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A model of resilient supply chain network design: A two-stage programming with fuzzy shortest path

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ABSTRACT

A supply chain network design needs to consider the future probability of reconfiguration due to some problems of disaster or price changes. The objective of this article is to design a reconfigurable supply chain network by optimizing inventory allocation and transportation routing. A two-stage programming is composed according to Benders decomposition by allocating inventory in advance and anticipating the changes of transportation routings; thus the transportation routing is stochastic in nature. In addition, the fuzzy shortest path is developed to solve the problem complexity in terms of the multi-criteria of lead time and capacity with an efficient computational method. The results and analysis indicate that the proposed two-stage programming with fuzzy shortest path surpasses the performance of shortest path problem with time windows and capacity constraint (SPPTWCC) in terms of less computational time and CPU memory consumption. Finally, management decision-making is discussed among other concluding remarks.

1. Introduction

Supply chain (SC) network design requires not only robustness to cope with errors during execution, but also resilience as 'the ability of a system to return to its original state or move to a new, more desirable state after being disturbed', which demands a combination of flexibility and adaptability (Christopher & Peck, 2004). Thus, the term "risk" is introduced to signify the probability that the supply chain could be damaged. The risk comes from internal process, external demand, supply and control. There are abundant topics on internal process optimization and control: for instance, the introduction of radio frequency and identification (RFID) and vendor managed inventory (VMI) to increase SC visibility (Kristianto, Helo, Jiao, & Sandhu, 2012a; Lin, Chang, Hung, & Pai, 2010). On the other hand, while disruptions in the SC are realistic possibility that companies must address, there is lack of capability to capture them efficiently. Therefore a recovery logic by managing time and inventory as two buffers in the SC is the key to making a supply chain resilient (Schmitt & Singh, 2012).

The nature of resilient SC networks compared to other SC networks (i.e., agile and lean) presents its own set of challenges, which must be addressed effectively in order for a company to remain competitive. First, SC network design comprises several configurations of transportation routings to reduce the impact of a disruption if and when it occurs. Second, the whole scenario of SC network configurations must trade off efficiency and redundancy so as to accommodate the strategic disposition of additional capacity and/or inventory at potential 'pinch points' (Christopher & Peck, 2004). The additional surplus capacity provides more flexibility than inventory investment if the resilience is taken into consideration. The additional surplus capacity enables new location delivery for a new SC member whenever a disruption occurs. In that case production capacity changes are necessary to meet a new demand level.

Furthermore, there is an opportunity to improve SC velocity and acceleration by reducing inbound lead times and non-value added time. A study of dynamic facility layout problems (Dong, Wu, & Hou, 2009) provides a useful insight on using a multi-criteria decision of inventory, excess capacity allocation and transportation routings to allow potential 'pinch points' for improving supply chain velocity (Christopher & Peck, 2004). The multi-criteria decision provides supply chain robustness by generating capabilities of (1) reducing cost and/or improving customer satisfaction under normal circumstances, and (2) sustaining SC operations during and after a major disruption (Tang, 2006).

Considering the above mentioned important properties of SC resilient network design, previous contributions are available from operational to strategic level. On the strategic level, jointly capacitated facility location and transportation planning are optimized by using, for instance, a stochastic solution (Santoso, Ahmed, Goetschalckx, & Shapiro, 2005), path diversity design and flow restora-

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tion (Tomaszewski, Pioro, & Zotkiewicz, 2010). In general, these methods provide a backup plan in providing several solution scenarios if the primary networks are disrupted. On the tactical level, strategic inventory allocation under demand uncertainty (Kristianto, Gunasekaran, Helo, & Sandhu, 2012b) reduces safety stock placement (Christopher & Peck, 2004) by anticipating demand and supply uncertainties. Concurrently, multi-commodity distribution systems (Geoffrion & Graves, 1974) link the tactical and strategic planning. While the operational level planning could affect SC velocity and capacity, however, little attention paid to linking the operational to the strategic level. Among the few existing studies, for instance Kristianto, Helo, and Jiao (2012c) have designed reconfigurable production systems to increase the level of path diversity and flow restoration and therefore attain surplus capacity (Christopher & Peck, 2004). The solutions in the latest literature are not available for enterprise wide application so that other sources of SC network disruption, for instance non-reliable transportation lead times and suppliers are not considered in the solution. Therefore, the research gap has to be filled by designing an integrated multi-level resilient SC network for reducing the impact of a disruption by allocating additional capacity and/or inventory at potential pinch points efficiently, with or without reliable delivery and supply.

In considering the objective of the article, the following research questions (RQ) are raised:

1. (RQ1) How does resilient SC design reduce the impact of a disruption if and when it occurs?
2. (RQ2) How does resilient SC design trade off efficiency and redundancy so as to accommodate the strategic disposition of additional capacity and/or inventory at potential 'pinch points'?
3. (RQ3) In terms of allowing for potential 'pinch points', what is the key factor that influences supply chain velocity?

To address the above questions, the following sections are composed as follows: Section 2 identifies a solution strategy. Section 3 focuses on the shortest path problem with time windows and capacity constraint. Section 4 introduces two-stage programming. Section 5 examines the Benders decomposition for solving two-stage programming. Section 6 validates the models according to the problem example. Section 7 discusses the optimization result and provides managerial implications. Finally, Section 8 concludes the paper by giving future research directions based on research limitations.

2. Solution strategy

A comprehensive study of strategic network planning and the flow of goods in the networks need to be conducted also on a space and time basis (Goetschalcks & Fleischmann, 2002). On a spatial basis, the capability to expand or shrink the number of potential 'pinch points' is necessary to adapt the required level of capacity and or/inventory due to future potential disruptions. For example, during a situation where the supply location is relocated or the product specifications are changed due to a severe disaster or government regulation changes, the SC may choose a different geographical area of supply for up to the next 3 years. But if, starting in year four, another scenario of raw material scarcity and price changes occurs, the most economic production-distribution strategy may be to manufacture the products closer to the area of supplies (Goetschalcks & Fleischmann, 2002). The expanding or shrinking of the number of potential 'pinch points' has to be holistic, and it potentially becomes redundant without global optimization and considering the stochastic nature of resilient SC networks (Goetschalcks & Fleischmann, 2002). Thus, a two-stage optimization of structural and master planning is then used to maximize profit, customer service and flexibility at minimum risk.

In this regard, this paper proposes a two-stage approach to resilient SC network design. At the first stage, inventory allocation is scrutinized for meeting the different scenarios of excess capacity and total costs of the second stage. At the second stage, SC network design is constrained by total costs and time windows, which is formulated as a shortest path problem with time windows and capacity constraint (SPPTWCC). The Benders decomposition algorithm is applied to solve this optimal configuration problem owing to its high computational efficiency (Saharidis, Minoux, & Ierapetritou, 2010). Unlike the ordinary shortest path problem, which can be solved in polynomial time in graphs without negative cycles, the SPPTWCC is NP-hard due to the nonlinear relationship between time windows (TW) and capacity constraint (CC), and, as such, is believed not to be efficiently solvable.

In solving the NP-hard problem, soft computing (i.e., fuzzy logic, neural networks and genetic algorithm GA) has been widely successfully implemented for optimizing SC design. Some applications, for instance manufacturing flow management, order fulfillment, demand management, supplier relationship management, product development and commercialization, return management, customer service management and customer relationship management are most improvement areas of SC design. GA and fuzzy logic are the two most used tools and manufacturing flow management is the most popular application area (Ko, Tiwari, & Mehnen, 2010 and references therein). While GA most probably cannot guarantee the global optimum solution, fuzzy logic can potentially be implemented within a deterministic global optimization tool for achieving the global optimum solution. The current article embeds a fuzzy shortest path into two-stage programming in order to find the global optimum solution at polynomial time by converting the second stage formulation from SPPTWCC to ordinary SPP.

3. Shortest path problem with time windows and capacity constraint (SPPTWCC) for inventory and excess capacity allocations

The SPPTWCC is built over generic networks and routings {*GNR*} which are presented as a directed graph $G^k = (V^k, A^k)$ for feasible vehicle routing with k serving a set of generic operations (GOs) V^k and a set of transportation arcs A^k. The A^k is a set of binary network flows, variable $x^k_{i,j}$ that has a unity value if there is a pairing from GOs i to j to configure a route k, and zero for otherwise.

The {*GNR*} has restricted routes from the lowest to the highest hierarchy of station. Each feasible route of {*GNR*} ρ^k is indexed by p and is included in the set of extreme points of {*GNR*} structures, $\forall p \in \rho^k$. Each k is composed by linking one GO to another GO in such a way that the combination of some feasible routes forms a single shortest path.

For each path k, arc $x^k_{i,j}$ is configured according to a set of feasible routing $\forall p \in \rho^k$ in such a way that $i, j \in V$, $\forall k \in K$, $\forall p \in \rho^k$ and therefore the arc $x^k_{i,j}$ is rewritten as $x^k_{i,j,p}$. Each $x^k_{i,j}$ requires a transportation time t_{ij} to link GOs i and j within time windows (t^e_i, t^l_i). Consequently, the transportation cost for path k within a set of extreme points p is reformulated as $C^k_p = \sum_{p\in\rho^k}\sum_{i,j\in A^k} c_{i,j}x^k_{i,j,p}$. A path parameter $u^k_p = 1$ holds if the path p is used by {*GNR*} k and zero for otherwise.

Definition 1. A path x_{ij} from i to j dominates another path $\overline{x}_{ij}$ from i to j if the objective vector of path x_{ij}, π_{ij} is higher than the objective vector of path $\overline{x}_{ij}$, $\overline{\pi}_{ij}$ for at least one k.