introduce the optimization model, we use the following notations to present the objective function and main constraints which are evaluated through a simulation procedure. The minimum unit we consider in the model always refer to the Stock Keeping Unit (SKU).

Notations:

M : set of intermediate storage points including DCs or WHs or hubs indexed by i .

Plant: index by 0.

Source candidates: intermediate storage points and the plant, indexed by $k \in M \cup \{0\}$.

Nr : set of retailers, indexed by j .

T : configuration time of the inventory system, indexed by n .

$Dis1_{ij}$: distance between storage point $i \in M$ and retailer $j \in Nr$.

$Dis2_{ki}$: distance between facilities $k \in M \cup \{0\}$ and $i \in M$.

$LT1_{ij}$: lead time between storage point $i \in M$ and retailer $j \in Nr$.

$LT2_{ki}$: lead time between facilities $k \in M \cup \{0\}$ and $i \in M$.

Dmd_{jn} : daily end customer demand at retailer j which is normally distributed with average parameter u_j and standard deviation σ_j .

u_j : average demand per unit time at retailer j .

σ_j : standard demand deviation per unit time at retailer j .

$f_j(x)$: demand density function at retailer j .

LS_j : expected lost sales at retailer j for end customer demands unsatisfied.

h_j : holding cost per unit/time holding at retailer j .

H_i : daily holding cost per SKU at intermediate storage point i for daily stocking costs.

hd : handling cost per SKU for entering and leaving the stocking facilities.

p_j : penalty cost per SKU per unit time of unmet orders from retailer $j \in Nr$, proportional to product value.

$f_d(q_j, Dis1_{ij})$: transportation cost from point $i \in M$ to retailer $j \in Nr$, which is a function of quantity and distance transported.

$f_u(Q_{ik}, Dis2_{ki})$: transportation cost from points $k \in M \cup \{0\}, (k \neq i)$ and $i \in M$, which is a function of quantity and distance transported.

A : fixed ordering cost per order.

IL_{in} or IL_{jn} : inventory level at intermediate storage point $i \in M$ or retailer $j \in Nr$ at n th day.

IP_{in} or IP_{jn} : inventory position at intermediate storage point $i \in M$ or retailer $j \in Nr$ at n th day, inventory level plus inventory on arrival.

Decision variables:

(q_j, s_j) : replenishment policy of retailer j - q_j for batch size and s_j for reorder point.

R_i : the reorder point of storage point $i \in M$

Q_{ik} : the batch size (order quantity) of storage point $i \in M$'s from other points $k \in M \cup \{0\}, (k \neq i)$.

x_{kin} : binary variable of whether choose point $k \in M \cup \{0\}, (k \neq i)$ to satisfy the replenishment order of storage point $i \in M$ at time n th day.

x_{ijn} : binary variable of whether choose facility $i \in M$ to satisfy the replenishment order of retailer j at time n th day.

For PoSs of retailers:

For each retailer, the decision parameters (q_j, s_j) are decided as follows by the model of Giard (2005) in Page 839.

$$\begin{aligned} \text{Total cost } G &= h_j \left(\frac{q_j}{2} + s_j - u_j LT1 + \frac{LS_j}{2} \right) + \frac{pu_j}{q_j} LS_j + \frac{u_j}{q_j} A + cu_j \\ &= \frac{u_j}{q_j} A + cu_j + h_j \left(\frac{q_j}{2} + s_j - u_j LT \right) + \left(\frac{h_j}{2} + \frac{pu_j}{q_j} \right) LS_j \\ LS_j &= \int_{s_j}^{\infty} (x - s_j) f(x) dx \end{aligned}$$

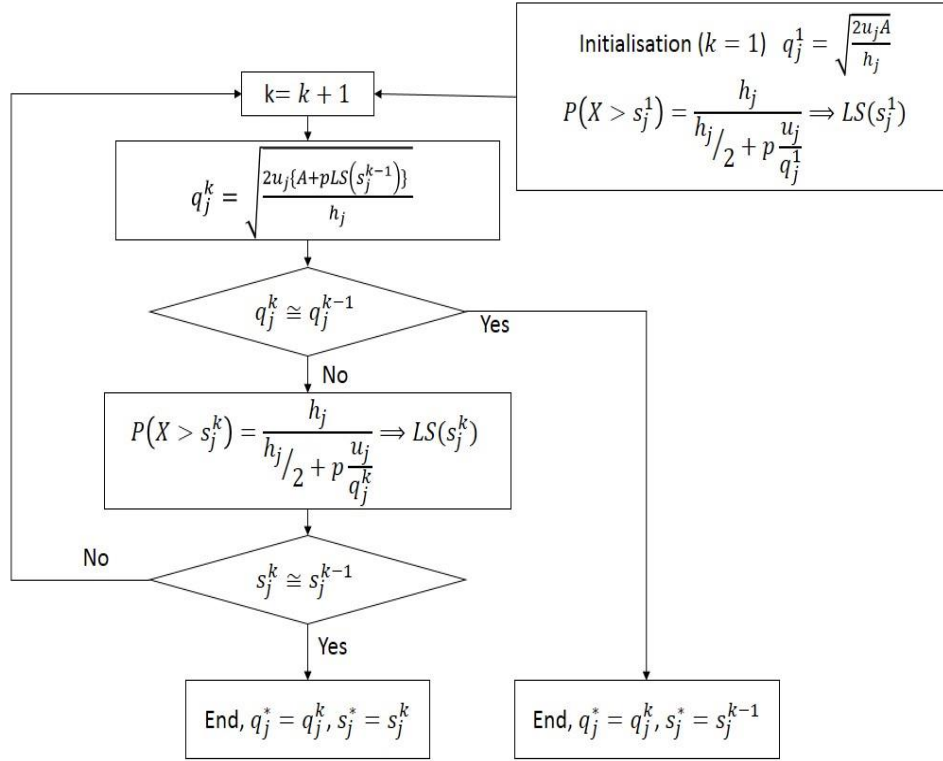
Hence:

$$q_j^* = \sqrt{\frac{2u_j [A + pLS_j(s_j^*)]}{h_j}}$$

$$LS_j' = - \int_{s_j}^{\infty} f(x) dx = -P(X > s_j)$$

$$P(X > s_j^*) = \frac{h_j}{h_j/2 + p \frac{u_j}{q_j^*}}$$

The optimal (q_j^*, s_j^*) is obtained by the algorithm shown in Figure 22 :

Figure 22. Algorithm of determination of optimal (q_j^*, s_j^*) under lost sales

Decisions in intermediate stocking points (WHs and DCs or Hubs):

The optimal decisions of (q_j^*, s_j^*) at retailers are used as input for the optimization model of inventory decisions of the distribution network of hubs where the objective function is as follows:

Minimize C_{tot}

$$\begin{aligned}
 &= \left[\sum_{i=1}^M \sum_{n=1}^T IL_{in} H_i \right]_{(1)} + \left[\sum_{j=1}^{Nr} \sum_{n=1}^T \sum_{i=1}^M x_{ijn} (f_d(q_j, Dis1_{ij}) + q_j * hd) \right]_{(2)} \\
 &+ \left[\sum_{i=1}^M \sum_{n=1}^T \sum_{k=0, k \neq i}^M x_{kin} (f_u(Q_{ik}, Dis2_{ki}) + A + 2Q_{ik} * hd) \right]_{(3)} \\
 &+ \left[\sum_{n=1}^T \sum_{j=1}^{Nr} \left(1 - \sum_{i=1}^M x_{ijn} \right) * u_j * p_j \right]_{(4)}
 \end{aligned}$$

Subject to:

$$0 \leq \sum_{i=1}^M x_{ijn} \leq 1 \quad \forall j \in Nr, \forall n = 1 \dots T \quad (5)$$

$$x_{ijn} \in \{0,1\} \quad \forall i \in M, \forall j \in Nr, \forall n = 1 \dots T \quad (6)$$

$$0 \leq \sum_{k=0, k \neq i}^M x_{kin} \leq 1 \quad \forall i \in M, \forall n = 1 \dots T \quad (7)$$

$$x_{kin} \in \{0,1\} \quad \forall i \in M, \forall k \in M \cup \{0\}, i \neq k, \forall n = 1 \dots T \quad (8)$$

$$R_i, Q_{ik} : \text{Integers}, \forall i \in M, \forall k \in M \cup \{0\}, k \neq i \quad (9)$$

Relation (1) represents the total annual holding cost at intermediate storage points (hubs, WHs, DCs). Relation (2) indicates the total annual downstream transportation cost from intermediate storage points to retailers, and the handling costs for the quantities handled before leaving the storage points. Relation (3) describes the total annual upstream transportation costs from the plant to intermediate storage points and between intermediate storage points, the fixed ordering cost for each order placed by intermediate storage points, and the handling cost for goods entering and leaving the sites. Relation (4) introduces the penalty cost for replenishment orders from retailers that are not immediately satisfied. It is linear to the average level of demand and product value at the retailers. Equations (5) - (6) describe the constraint that the replenishment orders can only be met by one facility at a time. Hence, the model does not allow order splitting. Equation (9) indicates that the quantity demanded cannot be divided up or incomplete. Parameters such as IL_{in} or IL_{jn} and total annual cost are calculated and updated by a simulation procedure as below where T is assumed to be 365 days for one year. The decision variables are optimized through a metaheuristic method.

Simulation-based annual total cost calculation procedure:

Input: (Q_{ik}, R_i) optimized by metaheuristic and source selection strategy to decide x_{kin}/x_{ijn} each day.

- 1) *Initialize $n = 1$, initial stock at every hubs to be 0 SKU and $(s_j + q_j)$ for each retailer j . (q_j is the batch size, s_j is the reorder point of retailer j).*
- 2) *For each day, at the beginning of the day n , update inventory level at storage points with incoming in-transit stocks: $IL_{in} = IL_{in} + \sum_{k=0, k \neq i}^M x_{ki(n-LT2_{ki})} Q_{ik}$ at storage points $i \in M$ (arriving stocks that are orders at $(n - LT2_{ki})$ th day and arrive after lead time $LT2_{ki}$); $IL_{jn} = IL_{jn} + q_j * \sum_{i=1}^M x_{ij(n-LT1_{ij})}$ at retailer j .*
- 3) *For each retailer j : if $IP_{jn} \leq s_j$ (inventory position is lower than reorder point), place an order and use the source selection strategy to determine the source i^* (x_{i^*jn}) while respecting the constraints (5)-(6). If there is no available source, update the penalty cost of Relation (4), otherwise update Relation (2) and the inventory information at retailer j $IP_{jn} = IP_{jn} + \sum_{i=1}^M x_{ijn} q_j$ and at source i^* , $IP_{i^*n}/IL_{i^*n} = IP_{i^*n}/IL_{i^*n} - x_{i^*jn} q_j$.*
- 4) *For each storage point i : if $IP_{in} \leq R_i$, place an order and use the source selection strategy to determine source k^* ($x_{k^*in} = 1$) while respecting the constraints (7)-(8). Update the Relation (3) and the inventory information of at point i - $IP_{in} = IP_{in} + \sum_{k=0, k \neq i}^M x_{kin} Q_{ik}$; If source k^* is not the plant ($k^* \neq 0$), update inventory information at k^* - $IP_{k^*n}/IL_{k^*n} = IP_{k^*n}/IL_{k^*n} - x_{k^*in} Q_{ik}$.*
- 5) *Randomly generate end customer demands Dmd_{jn} according to normal distribution function respecting input parameters (u_j, σ_j) at retailer $j \in Nr$. At the end of the day, update inventory information at retailer j $IL_{jn} = MAX[IL_{jn} - Dmd_{jn}, 0]$ and $IP_{jn} = MAX[IP_{jn} - Dmd_{jn}, 0]$.*
- 6) *At the end of the day, calculate Relation (1) and update objective function C_{tot} by the sum of Relation (1) to (4).*
- 7) *If $n \leq T$, $n++$ and go to STEP 2).*
- 8) *Return annual total cost C_{tot} .*

4.3 Solution Approach

From the formulations, we can see that the problem is a non-linear optimization problem. The decision variables can be divided into two parts: optimal replenishment parameters for intermediate storage points R_i, Q_{ik} and source selection decision variables x_{kin}/x_{ijn} . As the sourcing variables are dynamically determined for each order, we propose metaheuristic method integrated with source selection strategy to optimize decision variables, as shown in Figure 23. The inventory decisions variables are decided by the optimization process where the objective function is calculated by the simulation in Section 4.2.2. The source selection strategy determines x_{kin}/x_{ijn} and the metaheuristic finds the optimal (Q_{ik}, R_i) . In traditional network, the sources are pre-assigned, therefore the source selection variables x_{kin}/x_{ijn} are always constant in this scenario.

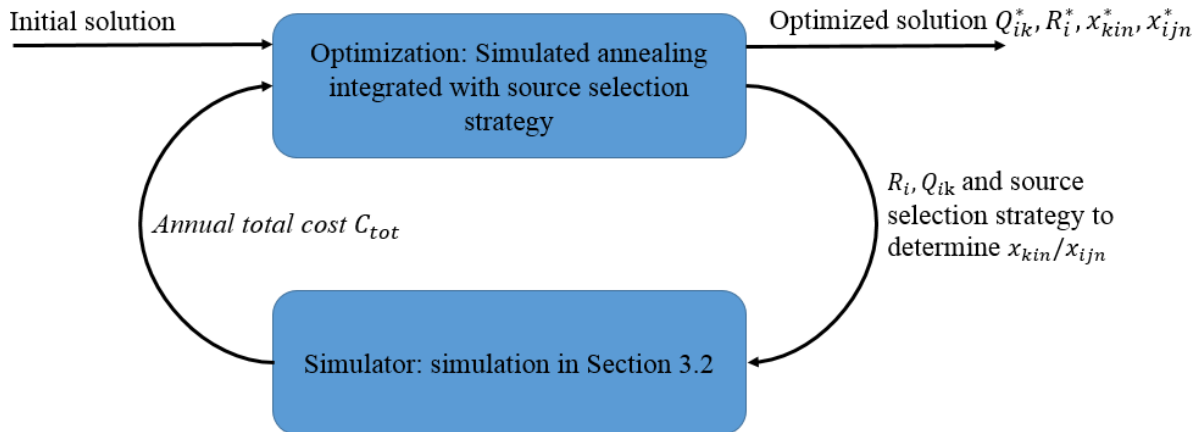


Figure 23 Solution approach illustration

In the PI, we propose four dynamic source selection strategies integrated in the metaheuristic to determine the source selection decision variables x_{kin}/x_{ijn} : 1) S1 – Source Substitution: among the supplying points with inventory level bigger than the ordering quantity, choose the nearest available candidate to the ordering point; 2) S2 - Maximum stock on hand: among the supplying points with inventory level bigger than the ordering quantity, choose the candidate with the highest inventory level; 3) S3 - Maximum ratio of (inventory level/lead time): among the supplying points with inventory level bigger than the ordering quantity, choose the candidate with the maximum ratio of (inventory level/lead time between the candidate and the

ordering point); 4) S4 - Maximum ratio of (inventory level/distance): among the supplying points with inventory level bigger than the ordering quantity, choose the candidate with the maximum ratio of (inventory level/distance between the candidate and the ordering point).

For all scenarios, a simulated annealing algorithm is constructed to optimize the replenishment parameters of intermediate storage points with the simulation procedure presented previously. There exists other algorithms for the optimization of VMI models such as generic algorithm (Pasandideh, Niaki, and Nia 2011), tabu search (Shahvari et al. 2012). Here the simulated annealing algorithm is used because it can achieve relatively good results in a reasonable time according to our numerical experiments.

4.4 Numerical Study

We compare the performance of the proposed PI inventory model with that of the classic inventory model and investigated the differences in performance for different configurations of a typical supply network. The performance ratio defined in Ng, Li, and Chakhlevitch (2001) is used to compare the scenarios. The classic inventory model is considered as the baseline and the performance ratio with other instances is the relative variation. As we have four dynamic sourcing strategies, we use PI-S1 to refer to PI inventory model integrated with Source Substitution strategy. The same logic goes for the index PI-S2, PI-S3, and PI-S4.

4.4.1 Experimental Design

4.4.1.1 The network

A single product network with a supplier supplying two regional retailer companies is studied and the location is shown in Figure 24. The three companies have areas of logistics activities in common and geographically preferential areas. The points of sale R1 and R2 are in geographical areas preferential to their respective retail company, while the points of sale R3 and R4 are in the area common to all three companies. It indicates the huge potential of the three companies sharing logistics activities such as transportation and storage capacity.

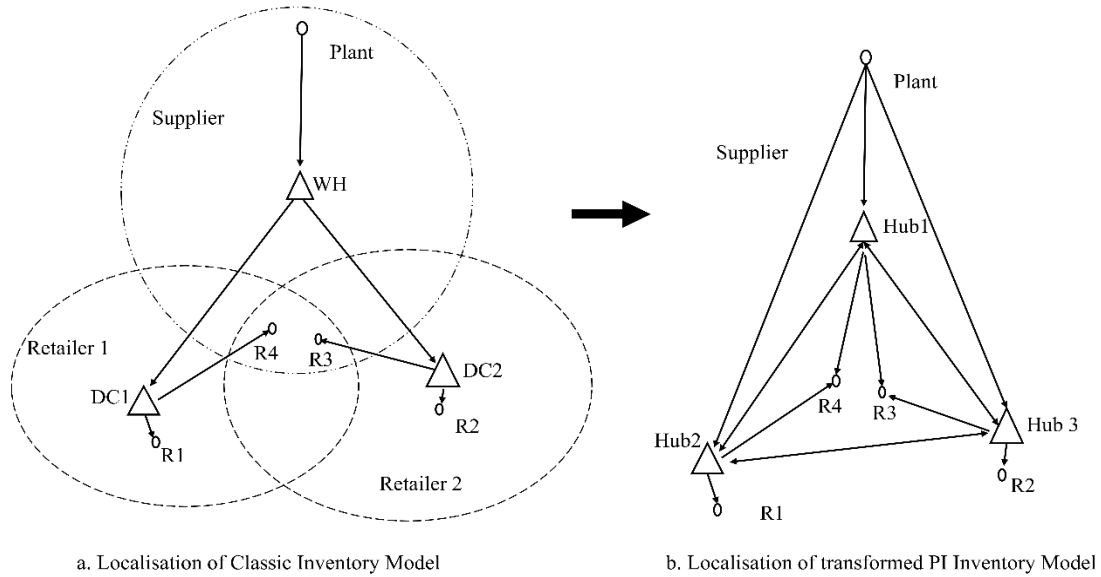


Figure 24. Location of the facilities in networks

In an extreme network location configuration, the companies share no area of logistics activity and all the facilities are geographically close to their own company. This network configuration is unfavourable for PI, as there is no possibility of different companies sharing resources. Meanwhile, the most favourable network for the PI approach is where all the companies share the same area of logistics activity, thus different actors within the network can access a comprehensive pool of resources. Hence, in this chapter, an intermediate case is applied, as depicted in Figure 24, where different companies have a common area of logistics activities as well as their own geographically preferential areas. The lead time is assumed to be 5 days between the plant and hubs, 1 day between hubs, and 2 days between hubs and retailers. The route distance matrix (km) is described in Table 7.

Source Destination	Plant	HUB1	HUB2	HUB3
HUB1	200	0	160	155
HUB2	350	160	0	165
HUB3	325	155	165	0
R1		170	15	160
R2		140	165	15
R3		100	95	90
R4		90	100	105

Table 7. Route Distance Matrix (km)

4.4.1.2 Costs modelling

Five logistics costs are considered: fixed ordering costs charged per replenishment order from hubs, WH or DCs; handling costs per SKU entering and leaving the storage facilities; penalty costs for replenishment orders from retailers not satisfied immediately, which is assumed to be a percentage of the product value and proportional to the average daily demand level at the ordering retailers; inventory holding costs; and transportation costs.

For the inventory holding cost, depicted in Figure 25, we consider two main parts: the storage cost per unit per year for storage space and the capital cost per unit per year, mainly for the inventory investment cost. The storage cost per unit per day for storage space is assumed to be 0.11 per m^3 /day in WH, DC or hubs, and 0.165 per m^3 /day at points of sale as the storage space rented at points of sale is usually more expensive than at intermediate storage points. The capital cost is proportional to the product value and can be 15% of the product value for the majority of companies. Here we consider the capital cost is 8% of the product value.

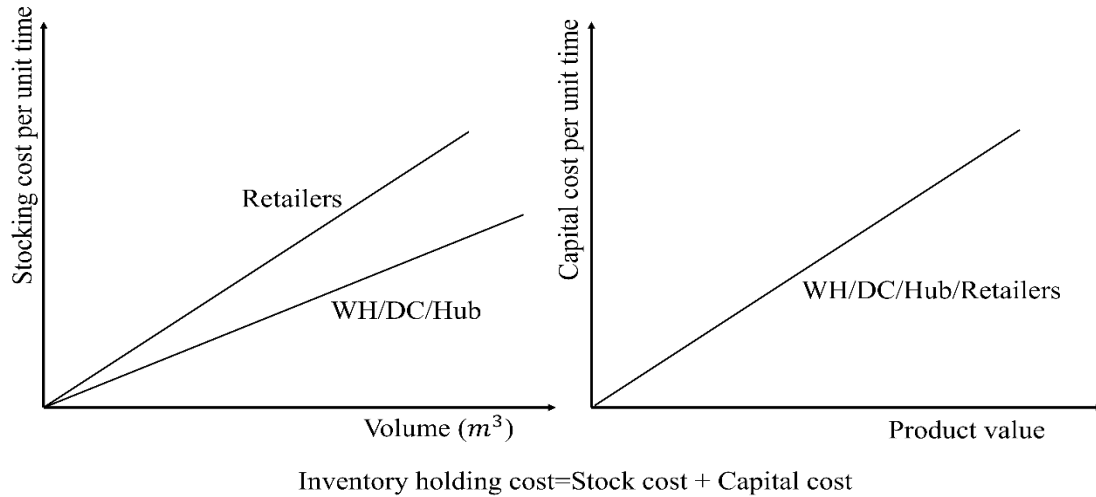


Figure 25. Inventory holding cost function

Regarding the Transportation cost, two types of transportation function are applied according to two main transportation solutions (Full Truck Load (FTL) and Less than Truck Load (LTL)): the step function, which represents the FTL solution, and the linear function, which represents the LTL solution, which are shown in Figure 26. The two functions are adopted to examine the impact of truck fill rates on inventory management. However, the distribution flows in PI are always mutualised by routing protocols and the average fill rate of the truck is 90%, as pointed out in Sarraj et al. (2014). Thus, we used the linear function cost setting (LTL) for transportation functions in the PI inventory model. The current transportation cost set with step functions (FTL) is applied with the classic inventory model, shortened to ClassicSTEP hereinafter. To eliminate the transportation effect, the classic inventory model with the LTL solution is also analysed, called ClassicLINEA hereinafter. The transportation cost from the plant to hubs and between hubs is assumed to be 1.4 (monetary units) per full truckload per km and 2.0 per full truckload per km from hubs to retailers. This assumption is based on the fact that the long-haul transportation cost is lower than the last mile transportation cost. Thus, according to different sets of functions, there are three network scenarios: PI inventory model with linear transportation function, classic inventory model with current step transportation cost (ClassicSTEP), and classic inventory model with PI linear transportation cost (ClassicLINEA).

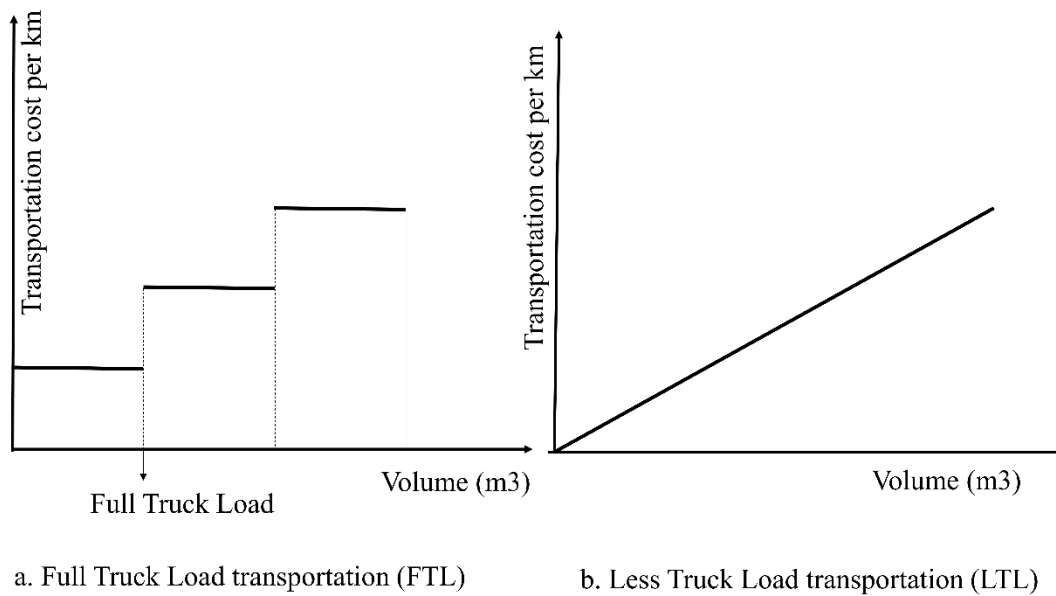


Figure 26. Transportation cost model

4.4.1.3 Input data and scenarios for experimentation

To assess the sensitivity of the model proposed, the impact of the following five parameters is analysed: fixed ordering cost $A=8/20/80$ (monetary units) per order (or 0 if the order is not satisfied), average demand level at retailers (value range: high/low, refer to Table 8), standard deviation of demand at retailers (value range: high/ low, refer to Table 8), product value 0.5/50 (monetary units) leading to different penalty costs and holding costs, and handling cost 0/2 (monetary units) for a pallet of goods entering and leaving each storage point. A pallet of goods is assumed to be $1.73 m^3$ and a unit of goods is assumed to be $0.003 m^3$ (equivalent to a 500 ml or 750 ml bottle of beverage). A SKU is a container of 6 units of goods. A full truckload is assumed to be 33 full pallets of goods. The penalty cost for retailer orders not satisfied immediately is considered to be 20% of the product value at intermediate storage points and 30% at retailers. Therefore, for each network scenario, there are $3(\text{ordering cost}) * 4(\text{categories of demands}) * 2(\text{product value}) * 2(\text{handling cost}) = 48$ instances. In conclusion, we have $48*6$ (ClassicLINEA, ClassicSTEP, PI-S1, PI-S2, PI-S3, PI-S4) = 288 instances.

Nodes	R1	R2	R3	R4
u1 (High)	240	288	144	192
u2 (Low)	30	45	20	46
σ 1 (High)	144	144	48	96
σ 2 (Low)	3	4	2	3
σ 3 (High)	15	20	10	8

Table 8. Daily average demand level and standard deviation at PoS of retailers (units of goods)

With all these setups and the methods presented in Giard (2005), the optimal replenishment parameters (SKUs) for retailers are obtained to minimize the total annual costs, including inventory holding costs, fixed ordering costs, and penalty costs for lost sales, with the required lead time constraints. The total annual cost is considered as the input data for the network of hubs. The optimal replenishment parameters for hubs are obtained using a simulated annealing method where the convergence ratio, the maximum temperature, and the maximum iteration number are 3%, 60, and 6000, respectively. These parameters are obtained through our experiments, which can achieve relatively good results within a reasonable time. For each instance, with the optimal replenishment parameters for each hub, we simulated the total system 100 times and evaluated the average total cost of the hub system, the average total inventory level of all hubs, the average end customer service levels at retailers, etc. All the experimental tests are developed in *Mathematica*® 10.0 on a PC with an Intel (R) Core (TM) i7-3940XM CPU 3.20 GHz and 32 Go RAM. As the optimisation problem is quite complicated, we normally expend 2 hours to obtain the good solutions by the simulated annealing algorithm programmed in the *Mathematica*.

4.4.2 Results Analysis

As there are 288 instances, we organize the results as follows: firstly we compare the results of PI-S1 to classic inventory models in detail. This is done as to outline the performance of PI and analyze quantitatively the new practices brought by PI to inventory management; then we will give out the optimal inventory control protocols for different configurations of the network.

Table 9 and Table 10 present the average performance ratios of the PI inventory model with S1 strategy (PI-S1) compared with classic inventory models ClassicSTEP and ClassicLINEA described in the previous section. Here for the sake of comparison, we use the average value as in Seidscher and Minner (2013) to study the effects of parameters by fixing one parameter and varying

the others. For example, as seen in Table 9 , for the instances where the average demand level is high, the average total cost of the distribution network are reduced 73% by the PI inventory model and 27% of the reduction comes from the holding cost whilst maintaining similar end customer service levels at retailers. For all instances, we observe that the proposed PI inventory model can reduce the total logistics cost compared to the classic inventory models with comparable or better end customer service levels at retailers as shown in Figure 27.

Parameter	u		σ		hd		c		A		
	High	Low	High	Low	0	2	0.5	50	8	20	80
Value	High	Low	High	Low	0	2	0.5	50	8	20	80
Total Cost	-73%	-82%	-77%	-78%	-78%	-76%	-74%	-81%	-84%	-79%	-70%
Service level	0%	3%	1%	2%	1%	2%	3%	0%	3%	1%	1%
Holding	-27%	-37%	-32%	-31%	-33%	-31%	-34%	-30%	-22%	-32%	-42%
Total Transport	-44%	-45%	-44%	-45%	-46%	-43%	-39%	-51%	-59%	-47%	-28%
Downstream Transport	-29%	-32%	-31%	-31%	-32%	-30%	-27%	-34%	-45%	-32%	-15%
Upstream Transport	-15%	-12%	-13%	-14%	-14%	-13%	-12%	-16%	-14%	-15%	-13%
Penalty	-2%	-1%	-1%	-1%	0%	-2%	-2%	-1%	-3%	-1%	0%
Ordering	1%	1%	1%	1%	1%	1%	0%	1%	1%	1%	0%
Handling	-1%	0%	-1%	-1%	0%	-2%	-1%	0%	-1%	-1%	-1%

Table 9. Average performance ratios of PI-S1 vs. ClassicSTEP

Parameter	u		σ		hd		c		A		
	High	Low	High	Low	0	2	0.5	50	8	20	80
Value	High	Low	High	Low	0	2	0.5	50	8 <td>20</td> <td>80</td>	20	80
Total Cost	-36%	-56%	-48%	-44%	-46%	-46%	-45%	-47%	-42%	-42%	-54%
Service level	0%	0%	0%	0%	0%	0%	0%	0%	0%	1%	0%
Holding	-25%	-51%	-40%	-36%	-41%	-36%	-36%	-40%	-32%	-32%	-51%
Total Transport	-4%	1%	-2%	-1%	-2%	-1%	-2%	-1%	-4%	-2%	1%
Downstream Transport	4%	5%	4%	5%	5%	4%	8%	1%	4%	6%	4%
Upstream Transport	-8%	-4%	-6%	-6%	-6%	-6%	-10%	-2%	-8%	-7%	-3%
Penalty	-1%	0%	0%	0%	0%	0%	0%	0%	-1%	-1%	1%
Ordering	-2%	-4%	-3%	-4%	-3%	-3%	-2%	-4%	-3%	-4%	-3%
Handling	-3%	-2%	-2%	-3%	0%	-5%	-4%	-1%	-3%	-3%	-2%

Table 10. Average performance ratios of PI-S1 vs. ClassicLINEA

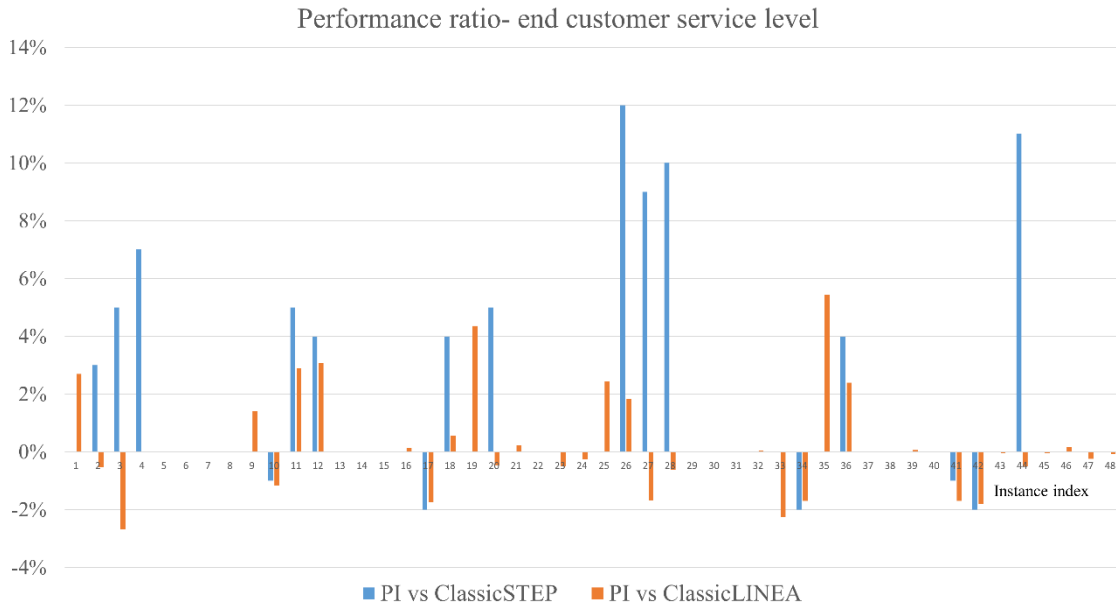


Figure 27. Average end customer service levels at retailers: PI-S1 vs. Classic

Table 9 shows an average saving of 77% in the total cost with the PI-S1 inventory model compared with the classic inventory model ClassicSTEP. The results reveal that the profits are mainly from the reduction of transportation costs when the fixed ordering cost is low and mainly from the reduction of holding cost when the fixed ordering cost is high. Because in classic inventory model the fill rate of trucks can barely to be full truck-load for tested instances, resulting in great difference in transportation costs, especially in downstream transportation cost to retailers. In addition, when the fixed ordering cost increases in the classic inventory model ClassicSTEP, the demand quantity of replenishment orders will be augmented, leading to improved truck fill rates and reduced distribution flows. As a result, the difference in total transportation cost as well as the total logistic cost is reduced.

Table 10 presents the average performance ratios of PI-S1 compared with ClassicLINEA, where the effects of transportation sharing are eliminated. In these instances, in comparison with classic inventory models with predetermined replenishment scheme, the PI can reduce averagely 18% in transportation cost through direct shipping when the objective is to minimize the travel distance. However, as the objective is to minimize the total annual cost, the results show direct shipping is not always the optimal solution. Moreover the transportation cost is not always reduced

by 18%. In these scenarios, we observe that the benefits are due mainly to the reduction in inventory holding cost, and the average saving of the total cost arrives to 46% with similar end customer service levels at retailers. In addition, the reduction percentage in total cost increases when the demand level decreases, and the fixed ordering cost and average demand variance increases. As a result of retailers with low level demands and high fixed ordering cost, the PI inventory model will compromise the downstream transportation costs from hubs to retailers to reduce the total inventory holding cost by grouping the distribution flows into one storage point, see Figure 28.a. However, in the classic inventory model, see Figure 28.b, the flow directions are always pre-determined and cannot adapt to changes in the economic environment.

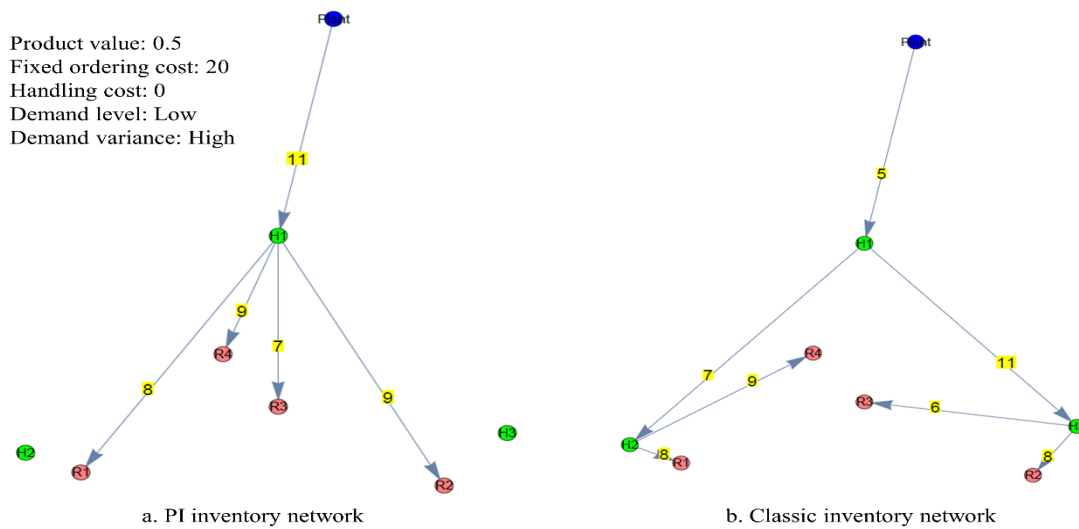


Figure 28. An instance of distribution flows comparison: PI-S1 vs. ClassicLINEA

Concerning the physical effects of PI inventory model, we can see that different configurations of the five parameters restrict logistic activities in PI, resulting in different configurations of distribution flows. When the fixed ordering cost is low and the product value is high, the distribution flows are partially centralized and partially decentralized to minimize the total cost, as seen in Figure 29.a. As the fixed ordering cost increases, the PI inventory model tends to group the distribution flows, as depicted in Figure 29.b.

Product value: 50
 Handling cost: 0
 Demand level: High
 Demand variance: High

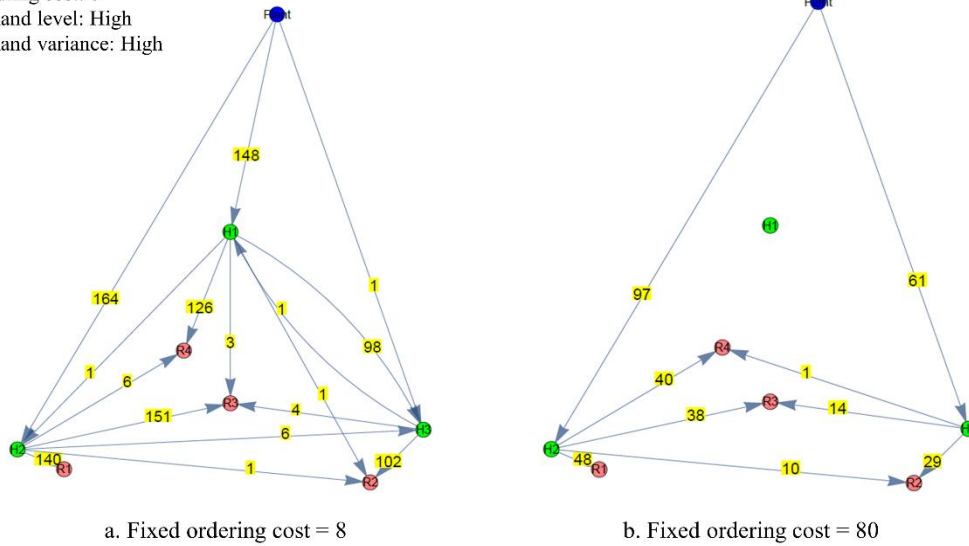


Figure 29. Instance of distribution flows in PI varying in fixed ordering cost: $A=8$ vs. $A=80$

Table 11 quantitatively illustrates the interactions between hubs. The percentage of transshipment is defined as the percentage of hubs' replenishment orders satisfied by other hubs. The percentage of multi-sourcing refers to the percentage of retailers' orders satisfied by other hubs other than the most regular hub. In general, as the transportation cost is set linear to the quantity and distance travelled, the network of distribution tend to be decentralized as to reduce the distances travelled. However, as the average demand rate and the product value increase, the percentages of transshipment and multi-sourcing increase as to reduce the total inventory holding cost and penalty cost for demands not satisfied immediately by pooling hubs' inventories. Moreover, the percentage of transshipment decreases when the handling cost increases as each transshipment arises additional handling operations. We also observe that the transshipment and multi-sourcing percentages decrease when the fixed ordering cost increases as the upstream distribution flows tend to be centralized when the fixed ordering cost increases. In conclusion, we can see that the percentage of interaction between hubs increases with high customer demand rates, low handling cost, high product value, and low fixed ordering cost.

Parameter	Value	Percentage Transshipment	Percentage Multi-sourcing
Demand level	High	2%	9%
	Low	0%	0%
Demand deviation	High	1%	5%
	Low	1%	5%
Handling cost	0	2%	5%
	2	0%	5%
Product value	0.5	0%	3%
	50	2%	7%
Fixed ordering cost	8	2%	8%
	20	1%	4%
	80	0%	3%

Table 11. Percentages of transshipments and multi-sourcing in PI

For each scenario under PI with different dynamic sourcing strategies, we use the same process to analyse the performance of PI with each strategy compared to classic inventory model. Table 12 concludes the results and outlines the optimal inventory control policies for different configurations of the network. From the table, we can see that the PI-inventory model with optimal dynamic sourcing strategy can significantly reduce the total logistic cost compared to current inventory model with predetermined strategies. However, there exist no one dominant inventory control policy for all configurations. For example, for the vendors with expensive products, it's more efficient for them to use S2 or S3 strategies which aim to consume the existing stocks around the network first as to reduce the total inventory level around the network. This table gives a guideline for the vendors applying Physical Internet to determine their optimal inventory control protocols.

End customer demand		Product value	Fixed ordering cost	Handling cost	Dominant model	Percentage Reduction in cost
Means	Variation					
High	High	Low	Low	None	PI-S1	-26%
High	High	Low	Low	Low	PI-S2	-39%
High	High	Low	High	None	PI-S4	-40%
High	High	Low	High	Low	PI-S4	-38%
High	High	High	Low	None	PI-S1	-36%
High	High	High	Low	Low	PI-S3	-35%
High	High	High	High	None	PI-S2	-36%
High	High	High	High	Low	PI-S2	-36%
Low	High	Low	Low	None	PI-S2	-55%
Low	High	Low	Low	Low	PI-S1	-50%
Low	High	Low	High	None	PI-S1	-56%
Low	High	Low	High	Low	PI-S1	-35%
Low	High	High	Low	None	PI-S2	-65%
Low	High	High	Low	Low	PI-S2	-66%
Low	High	High	High	None	PI-S1	-62%
Low	High	High	High	Low	PI-S1	-58%
High	Low	Low	Low	None	PI-S4	-25%
High	Low	Low	Low	Low	PI-S4	-40%
High	Low	Low	High	None	PI-S1	-37%
High	Low	Low	High	Low	PI-S1	-35%
High	Low	High	Low	None	PI-S2	-16%
High	Low	High	Low	Low	PI-S4	-26%
High	Low	High	High	None	PI-S2	-40%
High	Low	High	High	Low	PI-S3	-32%
Low	Low	Low	Low	None	PI-S2	-49%
Low	Low	Low	Low	Low	PI-S1	-52%
Low	Low	Low	High	None	PI-S1	-39%
Low	Low	Low	High	Low	PI-S4	-38%
Low	Low	High	Low	None	PI-S1	-57%
Low	Low	High	Low	Low	PI-S3	-65%
Low	Low	High	High	None	PI-S3	-65%
Low	Low	High	High	Low	PI-S1	-53%

Table 12. Optimal strategies for different configurations of the network

4.5 Conclusion

This chapter proposed an optimization model for the vendors applying the PI. Different from current SCM, the PI enables flexible and dynamic placements for users' stocks around the network and the open multiple sourcing options for orders. This chapter investigated a situation

that vendor optimizes inventory level of the whole network while satisfying buyers' orders. It is thus an innovative vendor managed inventory strategy enabled by PI. As replenishment decisions in PI are highly dynamic, i.e., sourcing point, order size, and reorder point are dynamic, a simulation-based optimization model was developed to solve inventory problems for the vendors using the PI. A simulated annealing method integrated with source selection strategies was applied to optimize inventory decisions. A simulation study followed to validate the optimized results. Numerical studies were taken out to compare the performance of current inventory model and the PI enabled inventory model.

From the results analysis, we conclude that the PI inventory model has a better performance compared with classic inventory models whilst reaching a comparable or better end customer service level with less shortages. The benefits mainly come from the following three parts: 1) the flexibility of network configuration as PI enables more sourcing and storage options compared to classic inventory models and more direct routes towards retailers; 2) the sharing of transportation means which significantly reduces transportation cost; 3) and the inventory pooling and interaction among hubs which will effectively reduce Bullwhip effects.

In addition, as inventory flows in PI are determined dynamically, so when the network settings change, e.g., change in ordering cost or handling cost or end customer demands, the inventory flows can quickly adapt to these changes if needed, whereas in classic inventory models the inventory flow structure always remains the same. This flexibility makes the inventory system more agile and robust to changes in the economic climate. More importantly, the PI inventory network enables the suppliers to rebalance and reallocate their stocks just near their consignees, which is a big difference from today's supplier-customer's relations.

Further research is also required to further sensitivity analysis. A wide range of different network parameters also needs to be examined. Finally, another important factor to study is the robustness of PI in coping with disruptive effects, when a hub becomes suddenly unserviceable, for example. Furthermore, the advantages and interactions between hubs in this chapter are restricted by the limited geographical coverage as well the small number of consignees in the joint logistics areas. High numbers of facilities in a large joint logistics area would lead to a significant change in the distribution scheme with more frequent transshipment between hubs and also more use of multi-sourcing in downstream distribution flows.

In this exploration work, we study the advantage of a new type of vendor-managed inventory with late allocation to the retailers. There is little doubt, this scheme proposes a drastic change compare to nowadays FMCG supply chain management that needs thus to be further investigated.

Part II. RESILIENCE OF PI ENABLED LOGISTICS MODELS

Part I studied inventory problems in the Physical Internet (PI) and demonstrated the efficiency and effectiveness of inventory control model applying the PI. As another arising challenges in today's SCM, the resilience of PI enabled models confronted to disruptions will be analysed in the rest of this thesis. We carry out this part of study by the following three steps.

Firstly, we take out a study to examine the literature in supply chain disruptions and resilience as to find disruptions and resilience problems in the PI and potential benefits brought by the PI, which is presented in Chapter 5.

Then continuing the research stream, the resilience of the proposed PI inventory models in Chapter 4 is studied. In this study, the plants of suppliers and the PI hubs are assumed confronted to unpredictable disruptions. The objective of this study is to find out whether applying the PI can help companies to mitigate disruptions risks and therefore improve their resilience. This study provides a guideline for companies to build resilient supply chains. This part of study is published in Yang, Pan, and Ballot (2016a) and provided in Chapter 6.

Next we go on the research by studying the resilience of Physical Internet enabled transportation system confronted to hubs' disruptions. This work is supported by National Research Agence¹¹ in France. The objectives are to provide a definition of resilience of the Physical Internet, to develop corresponding transportation protocols implanted with disruptions protocols and to analyse their performance to different disruptions. The results of this study is described in Chapter 7 and were presented in 3rd International Conference of Physical Internet, 2016, Georgia Tech, Atlanta, GA, US.

¹¹ <http://www.agence-nationale-recherche.fr/>

Chapter 5. Introduction to supply chain resilience and disruptions

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The objective of this chapter is to find resilience and disruption problems in the Physical Internet. To this end, we firstly give a brief introduction to supply chain resilience and disruptions as to outline the main existing methodologies in this domain. Then a discussion about the differences brought by the PI to resilience and disruption problems will be presented. The potential perspectives of the PI will be outlined.

5.1 Supply chain resilience and disruptions

5.1.1 Concepts and definitions

Since 2000, much research on supply chain disruptions and resilience have been conducted and have shown great potential. Supply chain disruptions are generally defined as unplanned events that hamper the supply chain system (Craighead et al. 2007; Ivanov, Sokolov, and Dolgui 2014). Disruptions may be caused by various factors such as natural disasters, political conflicts, financial crises, terrorism, or transportation infrastructure failures (Gurning and Cahoon 2011). The *Supply Chain Resilience* annual survey 2013¹² on over 519 companies from 71 countries reports that 75% of respondents experienced at least one SC disruption. In addition, 15% experienced disruptions that cost in excess of €1M and 9% experienced a single disruption that cost in excess of €1M.

There are generally two types of disruptions: facilities disruptions where the facilities become unserviceable (Snyder and Daskin 2005; Tomlin 2006; Cui, Ouyang, and Shen 2010), and transportation disruptions where the flow of materials is interrupted (Wilson 2007; Baghalian, Rezapour, and Farahani 2013; Schmitt 2011). The most common way that disruptions are modelled is to assume that the facility follows a two-state Markov process, either functioning or being disrupted (Tomlin 2006; Baghalian, Rezapour, and Farahani 2013; Snyder and Shen 2006b). Others use more general distributions such as *Erlang* distributions (Groenevelt, Pintelon, and Seidmann 1992). In addition to general distributions, recently (Klibi, Martel, and Guitouni 2010) analyse different types of vulnerable events and propose a Monte Carlo procedure to generate plausible

¹² <http://www.zurich.co.uk/NR/rdonlyres/4583C3DF-7854-4B37-B676-74ABCBA9267C/0/131029SupplyChainSurveyReportfinalallowres.pdf>

future scenarios. Recent review about SC disruptions can be found in (Ivanov, Sokolov, and Dolgui 2014).

The concept of resilience arose from a fusion of disciplinary concepts and ideas in material science to describe the capacity of a material to bounce back to its original shape after any deformation (Sheffi 2005b). Though the term resilience is used in a wide range of fields, the concept of resilience across them is closely related with the capability and ability of an element to return to a stable state after a disruption (Bhamra, Dani, and Burnard 2011). Recent comprehensive literature review about SC resilience can be found in four studies: Bhamra, Dani, and Burnard (2011) focus on the perspectives, concepts, and methodologies of resilience literature under SMEs (small and medium-sized enterprises) context; Ponis and Koronis (2012) investigate the concept of resilience in different areas and propose organisational and supply chain resilience; Roberta Pereira, Christopher, and Lago Da Silva (2014) employ a systematic review approach to find the role of procurement in achieving SC resilience; and Kamalahmadi and Parast (2016) review resilience both from enterprise and supply chain scope and develop a framework for the principles of SC resilience based on the framework of Christopher and Peck (2004).

Concluding the existing definitions in SC resilience, Kamalahmadi and Parast (2016) define the SC resilience as the adaptive capability of a supply chain to reduce the probability of facing sudden disruptions, resist the spread of disruptions by maintaining control over structures and functions, and recover and respond by immediate and effective reactive plans to transcend the disruptions and restore the supply chain to a robust state of operations. This definition is adapted in this research work. From the definition, we can outline three stages of supply chain resilience, as described in Figure 30.

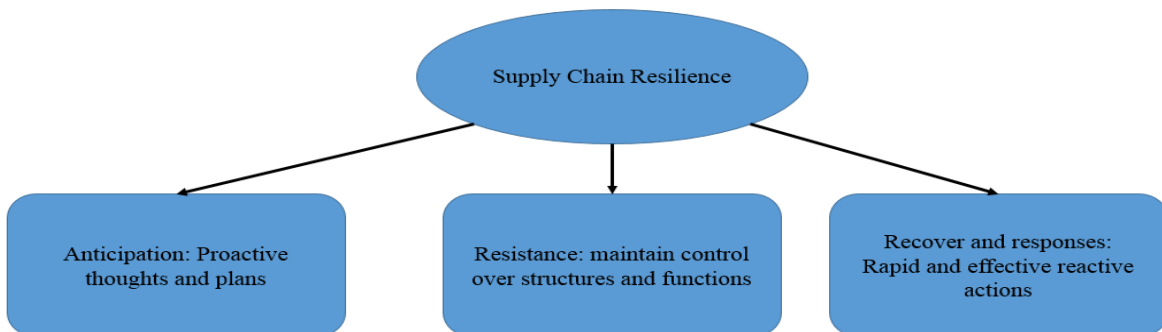


Figure 30. Phases of supply chain resilience by Kamalahmadi and Parast (2016)

- 1) Anticipation: SCs and operators should anticipate and prepare for the occurrence of disruptions. The impacts of disruptions should be understood and the contingency plans should be prepared.
- 2) Resistance: once a foreseen or unforeseen disruption occurs, the ability of the chain to resist and deactivate the perturbation before it expands would play a vital role to ensure the continuity of the operations.
- 3) Recovery and responses: Immediate and effective responses based on available resources are needed to minimize the negative impacts of disruptions.

5.1.2 Current strategies to mitigate disruption risks and their limits

To build resilient supply chains, four principles are often outlined in literature such as in (Christopher and Peck 2004; Mandal 2012), as seen in Figure 31: 1) SC Reengineering (Ponomarov and Holcomb 2009; Scholten, Sharkey Scott, and Fynes 2014); 2) Collaboration (Sheffi 2001; Nishat Faisal, Banwet, and Shankar 2006); 3) Agility (Ponomarov and Holcomb 2009; Ponis and Koronis 2012); 4) SC Risk Management (SCRM) culture (Sheffi 2005a).

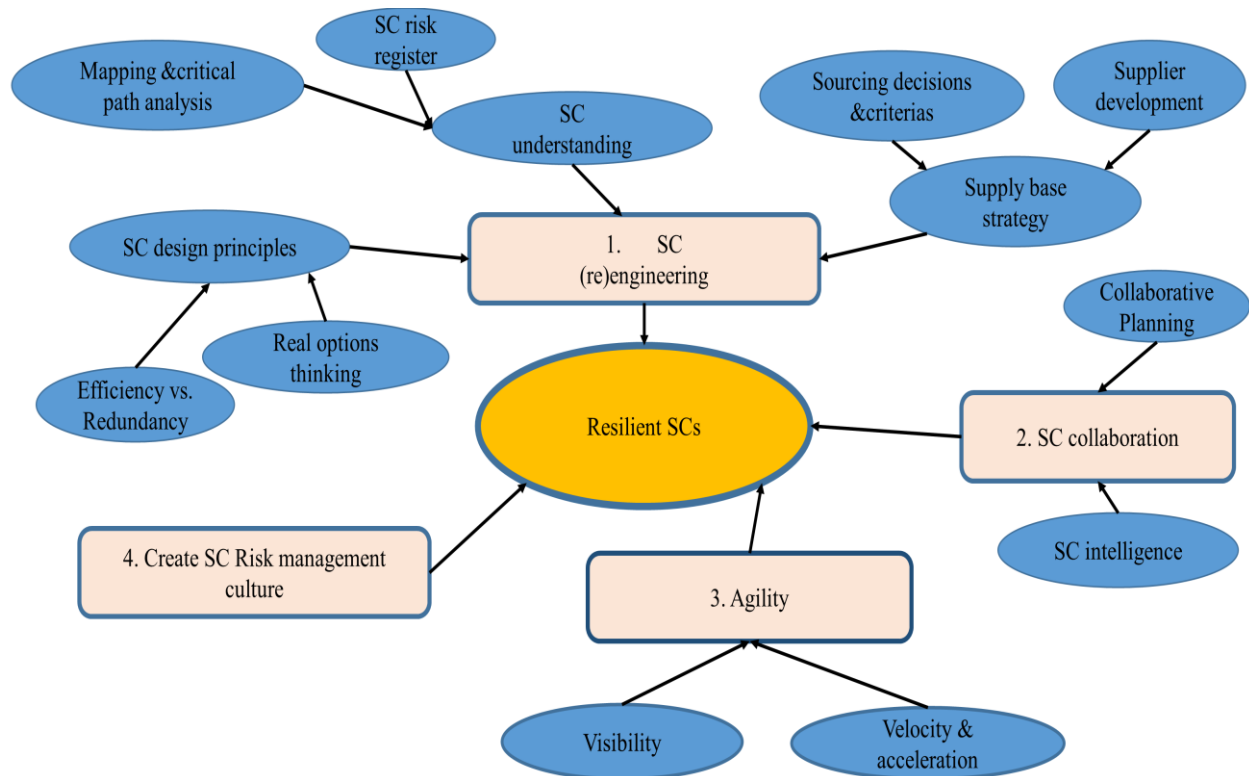


Figure 31. Supply Chain Resilience principles by Christopher and Peck (2004)

As PI is a new logistic concept and reengineer current supply chain systems for companies using it, our study falls into the scope of SC Reengineering aiming to create resilient supply chain systems. Since the risks are inherent in supply chains, considering SCRM becomes significantly necessary in the design of supply chains. Hence, traditional supply chains need to be redesigned as to embed the resilience into their design. Kamalahmadi and Parast (2016) outline two research streams to reengineer supply chains: 1) literature on improving supply chain flexibility and redundancy; and 2) examination of impacts of main characteristics of the network to resilience.

Under the concept of resilience, the flexibility refers to have multiple options to better respond to unplanned situations such as having flexible production systems or multiple suppliers (Tomlin 2006; Schmitt 2011; Iakovou, Vlachos, and Xanthopoulos 2010; Simchi-Levi, Wang, and Wei 2013; Skipper and Hanna 2009). Though this flexibility enables the addition of new replenishment schemes in face of disruptions, the additional flexibility are only restricted within their own pre-determined logistics networks with reserved backup sources. Another way to improve the SC resilience is through creating redundancies across a supply chain, for example by having redundant stocks. The redundancy has been demonstrated as an efficient strategy to improve SC resilience (Groenevelt, Pintelon, and Seidmann 1992; Arreola-Risa and DeCroix 1998; Sheffi and Rice Jr 2005). However, the redundancy of the systems of production and distribution might conflict with the efficiency and effectiveness target.

Another important research stream within SC Reengineering studies concepts such as density, locations, complexity, and node criticality as the main characteristics that need to be considered in network design to build resilient SCs (Snyder and Daskin 2005; Craighead et al. 2007; Kim, Chen, and Linderman 2015). Snyder and Daskin (2005) aim to optimize facility locations confronted to random failures. Craighead et al. (2007) examines the impacts of network characteristics of nodes to resilience. Density is defined as the geographical spacing of nodes within a supply chain. Complexity is defined as the total number of nodes and material flows in a given SC. Node criticality is defined as the importance of node within a SC. They find that network characteristics of a supply chain fortify the severity of disruption while mitigation capabilities (waring and proactively/reactively respond to disruptions) reduce the severity of disruption. Kim, Chen, and Linderman (2015) use the graph theory to conceptualize supply chain network and emphasize the importance of network level resilience. They indicate that the network structure

significantly determines the likelihood of disruptions and different network structure of entities have different levels of resilience. Besides, the resilience of network improves when the structural relationships in a network follow the power-law distribution. In conclusion, these studies help companies to optimize their SC networks to protect against future disruptions. However, the decisions of SC network design are made once the network is defined. It is therefore difficult to agilely adapt their supply chains to future random unpredictable disturbances.

Nevertheless the demonstrated efficiency of literature on SC resilience, the current research are based on current diverse independent logistics networks. Differently, our research focuses on PI, a fully interconnected, open, dynamic logistics system. In such systems, the nodes (e.g., WH, DC) are interconnected and the facilities and means of transportation can be dynamically organized and allocated in the short-term or long-term according to the economic environment. As a result, decisions can be made dynamically, agilely, and thus optimally. These kinds of systems and their resilience have been rarely addressed in the literature on SC disruption and resilience research.

Therefore, it is a new research question and a new research topic with regard to PI and SC disruptions.

5.2 Potentials of PI to Supply Chain Resilience and disruptions

Assume that current herichical logistics organisations are inherent limit for current research on SC resilience, this research focuses on disruption and resilience problems in an open, interconnected logistics system - the Physical Internet (PI). As discussed in previous chapters, instead of fixed and dedicated logistics networks in traditional SC network designs, the distribution and storage system in PI is transformed into a common, open, interconnected logistics service of PI-hubs used by many companies. The PI-hubs and means of transportation may be provided and managed by one or several Logistics Service Providers (LSP) as long as they are interconnected.

Initially, in PI, companies pay to use the same facilities and means of transportation instead of owning or renting them, see FLEXE for storage or CRC Services for transportation as first examples of such operators. So, theoretically the users can select the best storage points and means of distribution from among the offers in the interconnected network – the PI. In addition, as all PI sites and transportation means are open and “shared”, storage and distribution options for a company, including location, capacity and means of transportation, are flexible according to its

short or long-term demands. In this way, companies can quickly adjust their inventory locations and levels as well as transportation plans according to changes in the economic climate such as seasonal variations in customer demand or unpredicted disruptions. Adjusting their supply chains to the changes including supply chain disruptions becomes more convenient as it concerns of a new distribution scheme within an existing global system instead of creating a new ad hoc network in current SCs, hence with potentials of improved resilience.

Previous studies have already proven the efficiency and effectiveness of PI enabled inventory models and transportation system thanks to its high flexibility, see in Chapter 3 and 4 and Sarraj (2013). Following on these studies, this part of study examines how PI enabled logistic models including inventory and transportation models deal with SC disruptions, which will be discussed in Chapter 6 and 7.

Chapter 6. Mitigating supply chain disruptions through interconnected logistics services in the Physical Internet

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The objective of this chapter is to investigate whether applying the Physical Internet helps companies improve the resilience of their supply chains confronted to disruptions. The results of this study has been published Yang, Pan, and Ballot (2016a).

6.1 Introduction

Nowadays, the increasing supply chain disruptions risks requires companies to build both efficient and resilient supply chains. To protect against disruptions, various risk mitigation strategies have been proposed in the literature involving inventory redundancy (Groenevelt, Pintelon, and Seidmann 1992; Arreola-Risa and DeCroix 1998), source/process flexibility (Tomlin 2006; Simchi-Levi, Wang, and Wei 2013; Snyder and Shen 2006a), network design or facility location problems (FLP) (Snyder and Daskin 2005; Cui, Ouyang, and Shen 2010), or enhancing contracts with external stakeholders such as buying insurance with unreliable suppliers (Gümüs, Ray, and Gurnani 2012). Previous studies have clearly proven the effectiveness and efficiency of these strategies. However, most of them are based on traditional hierarchical SC networks, where the performance is limited by dedicated assets and budget constraints. Currently, a logistics network is defined by and dedicated to a company or a group of collaborating companies, so current logistics services are a hierarchical set of diverse independent heterogeneous logistics networks. The storage and distribution schemes of product flows are usually fixed once the network has been defined. Even though full flexibility may exist within a company, logistics operations are always restricted within their own network. This chapter assumes that this fixity and independence is an inherent limit of traditional SC networks when dealing with disruptions.

According to this assumption, this chapter focuses on disruption and resilience problems in an open, interconnected logistics system called the Physical Internet (PI). More specifically, this chapter studies the resilience of the proposed PI enabled inventory model in Chapter 4. From the previous discussion, we can see that the PI inventory systems are open and dynamic. Hence, inventory decisions within PI are more complicated as the decisions concern not only how much to order and when to place orders, but also where orders should be placed. Most importantly, the decisions made for each order can be different. Therefore, the inventory control problem in PI is dynamic and contains more degrees of freedom. Previous studies demonstrated that new inventory models enabled by and applied in PI could help reduce inventory levels thanks to its high flexibility.

Following on from these studies, this chapter examines how the proposed inventory model applying the PI deals with supply chain disruptions, and whether applying PI helps companies improving their resilience. The resilience in this chapter is defined as resilience of one given company operating in a PI-context and when the system is impacted by hubs' and plants' disruptions.

This chapter tries to answer the following questions: 1) What are the main characteristics of PI to cope with disruptions at supply level including plants and hubs? 2) What kinds of decision models on controlling inventory can be used in PI to mitigate disruptions? 3) Does PI outperform the traditional SC network in terms of resilience with regard to disruptions at logistics facilities? To simplify the problem, we studied a single product inventory problem for FMCG (fast moving consumer goods) with both uncertain demands and stochastic disruptions at logistics facilities. Two types of network were considered in order to compare the performance of the currently most dominant supply network in the FMCG sector and PI. Facility disruptions were taken into account when plants or warehouses (hereinafter WHs) and distribution centres (hereinafter DCs) or hubs become unserviceable for a period.

A simulation-based optimization model is proposed for the supplier to determine (near-) optimal inventory control decisions for the distribution network to minimize the total annual logistics costs. A simulation study was then conducted to evaluate the optimized decisions. We believe that this study has made significant contributions to the literature with regard to supply chain disruptions and resilience, as it is a first step toward resiliency in an interconnected networks framework. And we try to investigate how interconnection between logistics services could make supply networks more resilient for a given shipper and its customers.

The rest of this chapter is organized as follows. Section 2 describes the PI inventory control model. A solution approach is given in Section 3. Section 4 presents the experimental designs of the numerical studies in FMCG chains and the results from the numerical studies. Finally, section 5 concludes the study and provides some perspectives for future research.

6.2 PI inventory model confronted with SC disruptions

6.2.1 Problem Description

This work concerns a single-product inventory problem with network supply disruptions. A plant (vendor) serves a group of Nr retailers via a distribution network of M intermediate storage points (WHs and DCs in a classic network and hubs in PI. The plant and intermediate storage points are assumed to face random disruptions. When the disruption occurs, the facility becomes unserviceable until the disruption ends. So, the disrupted facility can neither deliver nor receive goods during the period of disruption. However, it is assumed that the inventories are not destroyed by the disruptions.

An adapted Vendor-Managed Inventory (VMI) decision framework is applied for the supplier. The vendor accesses the retailer inventory information and determines the inventory control decisions at hub level.). In classic supply network, the manufacturer (vendor) stocks their goods in their own WHs; and the DCs of retailers are served through WHs. The distribution flow directions are restricted and no capacity sharing is allowed among WHs and among DCs belonging to different companies. In PI, the distribution network is transformed into an interconnected network of hubs, which is shared by and open to all users including suppliers and retailers. Hence with the adapted VMI in PI, the vendor can decide on the sourcing point for each replenishment order, whereas with classic VMI the sourcing points in a traditional SC network are pre-determined (Waller, Johnson, and Davis 1999b). In other words, the VMI model is extended for different retailers thanks to interconnected logistics services in PI.

For the retailers, the data regarding demand from the FMCG industrial sector is normally distributed and independent. The model of Giard (2005) is used to locally compute the optimal inventory control decisions for each retailer. The objective of the model is to minimize the total cost including inventory holding costs, fixed ordering costs, and shortage costs for lost sales (end customer demands unsatisfied) with the required lead time constraints. The results are considered as the inputs of the optimization model for the vendor, which will be used in both a traditional FMCG supply network and the PI to compare their performance under disruption. For simplicity, the disruption process and profile in (Snyder and Shen 2006a) is studied in this chapter.

To validate the proposed model and its pertinence, different cost component and disruption process settings were analysed. A simulation-based optimization model with metaheuristic is proposed to find near-optimal decisions. This is followed by a simulation study to investigate the performance of the decisions in mitigating supply chain disruption risks. An illustration of the methodology can be found in Figure 32.

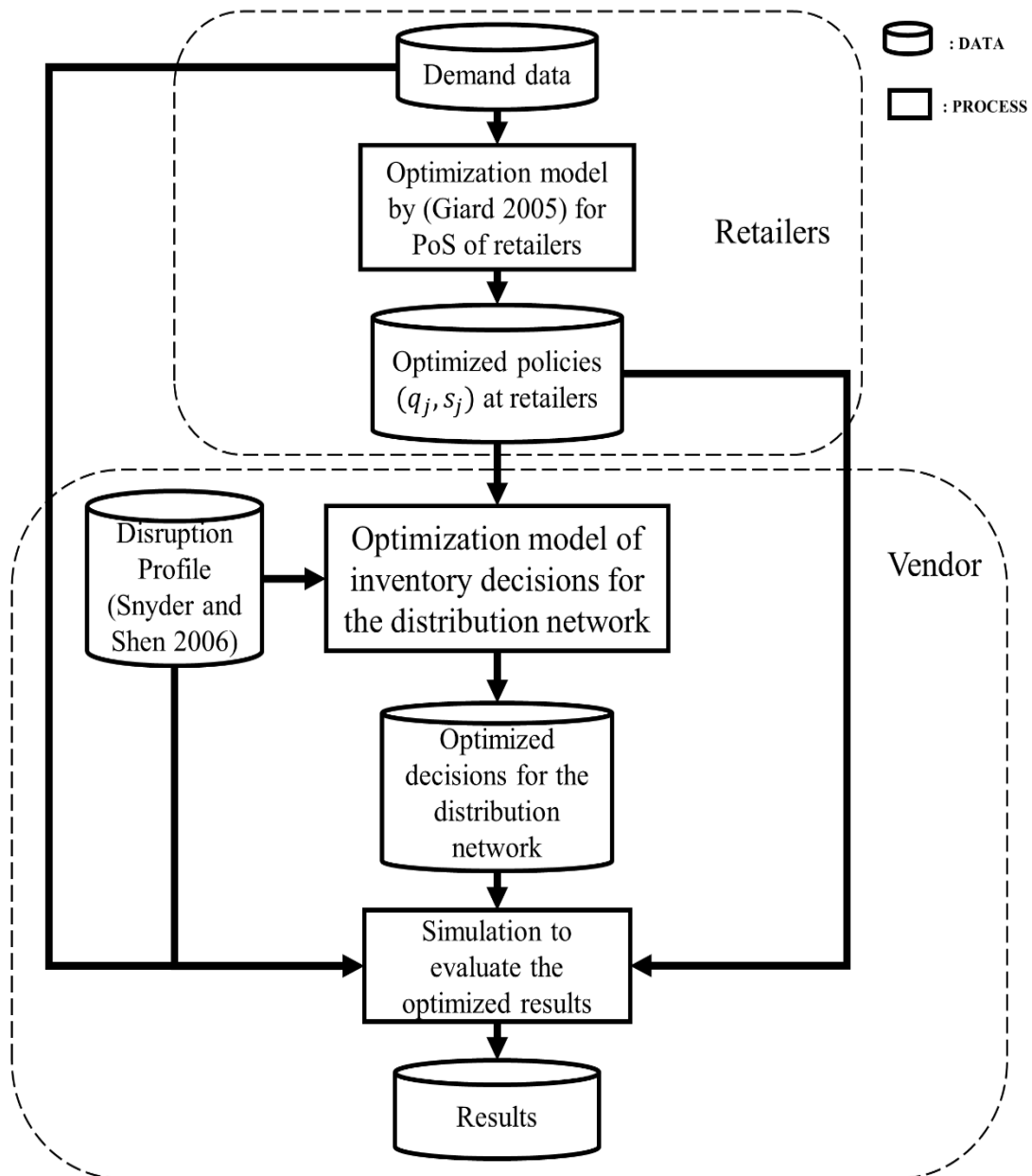


Figure 32. Illustration of methodology

6.2.2 Model Assumptions

We assume that each storage facility in the network follows (R, Q) review policy. Compared with other inventory review models such as periodic review (S, T) control systems, the (R, Q) review policy is adapted here because it is reported as the most used inventory review policy according to Waller, Williams, and Tokar (2008). The plant is assumed to have adequate stocks to meet demands and there are no capacity constraints for the hubs. The lead times among facilities and the location of each facility are given and remain the same for every scenario. The orders are completed on a first-come-first-served basis and no partial order splitting is considered in this chapter.

The network encounters two types of uncertainty: 1) uncertainty of independent end customer demands at the retailers' subject to normal distributions with a mean- u_j and a standard deviation- σ_j , devoted to $N(u_j, \sigma_j^2)$; 2) disruptions at the plant as well as the DCs, WHs, and hubs. We adopted the same disruption process as in (Snyder and Shen 2006a), which follows the two-state Markov chain (Normal/Fail) with a probability of disruption α_i (the node becomes unserviceable) and a probability of repair β_i (the node becomes normal), refer to Figure 33. The disrupted facility cannot place, receive and deliver orders until the disruption ends. The following three pairs of disruption profiles were applied: (0.001, 0.1), (0.05, 0.5), and (0.2, 0.9). As the probability that a facility is disrupted/non-disrupted for a given period can be computed as $\frac{\alpha_i}{\beta_i + \alpha_i} / \frac{\beta_i}{\beta_i + \alpha_i}$. The pair $(\alpha_i, \beta_i) = (0, 1)$ represents the network with no disruptions; $(\alpha_i, \beta_i) = (0.001, 0.1)$ indicates infrequent and long disruptions; $(\alpha_i, \beta_i) = (0.2, 0.9)$ describes short-term, frequent disruptions. We assume that the disruption profile used mainly corresponds to disruption events without destroying in-site stocks, for example equipment failures, labour strikes, and etc.

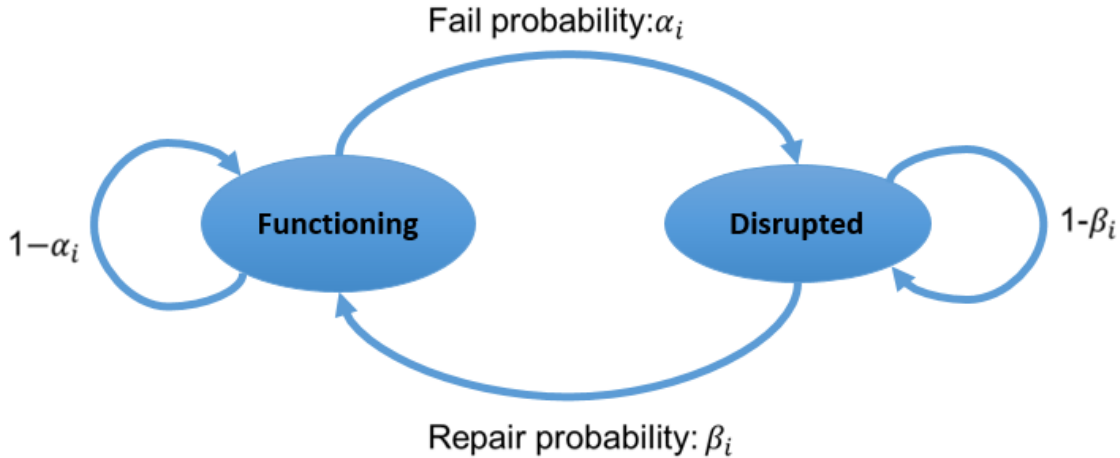


Figure 33. Disruption modelling

Within the economic scale, four logistics costs are considered: inventory holding cost, transportation cost, fixed ordering cost, and the penalty cost for orders from retailers unmet immediately. The holding cost is charged for each unit in stock per time unit at intermediate stocking points. The transportation cost for each delivery of goods is considered and is proportional to the distance and quantity transported. In addition, each replenishment order incurs a fixed ordering cost. Penalty costs are charged for orders from retailers unsatisfied immediately and are assumed to be proportional to the product value and average demand at retailers. The objective for the vendor is to find optimal inventory control solutions for the distribution network of intermediate stocking points (WHs and DCs in classic network or hubs in PI) to minimize total annual logistics costs, including inventory holding costs, fixed ordering cost, transportation costs, and penalty costs as described above.

6.2.3 Model formulations

A simulation-based optimization modelling method is applied in this chapter. It is a well-established method in the literature where the objective function and constraints are evaluated through simulation (Jalali and Nieuwenhuys 2015). To introduce the model, the following

notations are needed. The decision variables, main constraints and objective function are presented as follows.

Notations:

M : set of intermediate stocking points including DCs or WHs or hubs indexed by i, k .

Nr : set of retailers, indexed by j .

Plant: index by 0.

T : configuration time of the inventory system, indexed by n day (1 year = 365 days).

$Dis1_{ij}$: distance between intermediate stocking point $i \in M$ and retailer $j \in Nr$.

$Dis2_{ki}$: distance between points $k \in M$ and $i \in M$.

Dis_{0i} : distance between $i \in M$ and the plant 0.

(u_j, σ_j) : customer demand at retailer j subject to normal distribution $N(u_j, \sigma_j^2)$

(q_j, s_j) : replenishment policy of retailer j - q_j for batch size and s_j for reorder point.

A : fixed ordering cost per replenishment order placed.

h_i : daily holding cost per SKU at intermediate stocking point i for daily stocking costs.

p_j : penalty cost per SKU per unit time of unmet orders from retailer $j \in Nr$, proportional to product value.

c_1 : downstream transportation cost per kilometer per SKU from stocking points $i \in M$ to retailers $j \in Nr$.

c_2 : upstream transportation cost per kilometer per SKU from the plant (index by 0) to stocking points and among stocking points $i \in M$.

IL_{in} or IL_{jn} : inventory level at intermediate stocking point $i \in M$ or retailer $j \in Nr$ at the n th day.

UP_{in} : 0 if the facility is disrupted, otherwise 1.

UP_{0n} : 0 if the plant is disrupted, otherwise 1.

Decision variables:

R_i : reorder point at facility i .

Q_{i0} : facility i 's batch size (reorder quantity) from the plant.

Q_i : facility i 's batch size (reorder quantity) from other stocking sites.

x_{0in} : binary variable, $x_{0in} = 1$ if the plant is chosen to satisfy the replenishment order from site i at n th day, otherwise 0;

x_{kin} : binary variable, $x_{kin} = 1$ if the site $k \in M$ is chosen to satisfy the replenishment order from site i at n th day, otherwise 0;

x_{kjn} : binary variable, $x_{kjn} = 1$ if the site $k \in M$ is chosen to satisfy the replenishment order from retailer j at n th day, otherwise 0;

The objective function:

Minimize C_{tot}

$$\begin{aligned}
&= \left[\sum_{i=1}^M \sum_{n=1}^T IL_{in}h_i \right]_{(1)} + \left[\sum_{j=1}^{Nr} \sum_{n=1}^T \sum_{k=1}^M x_{kjn}c_1q_jDis1_{kj} \right]_{(2)} \\
&+ \left[\sum_{i=1}^M \sum_{n=1}^T \sum_{k=1, k \neq i}^M x_{kin}(c_2Q_iDis2_{ki} + A) \right]_{(3)} + \left[\sum_{i=1}^M \sum_{n=1}^T x_{0in}(c_2Q_{i0}Dis_{0i} + A) \right]_{(4)} \\
&+ \left[\sum_{n=1}^T \sum_{j=1}^{Nr} \left(1 - \sum_{k=1}^M x_{kjn} \right) * u_j * p_j \right]_{(5)}
\end{aligned}$$

Subject to:

$$0 \leq \sum_{k=1}^M x_{kjn} \leq \text{Min}[\sum_{i=1}^M UP_{in}, 1] \quad \forall j \in Nr, i \in M, \forall n = 1 \dots T \quad (6)$$

$$0 \leq \sum_{k=0, k \neq i}^M x_{kin} \leq \text{Min}[\sum_{i=0}^M UP_{in}, 1] \quad \forall i \in M, \forall n = 1 \dots T \quad (7)$$

$$x_{kjn} \in \{0,1\} \quad \forall k \in M, \forall j \in Nr, \forall n = 1 \dots T \quad (8)$$

$$x_{kin} \in \{0,1\} \quad \forall i \in M, \forall k \in M \cup \{0\}, i \neq k, \forall n = 1 \dots T \quad (9)$$

$$R_i, Q_{i0}, Q_i: \text{Integers}, \forall i \in M \quad (10)$$

The formula 1 represents the total annual holding cost at the hubs or DCs and WHs, formula 2 indicates the total annual transportation cost to satisfy replenishment orders from retailers, formula 3 describes the total annual transportation cost and fixed ordering cost to meet the replenishment orders of intermediate stocking points from other intermediate stocking sites,

formula 4 the total annual transportation cost and fixed ordering cost to meet the replenishment orders of intermediate stocking points by the plant, formula 5 introduces the penalty cost for orders from retailers unmet immediately, which is assumed to be proportional to average demand level at retailers. Equation 6 - 9 describe the constraints that the replenishment orders can only be met by one facility each time and can only be met by non-disrupted facilities, these constraints are extended from the model in Yang, Pan, and Ballot (2015). Equation 10 indicates that the demanding quantity cannot be allowed fractional or partial. As a simulation based optimization model, the objective function and constraints will be evaluated through a simulation.

6.3 Solution approach

From the formulations, we can see that the problem is a non-linear optimization problem. We can no longer obtain exact optimal solutions using closed-form expressions, especially with disruptions. Thus, we use simulation-based model to solve the problem where objective function and constraints are evaluated by the following simulation process.

Simulation-based annual total cost calculation procedure:

Input: (R_i, Q_{i0}, Q_i) and source selection strategy to decide $x_{kjn}/x_{kin}/x_{0in}$

Step 1: Initialization: initialize $n = 1$, initial stock at every hub to be 0 SKU and at every retailer j ($s_j + q_j$) (q_j is the batch size, s_j is the reorder point of retailer j). Initialize status at intermediate stocking points and the plant as functioning $UP_{in} = 1$, where $i = 0 \dots M$.

Step 2: At the beginning of the day n , randomly generate a real number $prob \in [0,1]$ and update disruption information at hubs and the plant according to their previous status and fail/repair probability (α_i, β_i) .

Step 3: For all non-disrupted stocking points, update inventory level at stocking points with incoming in-transit stocks.

Step 4: For disrupted stocking points, postpone the reception of incoming in-transit stocks until the disruption ends.

Step 5: Review stocks at retailers. For each retailer j , if $IP_{jn} \leq s_j$ (inventory position is lower than reorder point), based on source selection strategy, determine the source i^* ($x_{i^*jn} = 1$)

while respecting the constraints (6), (8). Update the inventory information at retailer j $IP_{jn} = IP_{jn} + \sum_{i=1}^M x_{ijn}q_j$ and at source i^* , $IP_{i^*n}/IL_{i^*n} = IP_{i^*n}/IL_{i^*n} - x_{i^*jn}q_j$.

Step 6: Review stocks at non-disrupted stocking points i where ($UP_{in} = 1$). For each non-disrupted stocking point i , if $IP_{in} \leq R_i$: based on source selection strategy, determine the source k^* ($x_{k^*in} = 1$), while respecting the constraints (7), (9). Update the inventory information of at point i ; If source k^* is not the plant ($k^* \neq 0$), update inventory information at k^* .

Step 7: Randomly generate end customer demands Dmd_{jn} according to normal distribution function respecting input parameters (u_j, σ_j) at retailer $j \in Nr$. At the end of the day, update inventory information at retailer j $IL_{jn} = \text{MAX}[IL_{jn} - Dmd_{jn}, 0]$ and $IP_{jn} = \text{MAX}[IP_{jn} - Dmd_{jn}, 0]$.

Step 8: Update objective function C_{tot} .

Step 9: If $n \leq T$, $n++$ and go to Step 2.

Step 10: Return annual total cost C_{tot} .

The decision variables can be divided into two parts: optimal replenishment parameters for intermediate storage points (R_i, Q_{i0}, Q_i) and source decision variables $x_{k_jn}/x_{kin}/x_{oin}$. As the objective function is estimated through simulation, in this chapter, we propose a metaheuristic integrated with a source selection strategy to optimize decision variables. In classic supply network, the sources are pre-assigned, therefore the source selection variables $x_{k_jn}/x_{kin}/x_{oin}$ are always constant and given in this scenario. In PI, a dynamic source selection strategy is integrated in the metaheuristic to determine the source selection decision variables $x_{k_jn}/x_{kin}/x_{oin}$. As a pre-defined strategy, the dynamic source selection strategy named Minimum Distance strategy from Yang, Pan, and Ballot (2015) and Pan et al. (2015) is applied in this work. The nearest candidate with enough stocks on hand to the ordering point is always chosen as the supply point. However, in our problem with disruptions, the conditions are enhanced as only non-disrupted storage points can be candidates.

Furthermore, in face of disruptions, two disruption management strategies are adapted and compared: passive acceptance and inventory mitigation (Tomlin 2006). Passive acceptance

indicates that the company passively accepts the disruption risks. Inventory mitigation (IM) refers to the inventory redundancy strategy in the literature which involves increasing inventory levels to reduce disruption risks. However, as the PI inventory model also enables sourcing flexibility and inventory pooling among hubs, hereafter we use the PI-IM to index IM strategy in PI.

6.4 Numerical Study

In this part we discuss the experimental design and performance results of the two networks: current, most dominant supply network in FMCG and PI. The performance of the different networks with different mitigation strategies is compared. The performance ratio defined in Ng, Li, and Chakhlevitch (2001) is adopted and four key performance indicators are used: total logistics cost, total inventory distribution network holding cost, total transportation cost, and average level of end customer service at the retailers' (referring to the percentage of customer demands met with on-hand stocks). The average performance ratios presented are the relative variations of compared two scenarios.

6.4.1 Inputs and Experimental Design

We consider a single product inventory problem where a supplier owns a plant and a WH serves the points of sale (PoS) of two regional retail companies from their own DCs. The WH and DCs are transformed into PI hubs and shared by the suppliers and retailers. The distance matrix is shown in Table 13 and the locations remain the same for all the scenarios. The lead times are given: one week (7 days) from the plant to the WH or hub, 1 day between hubs or from WH to DCs, and 3 days from hubs or DCs to retailers. The retailers face normally distributed daily end-customer demand, as given in Table 14. The fixed ordering cost for each order placed is assumed to be €15 (monetary unit) per unit. The transportation cost is assumed to obey the LTL (less than truckload) model: €1.40 per full truckload per km from the plant to hubs and €2.00 per full truckload per km from hubs to retailers. This assumption is based on the fact that the transportation cost for full long-haul truckloads is much lower than the last mile transportation cost. The inventory holding cost is considered from two perspectives: storage cost per unit per year for storage space (€0.11 per m^3 /day in hubs and €0.165 per m^3 /day at retailers') and capital cost per unit per year for other costs

(assumed to be 8% of the product value), i.e. investment cost. These data are from our previous projects.

Source Destination	Plant	Hub 1	Hub 2	Hub 3
Hub 1	100		166	143
Hub 2	236	166		272
Hub 3	206	143	272	
PoS 1/Retailer 1	264	184	41	269
PoS 2/Retailer 1	234	144	67	218
PoS 3/ Retailer 1	261	163	130	163
PoS 1/ Retailer 2	261	161	175	149
PoS 2/ Retailer 2	229	120	202	92
PoS 3/ Retailer 2	236	166	280	32

Table 13. Distance Matrix: kilometers

To evaluate the sensitivity of the model proposed, the following three parameters are analysed: the product value of €0.5, €5 or €20 (monetary unit) per unit, penalty rate for lost sales and unfulfilled orders (25% or 50% of the product value), and the disruption profile discussed in section 3. To facilitate the comparison of the different scenarios, we assume that the plant and the hubs face the same probability of disruption in each scenario. Therefore, with all these setups and the methods presented in Giard (2005), the local optimal replenishment parameters (1 SKU assumed to be 6 units) for retailers are shown in Table 14. This is considered as the input information for the distribution network optimization model which is solved by the proposed simulation-based model using a simulated annealing method with a convergence ratio, maximum temperature and maximum iteration number of 5%, 50, and 6000, respectively. These parameters are obtained through our experiments which can attain relatively good results within a reasonable time. The optimized results are then evaluated using a simulation of the total system conducted 50 times (refers to 50 years) for each instance, which is assumed to be enough time to evaluate the system. The average value of each performance indicator is obtained. All the experimental tests were developed in *Mathematica*® 10.2.0 on a PC with an Intel (R) Core (TM) i7-3940XM, 3.20 GHz CPU and 32 Go RAM. As the optimisation problem is quite complicated, we normally expend 2 hours to obtain the good solutions by the simulated annealing algorithm programmed in the *Mathmatica*.

Settings		PoS 1/R1	PoS 2/R1	PoS 3/R1	PoS 1/R2	PoS 2/R2	PoS 3/R2
Demand in unit		(200, 33 ²)	(160, 30 ²)	(100, 20 ²)	(135, 25 ²)	(144, 23 ²)	(192, 31 ²)
Penalty	Product	(s*, q*) at PoSs of retailers in SKU					
Rate	value	PoS 1/R1	PoS 2/R1	PoS 3/R1	PoS 1/R2	PoS 2/R2	PoS 3/R2
25%	0.5	(114, 529)	(92, 473)	(57, 374)	(77, 435)	(81, 448)	(109, 518)
25%	5	(121, 327)	(99, 293)	(62, 231)	(83, 268)	(87, 277)	(116, 320)
25%	20	(124, 188)	(102, 168)	(64, 133)	(85, 154)	(89, 159)	(119, 184)
50%	0.5	(117, 529)	(95, 473)	(59, 374)	(80, 434)	(83, 448)	(112, 518)
50%	5	(124, 327)	(101, 292)	(64, 231)	(85, 168)	(88, 277)	(118, 320)
50%	20	(127, 188)	(104, 168)	(65, 132)	(87, 154)	(90, 159)	(121, 184)

Table 14. Inputs of daily demand $N(u_j, \sigma_j)$ and (s^*, q^*) at retailers' PoSs

6.4.2 Results Analysis

To evaluate disruption risks, the scenario without disruptions (S1) is used as the baseline for the other scenarios with disruptions. According to different disruption mitigation strategies, we classify the results for each network into two groups: Scenario 2 (S2) with passive acceptance and Scenario 3 (S3) with inventory mitigation. Each scenario has a set of sub-scenarios due to different parameter configurations. Scenario performance is compared via performance ratio, which is computed by $(A-B)/B$ if we compare scenario A to scenario B for example.

6.4.2.1 Passive Acceptance

Figure 34, which represents the possible economic losses due to disruptions, shows the performance ratios of the total cost of scenarios with passive acceptance compared with scenarios without disruptions. From the Figure, we can see that the disruptions lead to a higher total annual logistics cost, which varies from 0% to 450% according to the different parameter configurations. For both the current supply network and PI, the augmentation in total cost due to disruptions is in line with the product value, penalty rate and disruption probability. In addition, the impact of

disruptions is not clear when the product value is relatively low or disruptions are rare, i.e. only 1% increase in total cost in current network when the product value is low with disruption profile A. This minor increase might also be a result of random variation by simulation, such as the 1% decrease in total cost in Figure 34 (Product value: low, B, 25%). The increase in total cost with passive acceptance is mainly due to the increase in penalty costs and penalty costs are relatively low when the product value is low and when disruptions are rare.

Sensitivity of performance ratios to product value

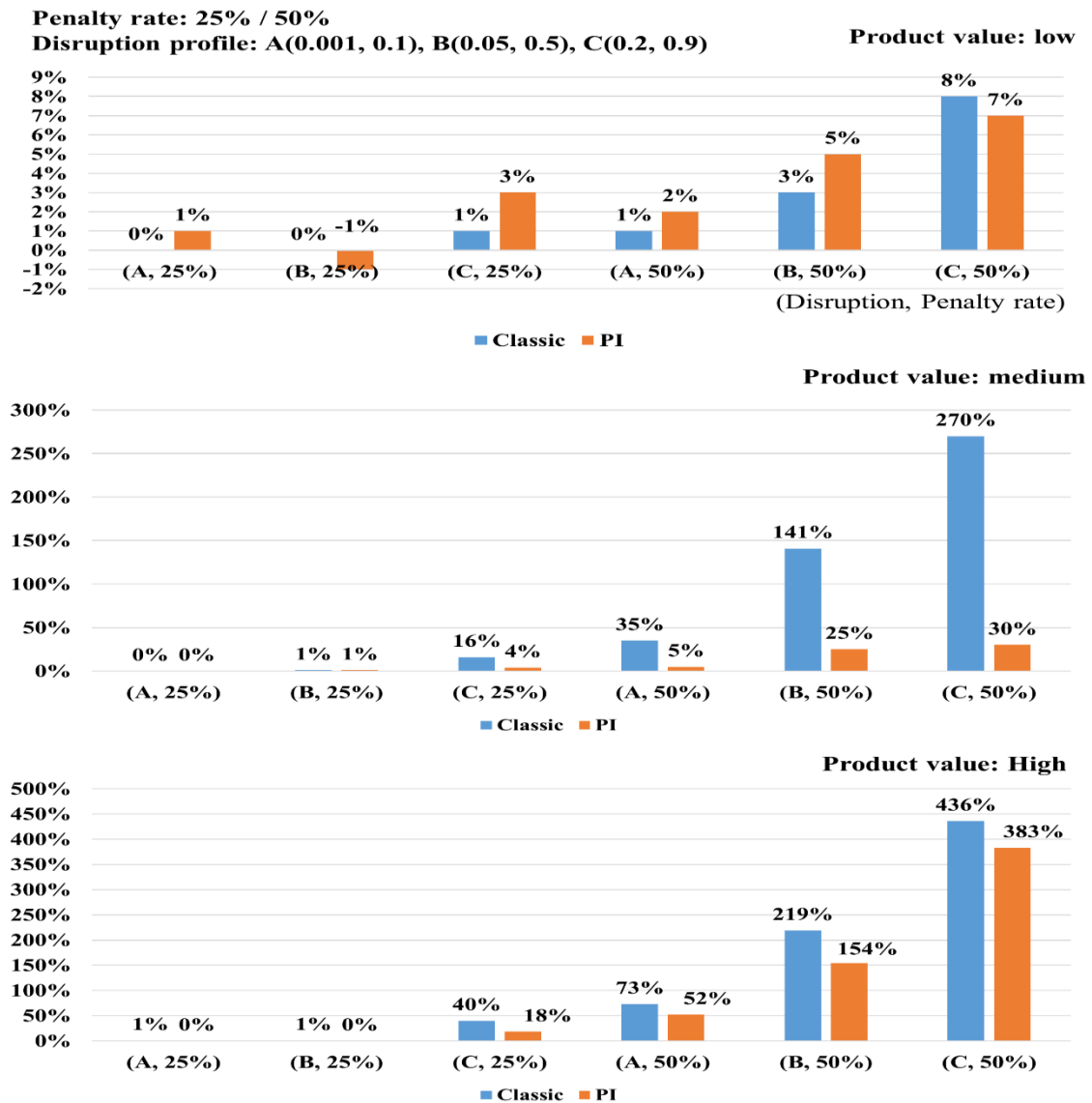


Figure 34. Performance ratios of total cost: S2 vs. S1

Regarding the difference in performance of the two networks, we can see that the PI inventory model is perturbed less than the current inventory model, as proven by the total cost. For the scenarios with relatively few disruptions and products of moderate value, i.e. scenarios with medium-value products and disruption profile B, the PI inventory model tolerates well the perturbations caused by disruptions, while the total cost of the current network has already risen by around 30%.

Table 15 illustrates the comparison between the average performance ratios for the two networks with S2. We reached the same conclusion as in Yang, Pan, and Ballot (2015) that the PI can significantly reduce the average total cost compared with the current inventory network, varying from 24% to 40%, and the benefits are mainly from the reduction in inventory holding costs and penalty costs. The reduction of total inventory holding cost is explained as a result of reduction in average inventory level in PI, compared to classic supply network, through the interconnection and inventory pooling among hubs. Besides, the penalty costs for orders unmet immediately decrease as more sourcing options are enabled in PI. When the disruption frequency is low, the reduction in total logistics costs is mainly due to the reduction in inventory holding costs through inventory pooling among hubs. When disruptions become more frequent, the gain in the reduction in penalty costs increases as more supply options are available in PI, though the transportation costs also augment as the interaction between hubs is more frequent to mitigate disruption risks. As a result, PI provides a better level of service for end-customers at retailers' PoSs compared with the classic network when disruptions are frequent.

Parameter	Value	Total Cost	Service Level	Holding	Transport	Penalty
Product value	Low	-24%	0%	-41%	-6%	-34%
	Medium	-31%	1%	-40%	-3%	-64%
	High	-40%	3%	-35%	6%	-67%
Penalty rate	Low	-31%	1%	-40%	-1%	-55%
	High	-33%	1%	-37%	-1%	-52%
Disruption	(0.001, 0.1)	-24%	0%	-41%	-6%	-34%
	(0.05, 0.5)	-31%	1%	-40%	-3%	-64%
	(0.2, 0.9)	-40%	3%	-35%	6%	-65%

Table 15. Average performance ratios of S2: PI vs. Classic with disruptions

6.4.2.2 Inventory mitigation

In this part, we test scenarios that involve increasing inventory levels in order to reduce disruption risks, called Inventory Mitigation (IM) and noted S3 here. Table 16 and Table 17 compare the performance of S3 and S2 (passive acceptance) for each network. Recall that the average performance ratios presented are the relative variations of the compared two scenarios.

Parameter	Value	Total Cost	Service Level	Holding	Transport	Penalty
Product value	Low	0%	0%	1%	1%	-9%
	Medium	-6%	1%	4%	2%	-34%
	High	-14%	0%	3%	0%	-9%
Penalty rate	Low	-4%	1%	4%	1%	-22%
	High	-7%	0%	3%	1%	-13%
Disruption	(0.001, 0.1)	0%	0%	0%	0%	-4%
	(0.05, 0.5)	-1%	0%	4%	0%	-17%
	(0.2, 0.9)	-14%	2%	4%	3%	-31%

Table 16. Average performance ratios of classic network: S3 vs. S2

Parameter	Value	Total Cost	Service Level	Holding	Transport	Penalty
Product value	Low	-3%	0%	0%	-3%	-22%
	Medium	-7%	0%	0%	-1%	-25%
	High	-22%	0%	7%	-2%	-64%
Penalty rate	Low	-6%	0%	2%	-1%	-38%
	High	-12%	0%	3%	-3%	-36%
Disruption	(0.001, 0.1)	-1%	0%	0%	0%	-33%
	(0.05, 0.5)	-6%	0%	4%	-1%	-37%
	(0.2, 0.9)	-21%	0%	5%	-5%	-42%

Table 17. Average performance ratios of PI: S3 vs. S2

From Table 16 and Table 17, both the classic network and PI increase inventory levels throughout the distribution network to reduce greater penalty costs caused by disruptions, i.e. 3% in PI and 4% in Classic compared with passive acceptance. So, when disruptions become more frequent, the reduction in total costs and penalty costs due to disruptions increases, which indicates that the IM strategy is an effective way of managing frequent disruption risks. Generally, PI outperforms the classic network in terms of reducing total costs and penalty costs, and total transportation costs are also reduced compared with the passive acceptance strategy in S2. This is explained by the fact that the PI inventory model with IM reduces the total cost and penalty costs not only through inventory redundancy at facilities, but also by allowing stock replacement and sharing throughout the entire network. For example, orders from the WH in the classic network can only be met when the disruption at the plant ends. However, orders from hubs can be met by any other non-disrupted hub if the plant is disrupted. This is the same for orders from retailers.

Parameter	Value	Total Cost	Service Level	Holding	Transport	Penalty
Product value	Low	-11%	1%	-36%	-2%	-42%
	Medium	-37%	1%	-39%	-5%	-82%
	High	-56%	1%	-43%	-5%	-81%
Penalty rate	Low	-27%	0%	-43%	-6%	-66%
	High	-42%	1%	-36%	-2%	-71%
Disruption	(0.001, 0.1)	-25%	0%	-43%	-6%	-58%
	(0.05, 0.5)	-34%	1%	-40%	-5%	-76%
	(0.2, 0.9)	-45%	2%	-35%	-1%	-71%

Table 18. Average performance ratios of S3: PI vs. Classic

Table 18 presents the difference in performance between the two networks with IM. It demonstrates the advantages of PI in inventory problems with disruptions, with a reduction of around 35% in total cost compared with the classic network when using the same mitigation strategy, as well as better levels of service for the end customers at the retailers.

Regarding the configuration of the PI, with both supply and demand uncertainties, the experimental results show that the inventories are decentralized between the hubs throughout the

network, and the retailers prefer to be supplied by the nearest hubs. However, as the frequency of disruption increases, the probability of orders from retailers being fulfilled by hubs other than the nearest is augmented, as well as the probability of stock movements among hubs. Figure 35 gives an example of annual distribution flows for the scenario where the product value and penalty percentage cost are 5 and 25%, respectively, for the disruption profile (0.2, 0.9). From the distribution flows, we can see that orders in the classic network are always satisfied by a predetermined sourcing point and so must wait when the sourcing point is disrupted, resulting in more lost sales. However, with PI, orders from retailers can be satisfied by any non-disrupted hub within the distribution network. So, if there is a facility with enough stock in the distribution network, the order can be fulfilled. As a result, the end customer service levels at retailers increase and the penalty costs for unfulfilled orders decrease, see Table 18.

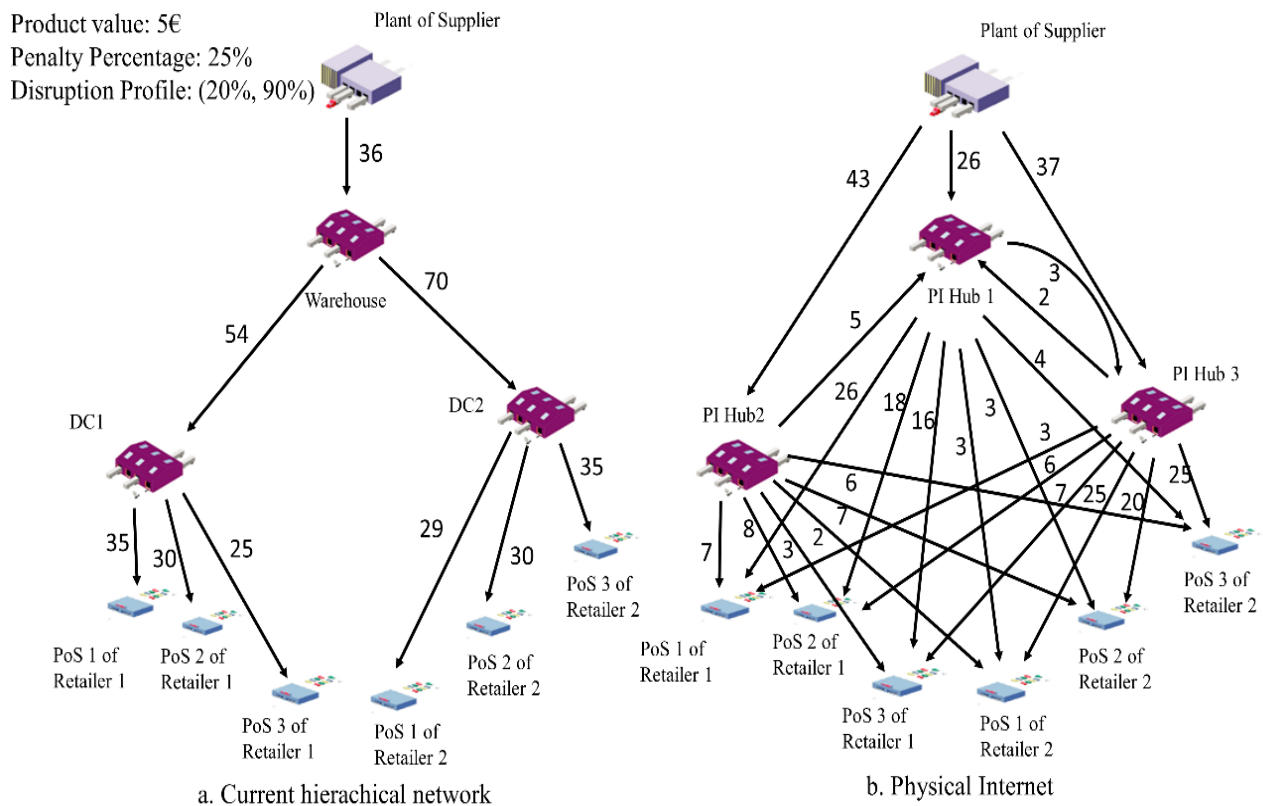


Figure 35. Example of annual distribution flows: PI vs. Classic

6.5 Conclusion

In this chapter, we studied how inventory models using PI respond to SC facility disruptions and their resilience. A simulation-based optimization model has been proposed to investigate the question through an experimental numerical study. The experimental results show that the PI inventory model outperforms current pre-determined inventory control models for demand uncertainties and supply chain disruptions. Moreover, the difference in performance increases when the product value, penalty costs and disruption frequency increase. We conclude that the benefits result mainly from increased agility, flexibility and delivery options enabled by the interconnected logistics services in PI. As one of the first studies investigating PI inventory control and resilience problems, this study may provide some qualitative and quantitative results that could be useful guidelines for the next steps. Moreover, this chapter also indicates a novel approach to build a resilient supply network that rests on PI.

Future research is needed to investigate the optimality of inventory control decisions and sourcing methods for the distribution network, as here we used a metaheuristic to obtain near-optimal results in order to compare performances. Further studies are also required to examine a network with more suppliers and consignees that is closer to a real case of interconnected supply networks. Furthermore, some studies are also necessary regarding the application of the inventory control models studied such as developing operational models and decision-making tools, studying managerial issues, and the adaptability of the models to different systems

Chapter 7. Resilience of Physical Internet Transportation System confronted to disruptions at hubs

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The previous chapter examined how inventory models using the Physical Internet (PI) respond to supply chain disruption and their resilience. Experimental results demonstrated that the inventory models applying the PI outperform current inventory models for both demand uncertainties and supply chain disruptions. The benefits mainly come from improved agility, flexibility and more delivery options enabled by the interconnected logistics services in PI. Following the research stream, this chapter aims to investigate the resilience of PI transportation system.

7.1 Introduction

The objective is to provide a quantitative study on the resilience of the PI, which is defined as the capacity of this open interconnected logistic system confronted to disruptions at hubs. Precisely, we try to answer the following questions: 1) What protocols should be applied when confronted to disruptions at hubs? 2) What's the resilience of PI? To this end, we extend the simulation model of PI transportation system of Sarraj et al. (2014) with random disruptions at hubs' level. When the hub is disrupted, all the logistics services will become unserviceable. The multi-agent simulation model by Sarraj et al. (2014) is used and extended with dynamic transportation protocols. Numerical studies are carried out to evaluate the performance with real industrial data from Sarraj et al. (2014) and different disruption profiles in the literature.

The rest of this chapter is organized as follows. Section 2 describes the multi-agent simulation model of PI transportation system. Section 3 presents the experimental designs of the numerical studies in FMCG chains and the results from the numerical studies. Finally, section 4 concludes the study and provides some perspectives for future research.

7.2 Simulation model of PI-transportation system with disruptions

This chapter deals with resilience problem of a PI transportation system with disruptions at hubs. The hubs are assumed facing random unpredictable disruptions. When a disruption occurs at a hub, all the logistics services at this hub are paralyzed until the disruption ends. To quantitatively analyse the problem, we develop a multi-agent simulation model of PI transportation system based on the model of Sarraj et al. (2014). As we concentrate on the resilience and disruptions problems, we use parts of the transportation protocols of this reference to build the model, such as containerization protocol to load goods in containers. A disruption agent is developed to simulate

disruptions at hubs which follow a two-state Markov process as in (Snyder and Shen 2006a), as discussed in Chapter 6. Besides, because the hubs may become unserviceable in our problem, the static transportation routing protocol in Sarraj et al. (2014) is no longer capable to such a system. Hence, dynamic transportation protocols with different disruption strategies are proposed. To validate the proposed model, we carry out numerical studies without disruptions of mass distribution in FMCG in France and compare results with Sarraj et al. (2014). The integration of the PI in SC network makes it difficult to compare the performance with current supply network. Therefore, only the scenarios applying the PI are analysed in our experiments. After validation of the proposed model, numerical studies of different disruptions profiles and strategies are taken out. Results of different scenarios are examined by the main KPIs to identify the impact of disruptions and the resilience of PI. An illustration of methodology is depicted in Figure 36.

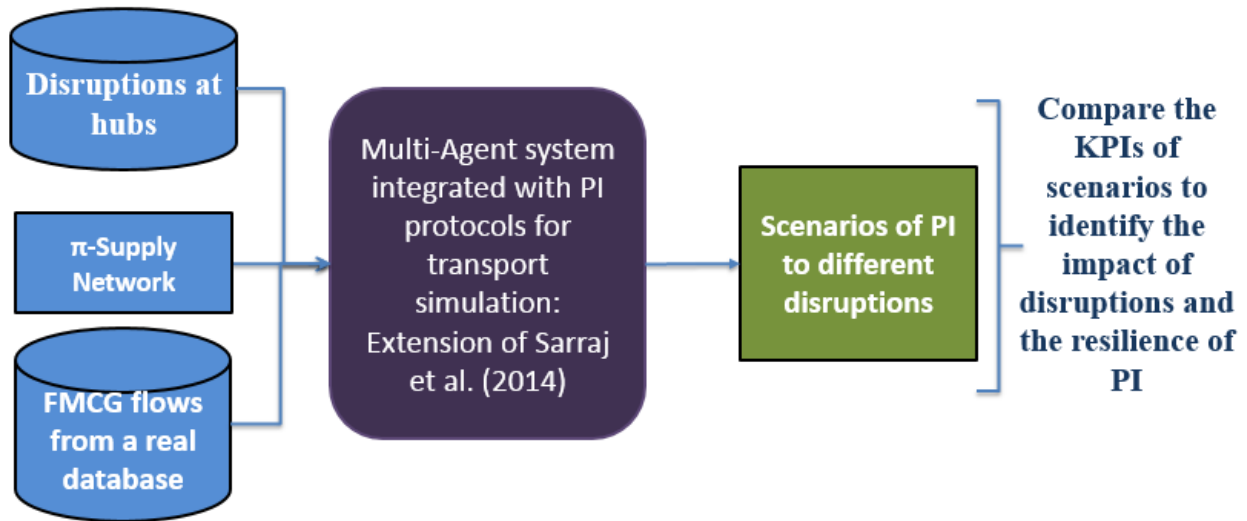


Figure 36. Methodology depiction

7.2.1 Simulating disruptions at hubs

The most common way that disruptions are modelled is to assume that the facility follows a two-state Markov process, either functioning or being disrupted (Tomlin 2006; Baghalian, Rezapour, and Farahani 2013; Snyder and Shen 2006a). Others use more general distributions such as *Erlang* distributions (Groenevelt, Pintelon, and Seidmann 1992). In addition to general

distributions, recently Klibi and Martel (2012) analyse different types of vulnerable events and propose a Monte Carlo procedure to generate plausible future scenarios.

Here we use the same disruption process as in (Snyder and Shen 2006a), which follows the two-state Markov chain (Normal/Fail) with a probability of disruption α_i (the node becomes unserviceable) and a probability of repair β_i (the node becomes normal). The disrupted facility cannot take out any operation until the disruption ends. That is, the disrupted hubs cannot receive nor dispatch transportation means until the disruption ends. We assume that the disruption profile used mainly corresponds to disruption events without destroying in-site stocks, for example equipment failures, labour strikes, and etc. The disruption agent hourly review the status of the hub. The probability that a facility is disrupted/non-disrupted for a given period can be computed as $\frac{\alpha_i}{\beta_i + \alpha_i} / \frac{\beta_i}{\beta_i + \alpha_i}$. Hence, different combination of α_i and β_i represents different types of disruptions, i.e. rare and long, frequent and short, and etc.

7.2.2 Transportation protocols in the PI

The diagram in Figure 37 presents the general process of shipping goods from a supplier to a consignee in the multi-agent PI transportation system. Firstly, each order is loaded in a “best” fitting PI-container or set of PI-containers. When a PI container is ready to be shipped, the best path towards destination is identified and is made of several segments, which could be start by a truck service, then continued with a train, and so forth until reaching destination where the goods are offloaded from the PI-containers. Between the transportation segments, PI-containers are handled in PI-hubs. Each time a container arrives at a hub, the hub finds the remaining best path for this container and best fitting transportation means for the next segment. The rules and optimizations that decide operations are called transportation protocols. Figure 38 gives an example of this transportation system.

From the discussion, we can identify three main groups of transportation protocols: containerization protocols to load orders in best fit containers, routing protocols to find the best path for containers until the destination, and container consolidation protocols to load containers to best fit transportation means. As the hubs may be disrupted, the routing protocols need to dynamically consider the available hubs according to the real status of the network. Therefore, dynamic routing protocols are needed.

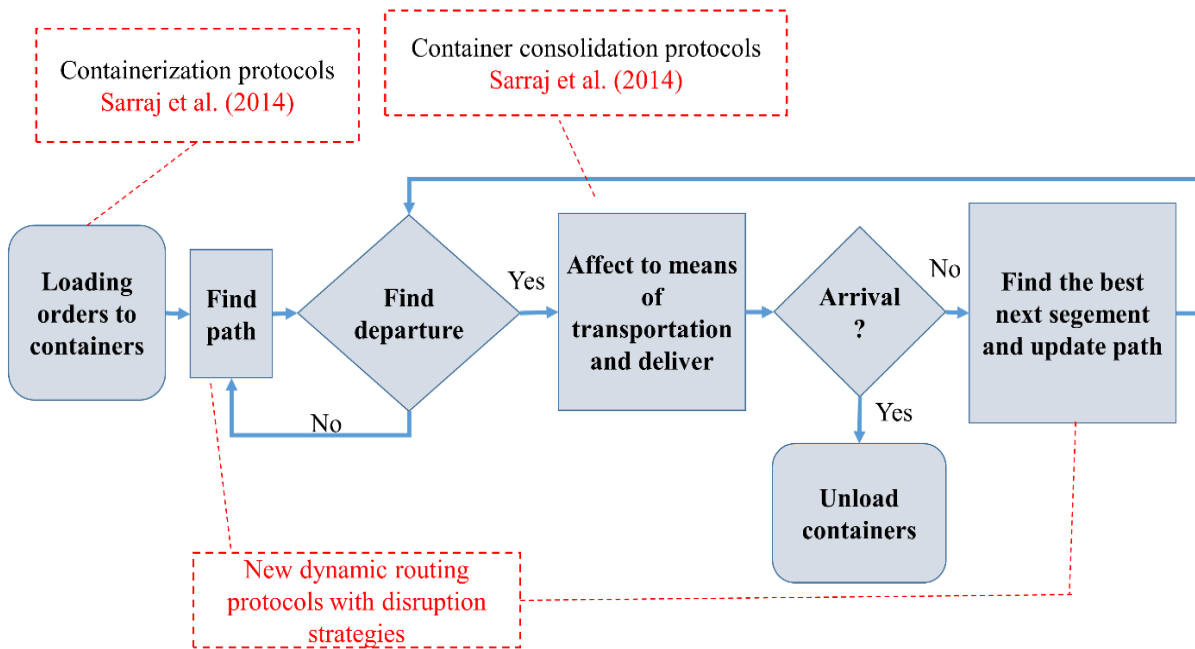


Figure 37. Goods shipping process in PI

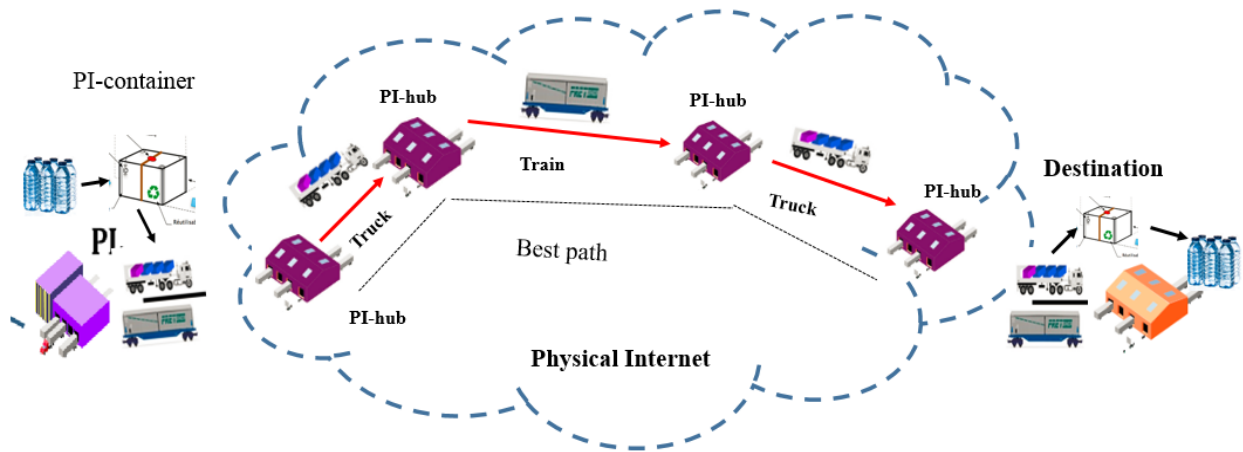


Figure 38. An example of shipping goods in PI

7.2.2.1 Containerization of goods in PI

We apply the goods containerization protocol by Sarraj et al. (2014) to load orders to best fit containers. This protocol specifies how products ordered for shipment are assigned to a best fit

PI-container or a set of PI-containers. It is equivalent to modular data encapsulation within Digital Internet. Based on the “pallet-wide” (PW) container which is an intermodal transport unit used in Europe, Sarraj et al. (2014) proposed a set of modular containers with different sizes $2.4\text{m} \times 2.4\text{m} \times \{1.2, 2.4, 3.6, 4.8, 6, 12\}\text{m}$. Given the set of PI modular container sizes, the containerization protocol first clusters orders to be shipped within the same period and heading for the same destination, either the same final consignee or some common intermediate storage points. Then the selection of specific containers for every order is taken out in order to first minimize the number of containers used and second to maximize container space utilization with weight and volume constraints. This is done as presented in Figure 39.

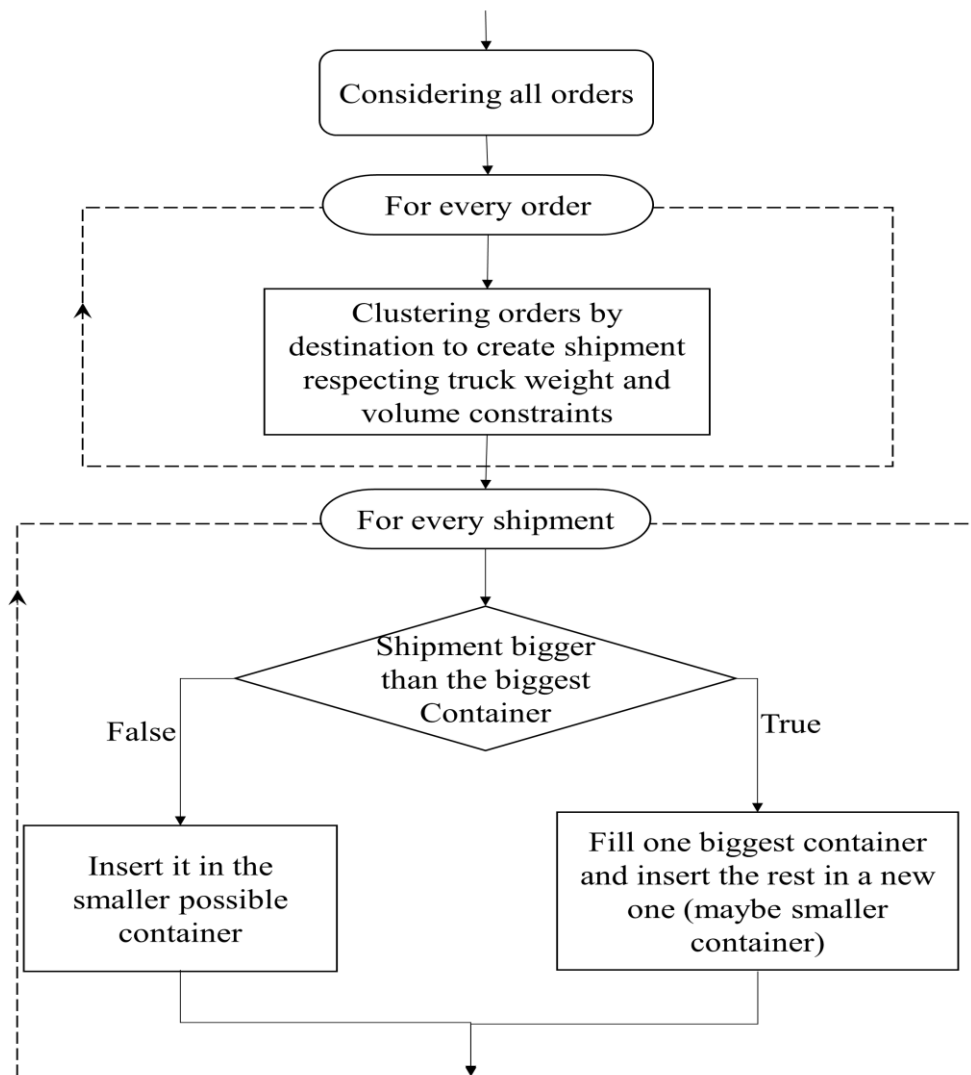


Figure 39. Goods consolidation protocol

7.2.2.2 Container routing

Routing is a key factor for network efficiency in both the Digital Internet and the PI. Based on the similarities and differences of Digital Internet and the PI, Sarraj et al. (2014) conclude the following important properties of PI routing protocols, see in Table 19.

Digital Internet	Physical Internet
Dynamic	Dynamic
Maintain a routing table at each node	Maintain routing tables at each node to deal with service updates and incoming flows
Hop-minimizing shortest approach	State-link routing approach
Focus on metrics, i.e. number of hops	Focus on metrics such as logistic costs
Delete data packets in case of delay	Change departure priorities or path in case of delay

Table 19. Difference in routing of datagram in Digital Internet and goods in PI

From their conclusion, we can see that the objectives differ significantly from one to another. This is explained as the negligible data transportation cost in Digital Internet. And in the PI, every freight operation occurs transportation and handling costs. A routing algorithm in a logistic network may seek certain service levels at customers, minimization of total logistic costs, better use of scheduled transportation means, and etc. In our model, we use the following two minimization objectives for the routing of containers.

Routing objectives:

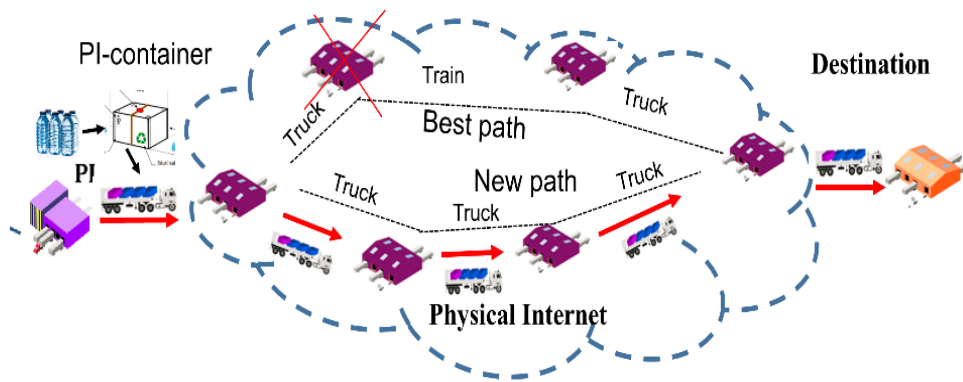
- 1) Total distance travelled from the source to the destination as it is related to the transportation cost and emission of gas emission.
- 2) Time, from the moment a container requests a departure until its arrival to the destination, including delivery time on road, handling time to load and unload from transportation means, and waiting time at facilities;

Disruptions mitigation strategies:

As there are disruptions at hubs, we extend the routing protocols with two different disruptions management strategies depicted in Figure 40. The first strategy called Disruptions Avoidance which avoids all the disrupted hubs for the routing. That is, if there is disrupted hubs in the path of the container, the container will route with another path without disruptions. This

strategy may mitigate the delay caused by disruptions but may augment logistic costs. Instead of avoiding all disrupted hubs, we proposed another disruption management strategy called Risk-taking. Under this strategy, the disrupted hubs will be considered with an estimated penalty time for the path finding. If the routing agent finds that disrupted path remains to be the best path according optimization criteria, then the containers will continue using the disrupted path and take risks. From the analysis, the strategy enables the routing agent to find global optimal routes but may also results in possible delay because of unpredictable long disruptions.

➤ Strategy 1: Disruptions avoidance – avoid all disrupted hubs.



➤ Strategy 2: Risk-taking – Consider a penalty during time for disrupted hubs.

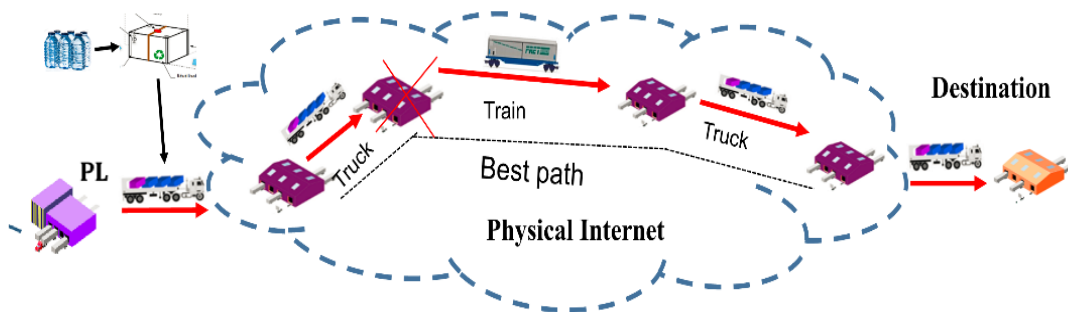


Figure 40. Disruptions protocols

Given the objective functions and disruption management strategies, we use a heuristic method to find real time routing solutions for containers as our problem is a large-scale problem. The A* algorithm (Dechter and Pearl 1985) is applied to find solutions in a reasonable time as our

case study covers a France nation-wide network of over 13, 000 arcs (roads and rails) and 500 nodes, and up to over a million containers to route concurrently. With this algorithm, each time a container arrives at a node, the best path till the destination will be find according to different objective functions and different disruption protocols.

7.2.2.3 Container consolidation on transportation means

Once the best paths for containers are outlined, the next step is to affect the containers to corresponding transportation means. At each node of the PI, there a set of scheduled or non-scheduled transportation means with time windows. Besides, the PI-containers arrive asynchronously at nodes. The objective of container consolidation protocol is to find the best fit transportation means for containers ready for departure as to minimize the number of transportation means while considering numbers of constraints such as the capacity and time windows of transportation means. Hence, it is a bounded Knapsack problem with time windows, which belongs to NP-hard problems. The complexity of the problem grows exponentially to the number of containers. To solve the problem, Brach-and-Bound algorithms are often used to find exact optimal solutions. For large-scale problems, approximation algorithms such as heuristic approaches are usually applied to find near-optimal solutions within a reasonable time. We apply the First Fit Decreasing (FFD) algorithm to this protocol which is demonstrated with efficiency in solving the problem by Sarraj et al. (2014). Knowing the crucial sorting criterion to the solution, the FFD method first sort the objects in a decreasing order by their size and then insert them into the first fit bins by order (Johnson et al. 1974).

7.3 Numerical Experiments

Given all the proposed transportation protocols, we build a multi-agent simulation model in *AnyLogic* to simulate the described PI-transportation system confronted to hubs' disruptions. To validate the proposed PI simulation model, we firstly used the same inputs and parameters to study performance of PI without disruptions as in Sarraj et al. (2014). After the validation of the model, we carry out numbers of numerical studies to investigate the performance of PI to different disruptions.

7.3.1 Input Data

7.3.1.1 Order flows and current supply network

We carry out numerical studies with a real industrial database of mass distribution in France. It consists of 12 weeks of distribution flows for 2 big retailers and their top106 common suppliers in 2006. The supply network includes 303 plants, 57 warehouses and 58 distribution centres all across France. The geographic position of facilities is specified by real longitude and latitude coordinates. The routes information between these facilities to hubs is registered in the ROUTE 120® IGN geographic information system in France, refer to Appendix. Three groups of FMCG goods are considered: liquids, grocery, and personal and home care products. In total, under current supply networks, there are 4451 flows, 2582692 full-pallets and 211167 orders of 702 kinds of products, which represents around 20% of the French FMCG market share for the considered family products (Sarraj et al. 2014). A view of current organisation of distribution flows is shown in Figure 41.

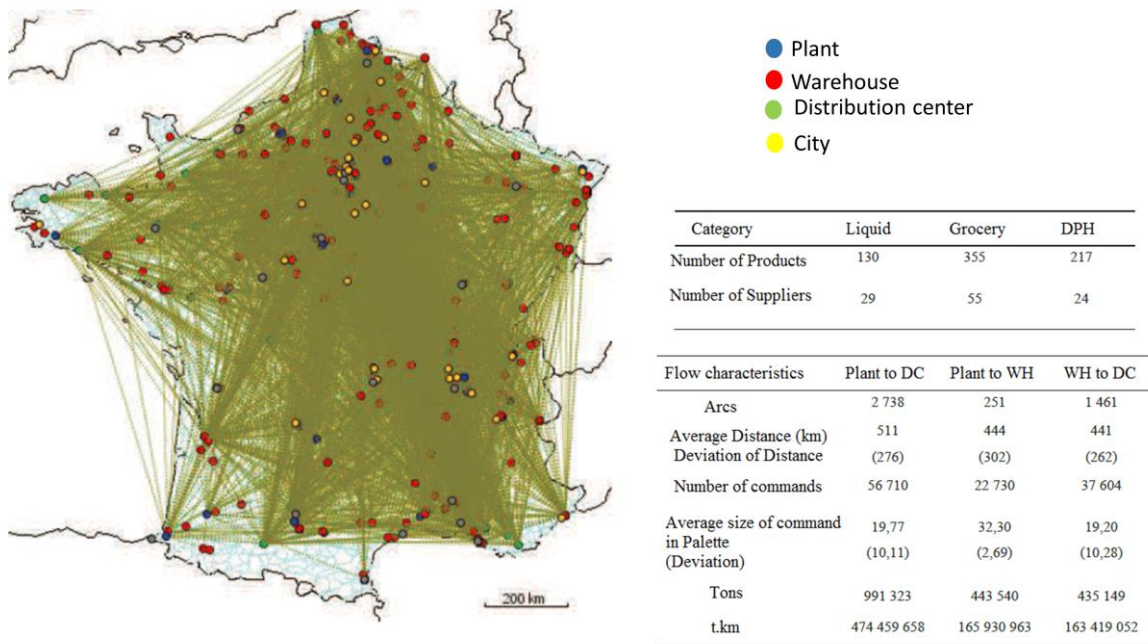


Figure 41. Distribution flows and inputs of current organisation

7.3.1.2 PI network

A PI network of 47 hubs is implanted in our model including 19 hubs offering multi-modal transportation (rail and road). This is an optimisation solution provided by Ballot, Gobet, and Montreuil (2012). An example of configuration of flows is presented in Figure 42. The PI-network is optimised according to a cost function with operation constraints such as maximum length of truck trips, and etc. More details can be found in the reference. Here we use it as an input for our model.



Figure 42. PI network, flow views by Ballot, Gobet, and Montreuil (2012)

7.3.1.3 Disruption profiles

Another important input is the disruption profiles. To compare the performance of PI to different types of disruptions, we use the disruption profiles offered by (Tomlin 2006; Snyder and Shen 2006a). The parameters and a brief description are provided in Table 20.

Index	Fail probability	Repair probability	Av. During (hour)	Max. During (hour)	Lost capacity of PI	Description
0	0%	100%	0	0	0%	No disruptions
1	1%	30%	3,2	20	3%	Rare, very long
2	5%	50%	1,99	14	9%	Rare, long
3	5%	70%	1,42	8	7%	Rare, mi-long
4	10%	50%	1,99	14	17%	Less frequent, long
5	10%	70%	1,43	8	13%	Less frequent, mi-long
6	20%	50%	1,99	14	29%	Frequent, long
7	20%	70%	1,43	8	22%	Frequent, mi-long
8	20%	90%	1,11	5	18%	Frequent, short

Table 20. Disruption profiles

With all these inputs, we take out numerical experiments on the multi-modal scenario (road and rail) as shown in Figure 43, where the PI is implanted in the current supply network.

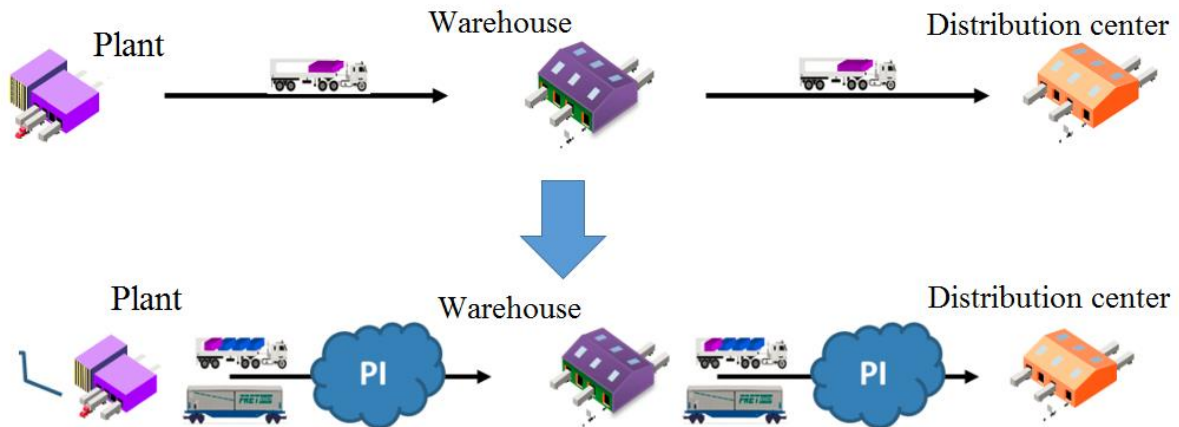


Figure 43. Current Supply network vs. Multi-modal PI transportation

7.3.2 Results analysis

Considering different disruptions (8 profiles), disruptions protocols (2) and routing criteria (2), thus we get 34 scenarios include the 2 scenarios with different routing criteria of the PI without disruptions. Please refer to Appendix for the initialisation of parameters. We use average lead time, total transport emission, and total logistics cost as the main KPIs to compare the performance of different scenarios. All the experimental tests are developed in *AnyLogic 6.8.0 University* on a PC with an Intel (R) Core (TM) i7-3940XM CPU 3.20 GHz and 32 Go RAM. Each simulation takes almost four hours' on the platform of *AnyLogic*. The results are grouped and recorded as shown in Figure 44.

Sce. Index	Chains Structure	Transport mean	Disruption profile	Disruption strategy	Routing Criteria	Average LT(hour)	CO ₂ (t)	Total Cost (M€)
0	PI-WH-DC	Truck	0	N/A	N/A	5.86	52 742	81.98
D.N.0	PI-PI-WH-PI-DC	Truck/train	0	N/A	Distance	7.62	30 544	66.206
D.A.1	PI-PI-WH-PI-DC	Truck/train	1	Avoidance	Distance	7.8	30 925	66.526
D.R.1	PI-PI-WH-PI-DC	Truck/train	1	Risk taking	Distance	8.51	31 520	67.439
T.N.0	PI-PI-WH-PI-DC	Truck/train	0	N/A	Time	7.36	33 356	67.735
T.A.1	PI-PI-WH-PI-DC	Truck/train	1	Avoidance	Time	7.5	33 436	67.867
T.R.1	PI-PI-WH-PI-DC	Truck/train	1	Risk taking	Time	7.9	34 741	69.614

Note: PI: plant, WH: warehouse, DC: distribution center, PI: Physical Internet, N/A: no action
Scenario index: (Routing criteria. Disruption strategy. Disruption profile)

Figure 44. Parts of results

As shown in picture, we use (Routing criteria. Disruption strategy. Disruption profile) to index scenarios. The scenario 0 represents current supply network without using PI. The scenario D.N.0 depicts the scenario using the PI without disruption where the routing criteria is the minimization of travel distance. The scenario D.A.1 depicts the scenario in the PI with disruption profile 1 and where the routing criteria is the minimization of travel distance. The same logic goes for the index of the other scenarios.

We firstly compare the results of scenarios without disruptions in our model to the results of (Sarraj et al. 2014) in order to validate our model. Then, these scenarios without disruptions in PI are used as baselines for the other scenarios with disruptions. For the KPIs of total emission of CO₂ and total logistics cost, we use the performance ratios to represent the results, which is

calculated by $(A-B)/B$ if we compare scenario A to scenario B. For the performance indicator of average lead time, we use the difference of absolute value between the two scenarios as the maximum average lead time is within 10 hours. In the rest of this section, we will present the results according to different KPIs.

7.3.2.1 Total logistic cost

Figure 45 and Figure 46 present the performance ratios of the total logistic cost of scenarios in PI with disruptions compared with scenarios without disruptions. From the figure, we can see that the disruptions result in augmentation of total logistic cost. However, the maximum augmentation of the total logistics cost is only 4% compared to 29% loss of capacity in PI hubs. Here the loss of capacity refers to the percentage of hours disrupted at hubs all around the PI. For example, 29% loss of capacity means each hour there is 29% of the hubs are disrupted and unserviceable. To look insight into the augmentation, Figure 47 describes the results of scenarios with Risk-Taking strategy under minimisation of distance criteria. From the figure, we conclude that the augmentation of total logistic cost is mainly come from the transportation cost of trucks and additional energy consumption cost. This is explained by increased number of “urgent” containers delayed by disruptions which will demand emergent delivery after disruptions.

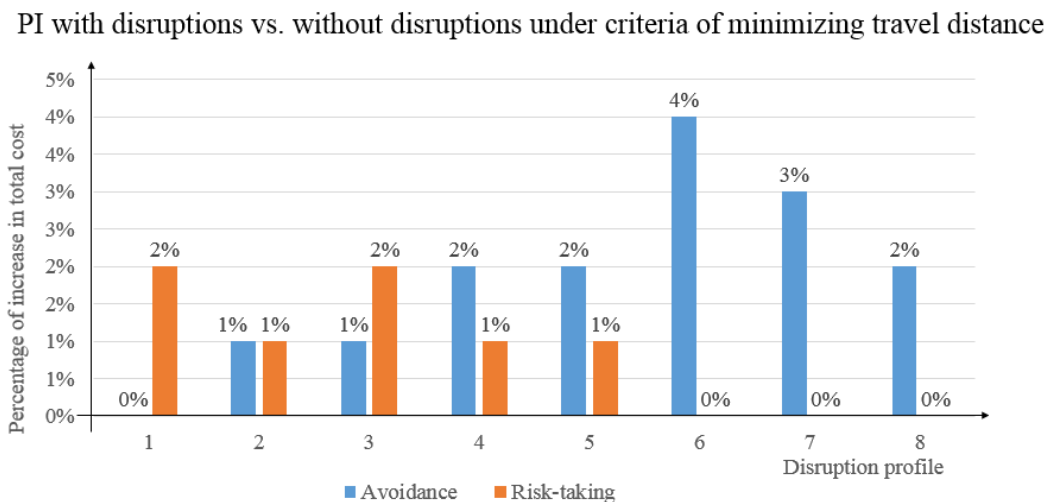


Figure 45. Performance ratios of Total logistic cost: PI with disruptions vs. PI without disruptions under minimisation of total distance

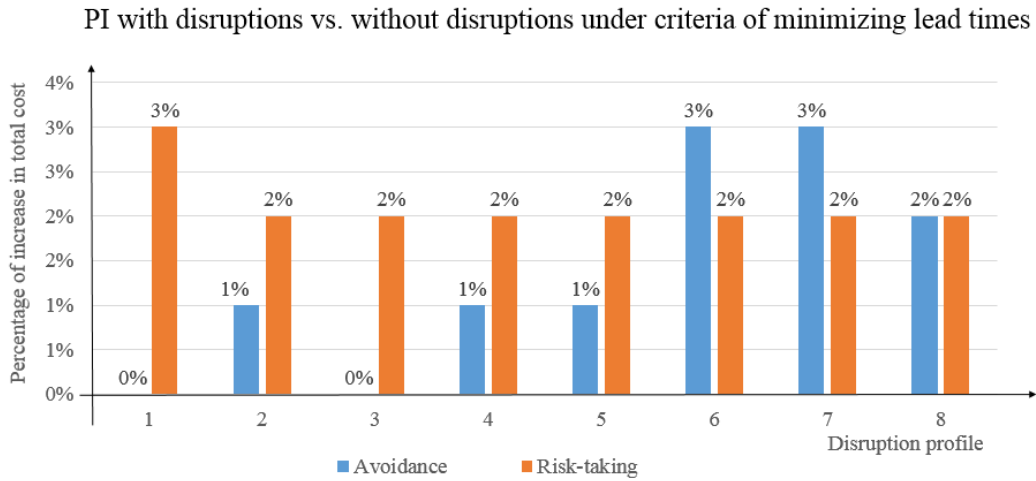


Figure 46. Performance ratios of Total logistic cost: PI with disruptions vs. PI without disruptions under minimisation of lead times

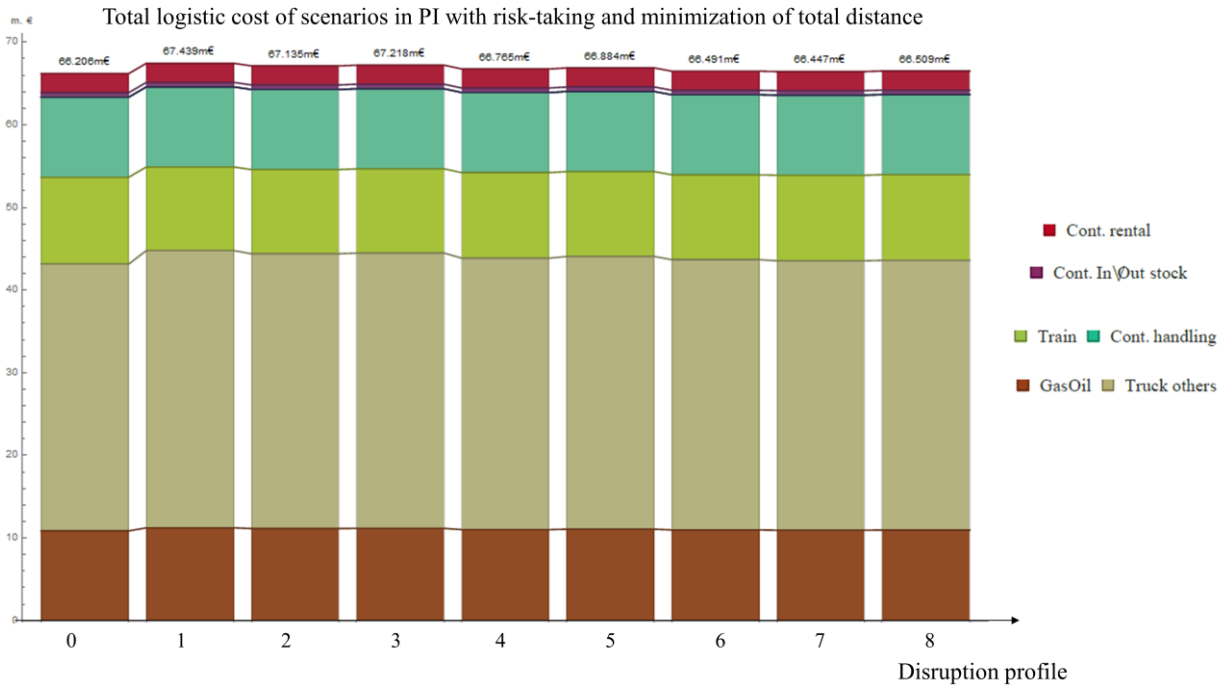


Figure 47. Total logistic cost in scenarios with Risk-taking and Minimisation of distance

Comparing the performance of two disruptions strategies, we can see that the avoidance strategy outperforms the risk-taking strategy with disruptions which are rare and last long. In reverse, when the disruption becomes more frequent, it's better to take the risk-taking disruption strategy.

7.3.2.2 Total emission of CO₂

Figure 48 gives an illustration of performance ratios for this performance indicator. In general, we find that the disruptions result in additional emission of CO₂ and the increase in CO₂ augment with the loss of capacity in PI. When averagely 29% of the hubs become regularly unserviceable, the total emission of CO₂ will increase 10% compared to scenario where hubs are always functioning. Besides, with minimisation routing criteria of distance, the risk-taking disruption mitigation strategy outperforms the avoidance strategy. Under minimisation routing criteria of lead time of containers, we observe the same trends as for the KPI of total logistic cost: the avoidance strategy outperforms the risk-taking strategy for rare long disruptions and the risk-taking strategy has a better performance for frequent disruptions.

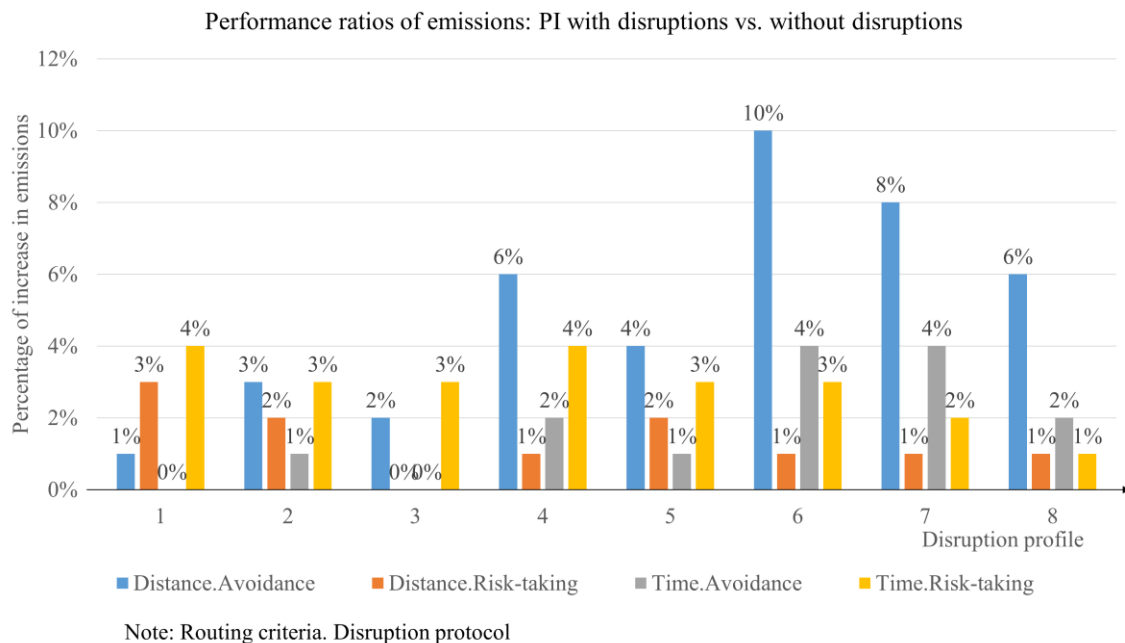


Figure 48. Performance ratios of total emission of CO₂

7.3.2.3 Average lead time of PI-containers

From the average lead time aspect, the PI-containers routing in the PI with disruptions will be delayed by the interruptions. However, the maximum average delay caused by the 29% regular loss of capacity in PI is only 1.83 hours over 8 hours in scenario without disruptions, as shown in Figure 49. Furthermore, under this KPI, the avoidance strategy dominantly outperforms the risk-taking strategy as it avoids all the disruptions in the routing.

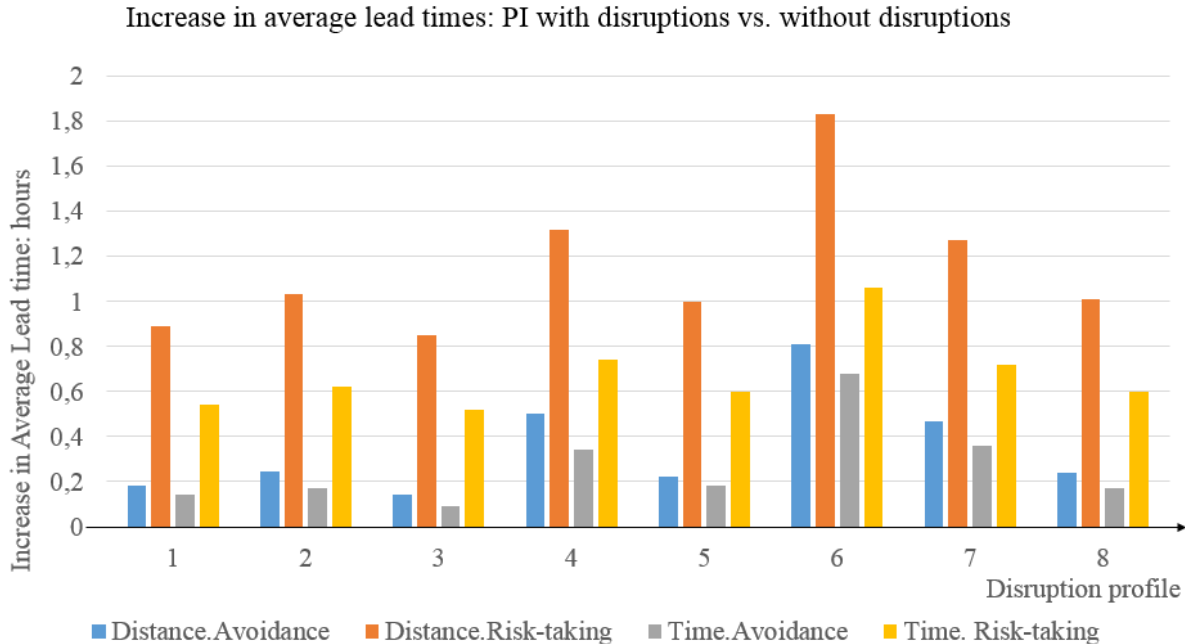


Figure 49. Increase in average lead times

7.4 Conclusion

In conclusion, we find that the disruption will cause maximum 4% additional total logistic cost, 10% additional total CO2 emission and 1,83 over 8 hours' delay of delivery of containers compared to 29% regular unserviceable time in PI hubs. That is, if customers accept 1.83 hours' delay, the performance of PI is rarely perturbed. In addition, Table 21 gives a conclusion of dominant disruption strategy to different scenarios. From the table, we find that there exists no one optimal protocol. It depends on the nature of disruptions as well as the objectives of services. For

example, if customers expect shorter lead times, it's better to adapt avoidance strategy and minimisation of time as the routing criteria. If the network is exposed with frequent random disruptions at hubs such as machine breakdowns, the transportation protocols with risk-taking strategy may result in less expenses and emission on disruptions.

In a word, in this exploration work, we studied the resilience of transportation system applying PI confronted to disruptions at hubs. And from the results, with dynamic transportation protocols, the performance of PI is rarely perturbed compared to the loss of capacity caused by disruptions. Hence, there is no doubt that the PI is a resilient system.

Routing Criteria KPIs	Distance			Time		
	Total cost	Lead time	CO ₂	Total cost	Lead time	CO ₂
Disruption profiles						
Rare, very long	A	A	A	A	A	A
Rare, long	A	A	R	A	A	A
Rare, mi-long	A	A	R	A	A	A
Less frequent, long	R	A	R	A	A	A
Less frequent, mi-long	R	A	R	A	A	A
Frequent, long	R	A	R	R	A	R
Frequent, mi-long	R	A	R	R	A	R
Frequent, short	R	A	R	R	A	R

Note: A – Avoidance, R – Risk taking

Table 21. Dominant disruption strategies

Future researches are required to study a comprehensive disruption profile as our study covers only certain categories of disruptions events. Another research stream is also required to integrate shippers' management strategies in the simulator, for example, the inventory management strategies of shippers as well as the priorities study.

Chapter 8. Conclusions and perspectives

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This chapter gives a synthesis of the main contributions of this dissertation, followed by a discussion of the limits in this research work. This chapter finishes with future perspectives to bring Physical Internet (PI) in reality.

8.1 Summary of the Dissertation

This thesis intends to study logistics models that take advantage of interconnected logistics services and which are more open, flexible and horizontally interconnected, in order to improve the efficiency, effectiveness and resilience of supply chain system. The Physical Internet (PI) is an innovative logistic concept based on interconnection of logistics networks and aims to integrate current logistics networks in an open global logistic system through modular containers, and standardized interfaces and protocols. Under this context, we use the PI as an example of interconnection of logistics networks though there exist other forms. We focus our study on two major activities in SCM: inventory management and transportation. Hence, the objective of this research is to investigate perspectives of the PI in inventory management and transportation to the arising challenges in efficiency, effectiveness and resilience. According to these different challenges of SCM, we grouped our research into two parts: Part I analysing the efficiency and effectiveness, and Part II examining the resilience. However, as the study about the efficiency and effectiveness of PI enabled transportation model has been already done by Sarraj (2013), we discussed the efficiency and effectiveness of PI enabled inventory control models in Part I.

In order to examine the perspectives of the PI to inventory management, we firstly analysed the inventory management in the literature as to outline the inventory problems in the PI and the new practices brought by the PI to inventory management. From the analysis, we found that the distribution network in the PI is an interconnected network of open hubs instead of multi-echelon hierarchical supply network with specialized facilities in current logistics system. Besides, in such a universal logistic system, the facilities and means of transportation are shared and can be dynamically allocated to the demands of each user including suppliers and retailers either in long or short terms. Hence the inventory decisions in PI were concluded as where, when and how much to place and satisfy order other than when and how much in classic inventory management decisions. Three main characteristics of PI enabled inventory models were outlined: 1) Possibility

of distributed stocks in hubs near end customers; 2) Transshipment of goods among hubs; and 3) multiple sources options for each order.

Then our study continued with a rule-based simulation model to quantitatively investigate the potential of the PI in reducing inventory levels around the network. (Q, R) inventory policy without backlog was used as our inventory management system. Three different categories of criteria were proposed in order to allow dynamic source selection when an order is placed in the PI: Source Substitution, Minimum Ratio and Minimum Sum. Numerical experiments in FMCG sector demonstrated that the PI inventory model with dynamic sourcing rules outperforms the classical inventory model for a given supply network.

With positive research feedbacks from the first step, we furthered this part of study by proposing an optimisation model, in order to quantitatively analyse the new practices and perspectives brought by the PI to inventory management. To this end, a situation where the vendors manage inventories in the PI was studied. Hence, it is an innovative “vendor managed inventory” strategy enabled by the PI. As replenishment decisions in PI are highly dynamic, i.e., sourcing point, order size, and reorder point are dynamic, a simulation-based optimization modelling method was used. To solve the model, a metaheuristic integrated with different sourcing strategies was developed. Numerical studies were carried out with data from FMCG industry. The results demonstrated that the PI inventory control model significantly outperforms current inventory model. Besides, the configurations of distribution flows may either be centralised or decentralised, or a combination of both according to different sets of logistics costs and different objectives of users. In addition, the distribution flows can quickly adapt to the economic environment if needed. They are dynamically determined according to the real time status of the network such as inventory levels of other hubs as well as the objectives of the vendors. More importantly, the results demonstrated that the PI facilitates the suppliers to rebalance and reallocate their stocks just near their consignees, which is a big difference from today’s supplier-customer’s relations. In conclusion, this part of study serves a guideline for the vendors of PI to how to distribute their products according to their objectives and economic climate, and as a guideline for the logistics service providers of the PI to develop inventory protocols.

Continuing the research stream, the second part of our research addressed the resilience of PI enabled logistics models confronted to supply chain disruptions. The objective of this part is

two folds: 1) Analyse whether applying the PI can help companies to improve the resilience of their supply chains; 2) Define and analyse the concept of resilience in the PI itself. To this end, we separated our study into two parts. Firstly, we extended the previous proposed inventory model with random disruptions at plants and hubs. We aimed to answer the question whether applying the PI can help the vendors to improve the resilience of their inventory system in face of disruptions. To validate the extended model, previous FMCG data were used with different disruptions profiles from the literature. From numerical experiments, we found that the frequent disruptions would lead to decentralised stocks around the network and frequent interactions among PI hubs. Besides, applying the PI inventory helps companies improving their resilience in reducing disruptions risks. The benefits are mainly from the increased agility, flexibility and multiple delivery options enabled by the open interconnected logistics services. This part of study indicates a new method for companies to build resilient supply chains.

Finally, a study about the resilience of the PI itself followed. Based on the literature, we defined the resilience of PI as the capacity of this open interconnected logistic system confronted to disruptions at hubs. To quantitatively study the resilience of the PI, we developed an extension of PI transportations protocols by Sarraj et al. (2014) with random disruptions at hubs. In face of disruptions, two different disruptions mitigation protocols were proposed and integrated. To validate the proposed model, a simulation was carried out with real industrial data in FMCG in France and different disruptions profiles by the literature. Results suggested that the disruptions at hubs result in increased total logistic cost, increased lead time for containers, and augmented emission of CO₂. However, the perturbation of performance of PI is much less than the loss of capacity in the PI caused by the disruptions. For example, the most frequent disruption caused regularly to 29% regular loss of capacity in the PI but only maximum 4% additional total logistic cost, 10% additional total CO₂ emissions and 1,83 over 8 hours' delay of delivery of containers. Hence, these results indicated that the PI is a resilient system to disruptions. Besides, we found that there exists no dominant optimal disruption or routing protocols. The optimality of protocols, which determines the logistics operations, depends on the nature of disruptions as well as the objectives of services. For example, if customers expect quick delivery, it's better to adapt avoidance strategy and minimisation of travel time as the routing criteria. If the network is exposed with frequent random disruptions at hubs such as machine breakdowns, the transportation protocols

with risk-taking strategy will result in less expenses and emission on disruptions. In conclusion, the part of study defines the concept of resilience in the PI and gives a guideline for the providers of PI to develop disruptions mitigation protocols to improve the resilience of PI.

In a word, this research work studies the inventory management in the Physical Internet and the resilience of Physical Internet enabled logistics models. It is the first time such a work is done and it should be upfront for the research of inventory management and resilience in such an open logistic system. From the results of studies, there is no doubt that the Physical Internet changes today's supply chains design and improve the performance of supply chain management both in efficiency and resilience.

8.2 Principal limits

The limits of this research work are concluded into the following three parts: limits of modelling, limits of scale of numerical studies and limits of solution methods and solutions.

8.2.1 Limits of modelling

Firstly, the proposed PI enabled logistics models are based on numbers of assumptions. Only the most sensitive factors to the optimization problem were considered such as the value of products. To simplify the problem, several constraints were not considered in our models such as the capacity of production of the plants and the stocking capacity of PI hubs. The lead times from the intermediate stocking points to points of sales are assumed to be identical. Besides, for the proposed inventory control model, only one vendor was considered. Nevertheless, if these assumptions change, new research questions will arise such as the priority and allocation of stocking capacity of PI hubs.

Furthermore, though the PI enabled inventory system and transportation system examined in this work, we haven't integrated both in one logistic system. The proposed PI inventory control model haven't integrated the other PI elements such as containerization protocols and routing protocols. To simplify the model, we used cost functions to represent the cost of these operations. For example, a transportation function was assumed to model the transportation cost in the PI instead of having real transportation cost by applying PI transportation protocols. However, sometimes, these cost functions would underestimate or overestimate the real costs. Jointly

considering both inventory control model with PI transportation protocols will better estimate the real cost of PI logistic system.

8.2.2 Limits of scale of numerical studies

The results obtained in this work are restricted by the limited scale of numerical studies. For example, for the proposed inventory model, numerical studies with one vendor were tested. The advantages and interactions among PI hubs are limited by the geometry of the network and the small number of consignees and vendors in the joint logistics areas. Big numbers of PI users in a large joint logistics area would lead to significant changes in the distribution schemes with much more interactions among hubs. Besides, for the study of resilience, limited representative disruptions profiles were examined. A Benchmark example will be needed to better compare the performance of proposed PI logistics models to current organisations with current resilience strategies.

8.2.3 Limits of solutions methods and solutions

Metaheuristic methods were used as to have relatively rapid and good solutions for the optimisation problems such as simulated annealing used for the inventory optimization model, and the A* algorithm used for the routing problems in transportation system. To better study the optimality, other metaheuristics methods are needed.

Secondly, though the proposed inventory control model gives a feasible solution for the users of the PI, the proposed decision framework are based on Vendor Manged Inventory strategy and centralised decision making. This would lead to significant complexity of decision making with increased numbers of plants and hubs. Thus, in the future, decentralised decisions tools need to be developed. For example, autonomous adaptive inventory protocols might be a solution.

8.3 Perspectives

Our research indicates that applying the PI can be a solution to significantly improve the efficiency of inventory management and the resilience of supply chains. The proposed VMI models can be applied to current platforms or logistics networks interconnected to certain degrees. For example, for the vendors or suppliers using the open warehousing platforms such as offered by the

Flexe.com or Stockbooking.com. Further studies are needed to develop control models for the buyers or retailers who control the stocks in the open network and who own or not the physical points of sales such as Amazon. Besides, to implement the proposed models, several challenges remain and further studies are needed such as managerial issues, information systems and operational models. This section discusses the following three main challenges to realise the PI.

8.3.1 Technological Innovation

Here we cite the following main technological innovations required by the implementation of the PI.

- 1) Design of smart modular containers. In the PI, goods will be embedded in modular standard and smart containers equipped with “smart” technology that enables the information of goods inside precisely tracked and monitored. Studies are needed as to define the containers, their functions, capabilities, etc.
- 2) Design of handling tools. New handling mechanisms corresponding to the use of containers must be developed as to efficiently and effectively load, transfer, convey and store containers.
- 3) Design of open shared infrastructures. The design of open infrastructure such as shared logistics centres will have to comply with system’s requirements.
- 4) Communicating information. The concept of PI is based on the interconnection of networks which results in an exchange of information flows to support the physical operations and flows. Thus, the supportive information system requires to be examined such as application of Internet of Things which connects physical objects to the Internet, smart data capture technology, robust and confidential information management system.

8.3.2 Organisational challenges

The concept of PI proposes a radical change in organisational management to companies:

- 1) Certified standardized environment. The networking of operations in diverse nature conducted by different independent stakeholders could lead to numerous problems of disagreement and misunderstanding, which will degrade the overall quality of the

PI. Thus, standardized certifications are needed as to reduce disputes by “speaking authentic language” when communicating.

- 2) Standardized protocols for interoperability processes. Standardized protocols are necessary to elaborate contracts among different actors as to facilitate and secure the exchange of flows.
- 3) Repositioning of stakeholders. The implementation of the PI may require companies refocus on a specialisation to the detriment, i.e. of coverage of a territory. Companies will have to redefine the competitive landscape as they join forces with other enterprises – including their rivals – to develop the PI. In fact, this movement has been already in progress in urban logistics where specialist service providers are positioning themselves to complement other offers with which they must interface in a certain way.

8.3.3 Culture change

Last but not most importantly, the biggest difficulty to adopt such an open global system lies on the change of culture: the fear of losing a competitive advantage or sharing a gain with competitors.

Besides, as discussed in the context of this research work, logistics has been so far considered as a concrete activity. Companies take out logistics activities with their own resources in their owned logistics facilities. Even if a part of logistics activities is outsourced, its scope is known and managed. The concept of the PI eliminates this aspect. The logistics activities are considered as “virtual” logistics services provided by the same or different logistics operators. Companies pay and use the abonnement of logistics services rather than own the resources. This change is theoretically difficult though the abonnement of logistics services will guarantee the same availability of resources even with more options. However, there exist encouraging examples from other domains, such as the success of the music site SPOTIFY.COM. Instead of owning the tapes or CDs, the SPOTIFY.COM proposed an abonnement of music listening services which offers more options of choices and is more ecological.

In a word, to survive from a vulnerable competitive economic environment and to make their supply chain more efficient and resilient, companies are highly encouraged and required to participate in the development of the Physical Internet.

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Appendix

Appendix 1: The routes information of ROUTE 120® IGN geographic information system in France is used for the PI transportation simulation in Chapter 7. The multi-modal (rail-road) stations presented in the following figure are applied.

NOM GARE MARCHANDISE	CODE POSTAL	TERMINAL TRANSPORT COMBINE	LATITUDE	LONGITUDE	LIAISON 1	LIAISON 2	LIAISON 3	LIAISON 4	LIAISON 5	LIAISON 6
AMBERIEU	1500		45,95	5,2833	VENISSIEUX	MACON	GRENOBLE	DIJON		
AMIENS	80000		49,9	2,3	DOURGES	DUNKERQUE	LE BOURGET	REIMS	SOTTEVILLE	
AVIGNON	84000	OUI	43,9483	4,8089	MIRAMAS	BEZIERS	BADAN GIOVRS VILLE	GRENOBLE		
BADAN GIOVRS VILLE	69520		45,6167	4,7833	VENISSIEUX	SAINT ETIENNE CHATEAUCREUX	AVIGNON	GRENOBLE		
BEZIERS	34500	OUI	43,4018	3,6966	AVIGNON	MIRAMAS	TOULOUSE ST JORY	ISSOIRE	PERPIGNAN	
BRETIQNY	91220		48,6167	2,3167	FLEURY LES AUBRAIS	JUVISY				
CAEN	14000		49,1859	-0,3591	SOTTEVILLE	LE MANS	GENNEVILLIERS			
CANNES	6150		43,5513	7,0128	MARSEILLE CANET					
CHAGNY	71150		46,9108	4,75333	GEVREY	NEVERS	MACON			
CLERMONT- FERRAND	63000	OUI	45,7833	3,0833	RIOM	ISSOIRE	SAINT ETIENNE CHATEAUCREUX	LIMOGES		
COGNAC	16100	OUI	45,7	-0,35	HOURCADE	POITIERS				
DIJON	21000		47,3167	5,0167	NANCY CHAMPAGNEULLES	MULHOUSE NORD	GEVREY	AMBERIEU	JUVISY	VALENTON
DOURGES	62119	OUI	50,4333	2,9833	SOMAIN	DUNKERQUE	LE BOURGET			
DUNKERQUE	59140		51,05	2,3667	SOMAIN	DOURGES	AMIENS			
EPINAL	88000		48,2333	6,55	NANCY CHAMPAGNEULLES	MULHOUSE NORD				
FLEURY LES AUBRAIS	45400	OUI	47,9667	1,9667	SAINT PIERRE DES CORPS	VERZON	BRETIQNY			
GENNEVILLIERS	95100		48,95	2,25	SOTTEVILLE	VERSAILLES CHANTIER	LE BOURGET	CAEN		
GEVREY	21220	OUI	47,2333	4,9	DIJON	CHAGNY				
GRENOBLE	38000		45,1667	5,7167	AVIGNON	AMBERIEU	SAINT JEAN DE MAURIENNE			
HAUSBERGEN	67200		48,5834	7,743	WOIPPY	MULHOUSE NORD	NANCY CHAMPAGNEULLES			
HENDAYE	64700	OUI	43,35	-1,75	HOURCADE					
HOURCADE	33130		44,8	-0,5333	HENDAYE	TOULOUSE ST JORY	COGNAC			
ISSOIRE	63500		45,55	3,25	BEZIERS					
JUVISY	91260		48,693	2,377	BRETIQNY	VERSAILLES CHANTIER	DIJON	VALENTON		
LA ROCHELLE	17000		46,1667	-1,15	POITIERS					
LE BOURGET	93350		48,9341	2,4358	GENNEVILLIERS	NOISY LE SEC	AMIENS	DOURGES		
LE HAVRE PLAINE	76600	OUI	49,4938	0,1077	SOTTEVILLE					
LE MANS	72000		48	0,2	RENNES	VERSAILLES CHANTIER	SAINT PIERRE DES CORPS	CAEN		
LIMOGES	87000		45,8315	1,2578	VERZON	TOULOUSE ST JORY	CLERMONT-FERRAND			
MACON	71000		46,35	4,8333	CHAGNY	VENISSIEUX	AMBERIEU			
MARSEILLE CANET	13001	OUI	43,2981	5,3841	CANNES	MIRAMAS				
MIRAMAS	13140	OUI	43,5833	5	MARSEILLE CANET	AVIGNON	BEZIERS			
MULHOUSE NORD	68100		47,75	7,3333	DIJON	HAUSBERGEN	EPINAL	EPINAL	REIMS	
NANCY CHAMPAGNEULLES	54000	OUI	48,6833	6,2	WOIPPY	HAUSBERGEN	DIJON			
NANTES	44000		47,2173	-1,5534	RENNES	SAINT PIERRE DES CORPS				
NEVERS	58000		46,9497	3,1481	VERZON	CHAGNY	RIOM			
NOISY-LE-SEC	93130	OUI	48,8915	2,4645	REIMS	LE BOURGET	VALENTON			
PERPIGNAN	66100	OUI	42,6976	2,8954	BEZIERS	HOURCADE	LA ROCHELLE			
POITIERS	86000		46,5833	0,3333	SAINT PIERRE DES CORPS	AMIENS	NANCY CHAMPAGNEULLES	WOIPPY		
REIMS	51100		49,25	4,0333	NOISY LE SEC	LE MANS				
RENNES	35700	OUI	48,0833	-1,6833	NANTES	NEVERS				
RIOM	63200		45,95	3,1333	CLERMONT-FERRAND	BADAN GIOVRS VILLE				
SAINT ETIENNE CHATEAUCREUX	42100		45,4333	4,4333	CLERMONT-FERRAND					
SAINT JEAN DE MAURIENNE	73300		45,25	6,2833	GRENOBLE					
SAINT PIERRE DES CORPS	37300	OUI	47,3522	0,6691	LE MANS	VERZON	NANTES	LIMOGES	FLEURY LES AUBRAIS	
SOMAIN	59490		50,3667	3,2833	DOURGES	DUNKERQUE	WOIPPY			
SOTTEVILLE	76500		49,4097	1,0901	LE HAVRE	GENNEVILLIERS	CAEN	AMIENS		
TOULOUSE ST-JORY	31790	OUI	43,7415	1,3709	LIMOGES	HOURCADE	BEZIERS			
VALENTON	94460	OUI	48,7667	2,45	JUVISY	NOISY LE SEC	DIJON			
VENISSIEUX	69200	OUI	45,6833	4,8833	MACON	BADAN GIOVRS VILLE	AMBERIEU			
VERSAILLES CHANTIER	78000		48,8	2,1333	LE MANS	JUVISY	GENNEVILLIERS			
VERZON	18100		47,2561	1,9357	FLEURY LES AUBRAIS	SAINT PIERRE DES CORPS	LIMOGES	NEVERS		
WOIPPY	57140		49,15	6,15	HAUSBERGEN	SOMAIN	NANCY CHAMPAGNEULLES	REIMS		

Figure 50. Multi-modal (Rail-Road) stations used in PI transportation model in Chapter 7

Appendix 2: Parameter settings of the transportation model in Chapter 7.

Name	Unity	Coef.Value	Coef.Value variable	Description
Road transport	Euro/ton-Km	0,11		unit cost
Rail transport	Euro/ton-Km	0,1		unit cost
Stock	Euro/ (day*cubic meter)	0,11		unit cost
Handling cost Type 1	Euro/handling/Container	10,4		unit cost
Handling cost Type 2	Euro/handling/Container	15,8		unit cost
Handling cost Type 3	Euro/handling/Container	21,2		unit cost
Handling cost Type 4	Euro/handling/Container	26,6		unit cost
Handling cost Type 5	Euro/handling/Container	32		unit cost
Handling cost Type 6	Euro/handling/Container	59		unit cost
Rail Consumption	KWH/Ton-km	0,022		Electricity
Rail emission	Kg CO2/Ton-Km	0,0035		
Road consumption per truck	litre/t-km		$0,297+0,005*t$ -km	littres of diesel by truck per t-km
Road emission per truck	Kg CO2/Ton-Km		$0,772+0,013*t$ -km	CO2 by truck per t-km
TruckWeightCapacity	kg	25000		
TruckVolumeCapacity	cubic meter	76,032		
TrainVolumeCapacity	cubic meter	456,192		
Transit	Euro/Container	0,26		unit cost
Inbound or Outbound Stock F1	Euro/Container Family 1	10		Unit cost $F1=2.4*2.4*(1.2, 2.4,..12)$
Inbound or Outbound Stock F2	Euro/Container Family 2	1		unit cost $F2=0.4*0.6*1.2$
Maximum waiting time	Hour	3		4,5h including 1h30 pour load/unload operation time

Table 22. Parameter settings of transportation model in Chapter 7

Résumé

Independent de la performance remarquable accomplie par la logistique d'aujourd'hui, les réseaux actuels sont majoritairement dédiés à un acteur et donc très peu interconnectés. Cette fragmentation conduit une difficulté de mutualisation des flux et dès lors à une efficacité limitée. Ces organisations dédiées et hétérogènes sont de plus en plus challengées par les nouveaux défis d'aujourd'hui posés à l'efficacité, l'efficience et la résilience. Pour répondre à cet antagonisme, un innovant concept logistique - l'Internet Physique (PI) - a été proposé. Dans ce système, les infrastructures et les moyens de transport peuvent être organisés de façon dynamique et attribués à court ou à long terme en fonction des besoins. Par conséquent, les décisions des opérations logistiques peuvent être prises de façon dynamique, agile, et donc de manière plus optimale. Cette thèse concentre les perspectives de PI concernant la gestion de stocks et du transport par rapport aux défis de l'efficacité et de la résilience.

Comme l'étude de l'efficacité de PI par rapport au transport a été déjà effectuée, le premier objectif de cette recherche est d'explorer les potentiels de l'interconnexion des réseaux dans la gestion de stocks, qui n'a par encore été adressé. À cette fin, nous examinons d'abord les trois nouvelles pratiques apportées par PI : 1) les stocks distribués à proximité des clients finaux; 2) le transbordement de stocks entre les hubs; 3) de multiples options dynamiques de sélection de la source pour chaque commande. Deux modèles de gestion de stocks correspondants sont proposés. Cette étude sert de guide pour des décisions de stockage pour les vendeurs dans un tel système logistique ouvert.

Après l'analyse d'efficacité de PI, la deuxième partie de cette thèse concerne la résilience des modèles de stockage et de transport dans PI confrontés à des interruptions dans la chaîne logistique. On a étendu les modèles de stockage et de transport avec interruptions imprévisibles dans les infrastructures telles que l'usine ou les hubs. Des stratégies différentes sont développées pour atténuer les risques de perturbation des flux. Des études numériques sont effectuées pour évaluer la performance des modèles proposés.

En résumé, cette recherche est la première qui étudie le potentiel de l'Internet Physique pour la gestion de stock et la résilience de ce système. D'après les résultats, il n'y a aucun doute que le PI change le design de chaîne logistique d'aujourd'hui et améliore la performance de gestion de logistique à la fois en efficience et en résilience.

Mots Clés : Internet Physique, Gestion de stock, Résilience, Interconnexion des réseaux logistiques, Transport, Interruptions de chaîne logistique

Abstract

Irrespective of significant performance achieved, today's logistics networks are overwhelmingly dedicated to an actor and therefore poorly interconnected. This fragmentation exhibits inevitable inefficiency and needs to be changed in respond to today's new arising challenges in efficiency and resilience. To solve this antagonism, an innovative concept - Physical Internet (PI) - has been proposed which is a fully interconnected, open, dynamic logistics system. In such a system, the facilities and means of transportation can be dynamically organized and allocated in the short-term or long-term according to the economic environment. As a result, decisions can be made dynamically, agilely, and thus optimally. This thesis studies the perspectives of the PI to inventory management and transportation regarding the challenges in efficiency and resilience.

As the efficiency of the PI to transportation has been carried out in literature, the first objective of this thesis is to explore the potentials of the PI to inventory management. To this end, we firstly qualitatively examine the new practices brought by the PI and conclude three main characteristics: 1) Distributed stocks near end customers; 2) Transshipment of inventories; and 3) multiple dynamic source options. Corresponding inventory models and solutions are proposed and evaluated with numerical experiments in Fast Moving Consumer Goods (FMCG). This part of study gives a guideline for the vendors applying the PI to make inventory decisions in such an open logistic system.

The second objective is to analyze the resilience of the proposed PI enabled inventory and transportation model confronted to disruptions. The proposed inventory and transportation model are extended with different disruptions at facilities including plants and hubs. Different disruption strategies are developed. Numerical studies in FMCG are carried out.

In a word, this research investigates the inventory management in the PI and the resilience of PI enabled logistics models. It is the first time such a work is done and it should be upfront. From the results of studies, there is no doubt that the PI changes today's supply chains design and improve the performance of supply chain management both in efficiency, effectiveness and resilience.

Keywords: Physical Internet, Inventory management, Supply Chain Resilience, Interconnection of logistics networks, Transportation, Supply Chain Disruptions