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Freight Transportation Resilience Enabled by Physical Internet

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Abstract: This paper investigates the resilience of Physical Internet (PI) enabled freight transportation system confronted to random disruptions. As a metaphor of the digital internet, the concept of PI aims to integrate independent logistics networks into a global, open, interconnected system. Prior research shows that the new organization can reduce transportation cost through flow consolidation. Continuing along these lines, this paper examines how PI deal with disruption problems at hubs as well as the resilience of such an open logistics system. To attain this, a multi-agent based simulation model is developed. Disruptions at hubs are considered and formulated by a two-state Markov process, with a probability of breakdown α_i and a probability of repair β_i. Faced with the disruptions, two PI-based transportation planning strategies are proposed and investigated: risk avoidance and risk-taking. Results of experimentation on fast-moving consumer goods (FMCGs) chains in France suggest that PI can provide better performance on resilience in freight transportation. This paper also indicates a novel approach to build a resilient distribution system.

Keywords: Freight Transportation, Resilience, Physical Internet, Disruptions, Multi-agent Simulation

1. INTRODUCTION

Since nowadays supply chains (SC) are much more global and complex than ever before, resilience is becoming a more and more important topic in chain management (SCM) to deal with 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. Examples include earthquake, inundation, fire, strikes, etc. Hendricks and Singhal (2005) report that even minor disruptions might cause enormous long term negative impacts on financial performance. As a consequence, SC disruptions expose companies within the supply chain to operational and financial risks. SC resilience is usually defined as the *ability of a system to return to its original state after being disturbed* (Christopher and Peck, 2004, Kim et al., 2015b). Resilience is therefore used as the indicator to measure the performance of a supply chain or network to adapt to disruptions.

To protect against disruptions, various risk mitigation strategies have been proposed in the literature involving inventory redundancy, source/process flexibility network design or facility location problems (FLP, or enhancing contracts with external stakeholders such as buying insurance with unreliable suppliers. 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. By that, storage and distribution schemes of product flows are usually predefined and fixed, once the network has been designed. Disruptions to storage points or distribution schemes may disastrously interrupt the SC. Even though flexibility may exist within a company to cope with disruption, 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-enabled freight transportation system confronted to disruptions at hubs. Inspired by the metaphor of Digital Internet, the Physical Internet (PI) aims to integrate current heterogeneous logistics networks into an open, interconnected global logistic system through standardized modular containers and logistics protocols. In such systems, the nodes (e.g., WH - warehouse, DC - distribution center, hubs) 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 optimally. In this work, we are interested in the resilience performance of PI in terms of transport. We here define the resilience of PI as *the capacity of the open interconnected logistic system confronted to disruptions to return to the status non-disrupted*. Precisely, this work addresses the following questions: 1) how logistics players can use PI to improve the resilience in transportation? 2) what transportation planning strategies can be used in PI to improve resilience, and how they perform?

The contribution of this paper is to quantitatively investigate the resilience of PI and, thus, to indicate a novel approach to build a resilient distribution system. To this end, we extend the simulation model of PI transportation system in Sarraj et al. (2014). Differing from the latter study, this work aims to simulate disruptions in PI and some corresponding resilient

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strategies. More specifically, we consider random disruptions at hubs' level and formulate them by a two-state Markov process, with a probability of breakdown α_i and a probability of repair β_i. When the hub is disrupted, all the logistics services will become unserviceable. Accordingly, we propose two resilient transportation planning strategies called resilient routing protocols based on PI: risk avoidance and risk-taking. A new multi-agent simulation model is developed based on the model in Sarraj et al. (2014). We then experiment the model and protocols on FMCGs chains in France.

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). Four principles of resilience are found in recent comprehensive literature review by Kamalahmadi and Parast (2016): SC Reengineering, Collaboration, Agility, and SC Risk Management (SCRM) culture. As PI is a new logistic concept and reengineer current supply chain systems for the companies using it, our study falls into the scope of SC Reengineering aiming to create resilient supply chain systems.

Kamalahmadi and Parast (2016) outline two research streams to reengineer supply chains for the sake of resilience: improve supply chain flexibility and redundancy, and examination of impacts of main characteristics of the network to resilience. The flexibility for resilience refers to have multiple options to better respond to unplanned situations such as having flexible production systems or multiple suppliers (Tomlin, 2006, Schmitt, 2011). Though this flexibility enables the addition of new replenishment schemes in face of disruptions, the additional flexibility is 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 (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.

From the literature, we can find that all solutions to improve SC resilience are based on dedicated and independent logistics networks that are managed by one company or a small group of companies. Differently, this paper focuses on PI, a fully interconnected, open, dynamic logistics system. These kinds of systems and their resilience have been rarely addressed in the literature on SC disruption research. The literature relating to PI has already looked at the efficiency problem, but rarely paid attention to the problem of resilience and disruption in transportation. 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. (2016) 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. This paper can be seen as an extension of the previous study in Sarraj et al. (2014) that investigates transportation efficiency in PI without considering any disruption in the network.

3. MULTI-AGENT SIMULATION MODEL DESIGN

This paper investigates resilience of a PI-enabled transportation system by considering disruptions at hubs in PI. In other words, it is assumed that the hubs may have random unpredictable disruptions – at any time and for any length of time. When a disruption occurs at a hub, all the logistics services at this hub are paralyzed and unserviceable – it is impossible to receive or send goods until the disruption ends. To quantitatively analyse the problem, we extend the multi-agent simulation model of PI transportation system in Sarraj et al. (2014). We use the transportation network (the network of PI) and some parts of the transportation protocols