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Performance evaluation of interconnected logistics networks confronted to hub disruptions

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Abstract: *This paper investigates performance of interconnected logistics networks confronted to disruptions at hubs. With traditional supply chain network design, companies define and optimize their own logistics networks, resulting in current logistics systems being a set of independent heterogeneous logistics networks. The concept of PI aims to integrate independent logistics networks into a global, open, interconnected system. Prior research has shown that the new organization can reduce the actual transportation cost through the optimization of full truckload and integration of different transportation means. Continuing along these lines, this paper examines how PI deal with disruption problems at hubs and the resilience of a supply system applying PI. To attain this, we developed a multi-agent based simulation model with dynamic transportation protocols. Random disruptions at hubs are considered. Two different disruptions management strategies are proposed. Case studies of mass distribution in France have been taken out. Results suggest that the performance of PI is much less perturbed compared to loss of capacity caused by disruptions. This paper indicates a novel approach to build a resilient distribution system.*

Keywords: *Disruption, Physical Internet, Simulation, Routing*

1. INTRODUCTION

Nowadays companies are experiencing an ever diverse and changing environment - arising pressure from global competition, rapid technological change, shorter product life-cycles, increasing consumer expectations, and etc. Adapting to these challenges increased supply chain complexity and resulted in more instability and unpredictability. As such, recent research topics in supply chain management (SCM) emphasize the need to address the design of supply chains (SC) that are both efficient and resilient to supply chain disruptions (Sheffi, 2005, Tomlin, 2006, Christopher and Peck, 2004). SC disruptions refer to unplanned and unanticipated events that hamper the normal flow of goods and materials within a supply chain. As a consequence, SC disruptions expose firms within the supply chain to operational and financial risks. SC resilience is usually defined as the capacity of a supply chain system to adapt to disruptions (Christopher and Peck, 2004, Ponomarov and Holcomb, 2009). Hendricks and Singhal (2005) report that even minor disruptions might cause enormous long term negative impacts on financial performance. Recent example shows in supply disruption to Toyota's car production caused by the Japanese earthquake 2011 which has contributed to the company missing profits forecasts by £620 million (Supply Management Magazine). Another well-known example seen in 2000, the shut-down of Philips's microchips factory caused by a fire accident led to at least $400 million potential revenues to Ericsson, while Nokia managed to this disruption effect by alternative suppliers (Latour, 2001).

To protect against disruptions, various risk mitigation strategies have been proposed in the literature involving inventory redundancy (Groenevelt et al., 1992, Arreola-Risa and DeCroix, 1998), source/process flexibility (Tomlin, 2006, Simchi-Levi et al., 2013, Snyder and Shen, 2006), network design or facility location problems (FLP) (Snyder and Daskin, 2005, Cui et al., 2010), or enhancing contracts with external stakeholders such as buying insurance with unreliable suppliers (Gümüs et al., 2012). Previous studies have clearly proven the effectiveness and efficiency of these strategies. 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 paper assumes that this fixity and independence is an inherent limit of traditional SC networks when dealing with disruptions.

According to this assumption and following our previous study in PI, this paper aims to investigate the resilience of PI distribution system. The objective is to provide a quantitative study on the resilience of PI, which is defined as the capacity of this open interconnected logistic system confronted to disruptions at hubs to return to the status non-disrupted. 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. A multi-agent simulation model with dynamic transportation protocols is developed. 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 paper is organized as follows. In Section 2, we discuss the related works in the literature. In Section 3, the optimization model developed to PI inventory problem will be presented. Then, in Section 4 the optimization model will be implemented in case studies of FMCG chains. A number of scenarios are proposed and studied in order to validate the model and study the pertinence of model in different configuration of network. Finally, Section 5 concludes this paper by giving some perspectives to the next works.

2. LITERATURE REVIEW

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, 2005). 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 et al., 2011).

Recent comprehensive literature review about SC resilience can be found in four studies: Bhamra et al. (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 et al. (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). There are mainly four principles of SC resilience can be found in literature: SC Reengineering, Collaboration, Agility, and SC Risk Management (SCRM) culture, as seen in Figure 1. 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.

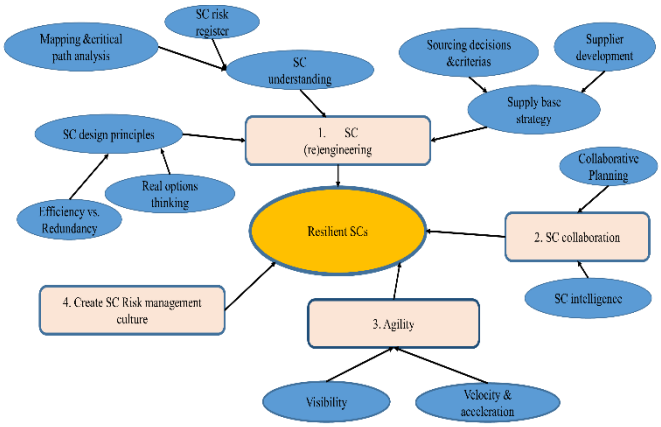


Figure 1. Supply Chain Resilience principles by Christopher and Peck (2004)

As 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: literature on improving supply chain flexibility and redundancy and 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 et al., 2010, Simchi-Levi et al., 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 et al., 1992, Arreola-Risa and DeCroix, 1998, Sheffi and Rice Jr, 2005). However, the distribution scheme of companies always remains the same except to increase inventory levels.

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 et al., 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 et al. (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, this paper 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 research.

Furthermore, the literature relating to PI has already looked at the efficiency problem, but never the problem of resilience and disruption. Sarraj et al. (2014) propose a simulation model of PI transportation system implemented with containerization and routing protocols. They study the transportation performance of PI 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. Pan et al. (2015) and Yang et al. (2015) study the efficiency of inventory models applying PI and demonstrate that PI inventory models with dynamic sourcing strategies outperform current inventory models, as PI enables more supply and replenishment options. However, the authors were unable to find a paper in the literature that examines the resilience of the proposed logistics models applying PI to SC disruptions. Therefore, it is a new research question and a new research topic with regard to PI and SC disruptions.

To address the question, this paper follows the same methodology used in the relevant work by Sarraj et al. (2014). Firstly, we describe the simulation model of PI transportation system confronted to disruptions at hubs, and next we evaluate the performance through a simulation study with real industrial database of mass distribution in France.

3. SIMULATION MODEL OF PI TRANSPORTATION SYSTEM CONFRONTED TO DISRUPRIONS

This paper 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, 2006). 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). After validation of the proposed model, numerical studies of different disruptions profiles and strategies will be taken out. Results of different scenarios are compared by the main KPIs to identify the impact of disruptions and the resilience of PI. An illustration of methodology is depicted in Figure 2.

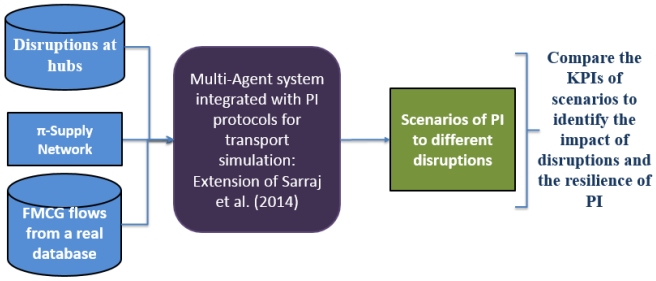


Figure 2. Methodology depiction

3.1 *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 et al., 2013, Snyder and Shen, 2006). Others use more general distributions such as Erlang distributions (Groenevelt et al., 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, 2006), 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), seen in Figure 3. 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.

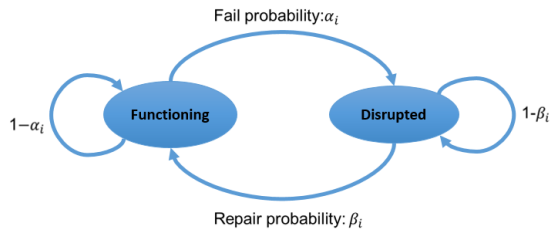


Figure 3. Disruption modelling

3.2 Transportation protocols in the PI

The diagram in Figure 4 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 5 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.

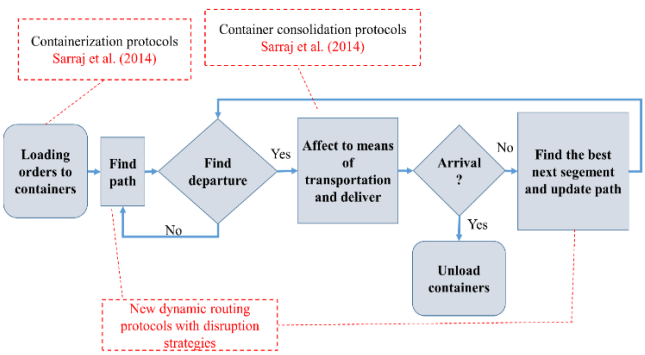


Figure 4. Goods shipping process in PI

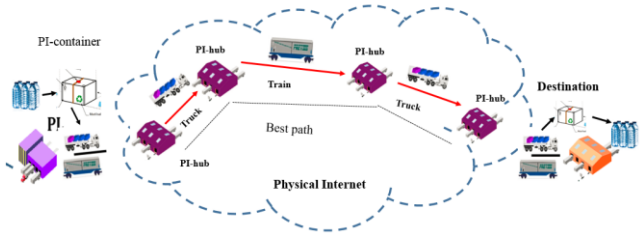


Figure 5. An example of shipping goods in PI

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 2.4m*2.4m*{1.2, 2.4, 3.6, 4.8, 6, 12}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 6.

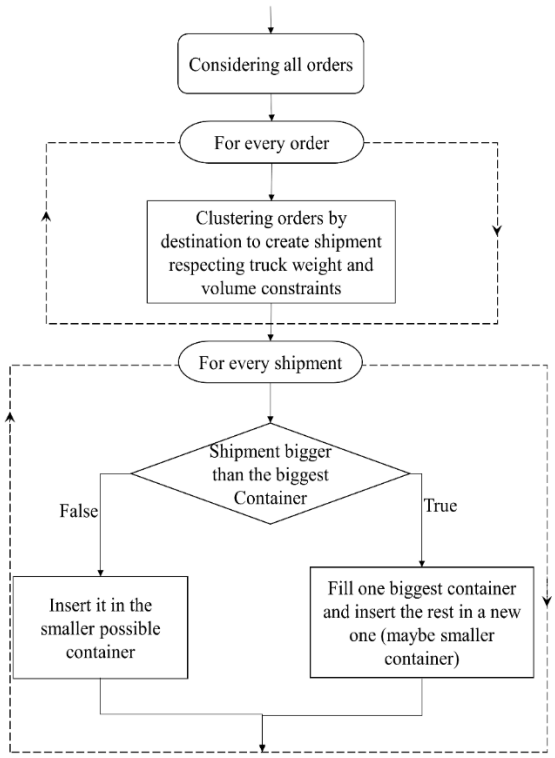


Figure 6. Goods consolidation protocol

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 1.

Table 1. Difference in routing of datagram in Digital Internet and goods in PI

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

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 7. 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.

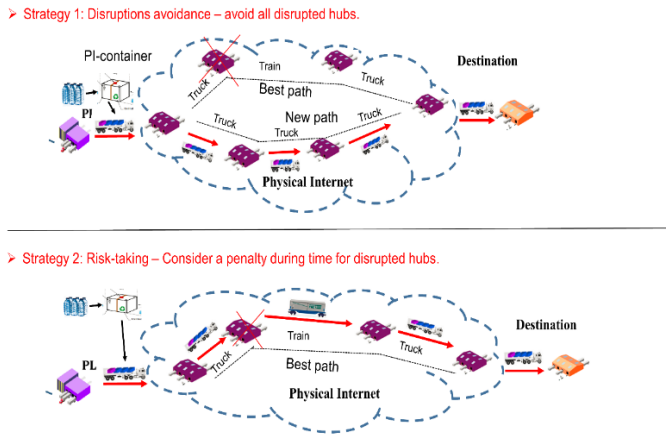


Figure 7. Disruptions protocols

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.

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).

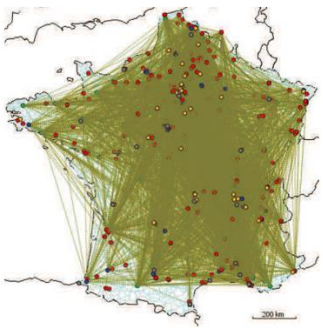
4. NUMERICAL EXPERIMENTS

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.

4.1 Input Data

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 8.



Category	Liquid	Grocery	DPH
Number of Products	130	355	217
Number of Suppliers	29	55	24

Flow characteristics	Plant to DC	Plant to WH	WH to DC
Arcs	2 738	251	1 461
Average Distance (km)	511	444	441
Deviation of Distance	(276)	(302)	(262)
Number of commands	56 710	22 730	37 604
Average size of command in Palette	19,77	32,30	19,20
(Deviation)	(10,11)	(2,69)	(10,78)
Tons	991 323	443 540	435 149
t.km	474 459 638	165 930 963	163 419 052

Figure 8. Distribution flows and inputs of current organisation

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 et al. (2012). An example of configuration of flows is presented in Figure 9. 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.

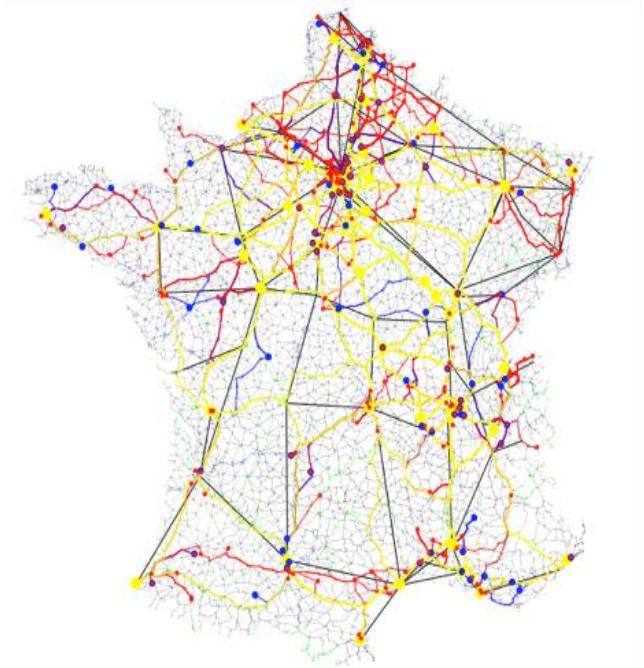


Figure 9. PI network, flow views by Ballot et al. (2012)

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, 2006). The parameters and a brief description are provided in Table 2.

Table 2. Disruption profiles

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

With all these inputs, we take out numerical experiments on the multi-modal scenario (road and rail) as shown in Figure 10, where the PI is implanted in the current supply network.

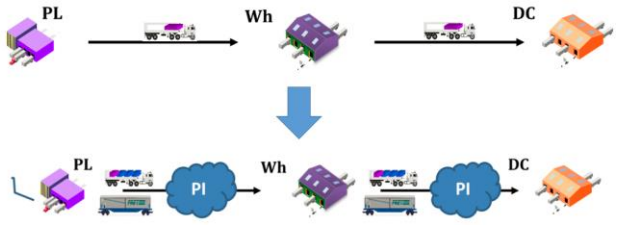


Figure 10. Current Supply network vs. Multi-modal PI transportation

4.2 Results analysis

Considering different disruptions (8 profiles), disruptions protocols (2) and routing criteria (2), thus we get 34 scenarios include the 2 scenarios of 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.

We compare the results of scenarios without disruptions in our model with the results of (Sarraj et al., 2014) to validate the 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. 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.

Total logistic cost

Figure 11 and Figure 12 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 hubs disrupted per hour 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 13 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.

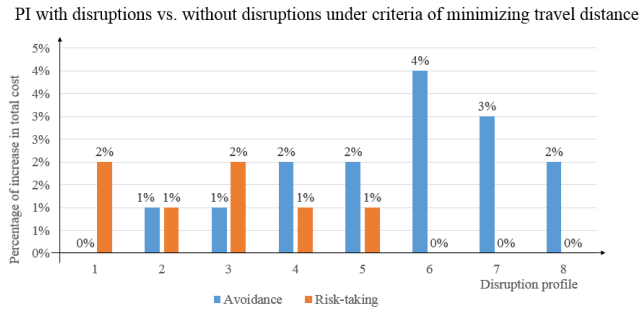


Figure 11. Performance ratios of Total logistic cost: PI with disruptions vs. PI without disruptions under minimisation of total distance

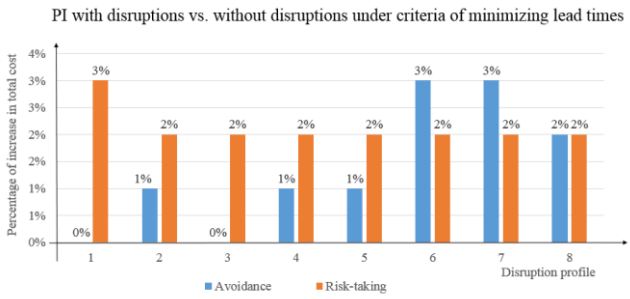


Figure 12. Performance ratios of Total logistic cost: PI with disruptions vs. PI without disruptions under minimisation of lead times

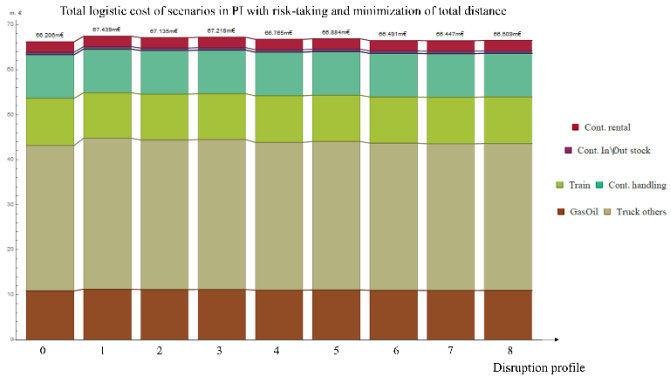


Figure 13. Total logistic cost in scenarios with Risk-taking and Minimisation of distance

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.

Total emission of CO2

Figure 14 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.

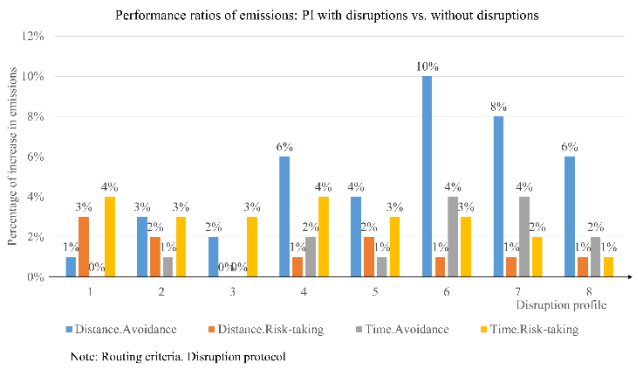


Figure 14. Performance ratios of total emission of CO2

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.

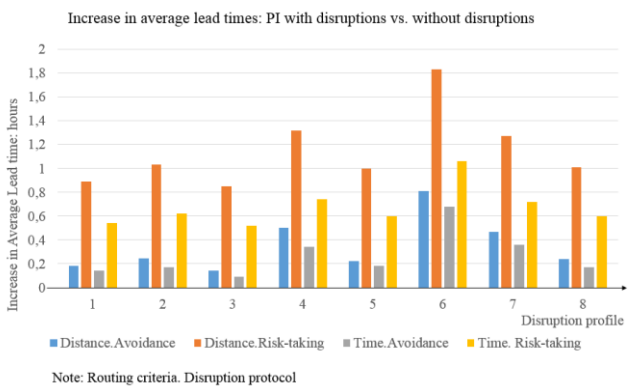


Figure 15. Increase in average lead time

5. 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 loss of capacity in PI. That is, if customers accept 1.83 hours' delay, the performance of PI is rarely perturbed. In addition, Table 3 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.

Table 3. Dominant disruption strategies

KPIs		Total cost	Lead time	CO2	Total cost	Lead time	CO2
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
Routing Criteria		Distance			Time		

Note: A – Avoidance, R – Risk taking

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.

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