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Bi-objective optimization of a three-echelon multi-server supply-chain problem in congested systems: Modeling and solution

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A B S T R A C T

A novel bi-objective three-echelon supply chain problem is formulated in this paper in which cross-dock facilities to transport the products are modeled as an M/M/m queuing system. The proposed model is validated using the epsilon constraint method when applied to solve some small-size problems. Since the problem belongs to the class of NP-hard and that it is of a bi-objective type, a multi-objective particle swarm optimization (MOPSO) algorithm with a new solution structure that satisfies all of the constraints is developed to find Pareto solutions. As there is no benchmark available in literature, three other multi-objective meta-heuristic algorithms called non-dominated ranking genetic algorithm (NRGA), non-dominated sorting genetic algorithm (NSGA-II), and multi-objective imperialist competitive algorithm (MOICA) are utilized as well to validate the solutions obtained for large-scale problems. The parameters of the solution algorithms are calibrated using the Taguchi method. The comparison results based on five multi-objective performance metrics used in the AHP-TOPSIS method show that the parameter-tuned MOPSO acts better than the other parameter-tuned algorithms to solve, small, medium, and large-size problems.

1. Introduction

Supply chain networks (SCN) have received remarkable attention due to growing international markets. A SCN involves all the activities related to producing and delivering products to customers. One of the most fundamental decisions in SCN design problems is to locate the facilities (such as suppliers, producer, and cross-docks) and allocating the customers so as the total cost of the network is minimized while customer demands are satisfied without delay. Although the main important goal in designing SCN is to minimize total network costs, the ability to meet customer demand for ever-shorter delivery times has critical importance. In other words, minimizing total required production and delivering time of the products to customers can be considered as well to improve customer's satisfaction.

The investigated SCN problem in this paper involves a multi-echelon stochastic capacitated network, where it is hybridized with routing and queuing problems in order to take into account the production and delivery times of the products. This makes it more applicable to real-world environments. SCN design problems, which are associated with human behavior, are strongly influenced by stochastic processes such as customer demand and customer entry time. Queuing theory encompasses some analytic techniques to obtain some performance measures of these stochastic systems including time-related indicators. These times include customer waiting and service times along with the idle times of the servers. Thus, in addition to consider the supply chain costs, this paper emphasizes on the time-driven performance metrics. To this aim a novel bi-objective queuing model is developed for an integrated three-echelon supply chain network under disruption. The objectives are: (1) minimizing the total cost including fixed, routing, distribution and production disruption cost and (2) minimizing the total required time including vehicle's travelling time, waiting time, service time, and the idle time of the servers at the cross-dock facilities. Note that the objective functions contradict each other because minimizing the total time usually comes with a higher total cost. As such, a bi-objective optimization problem is involved that requires a multi-objective meta-heuristic to solve medium and large-scale problems, because we will show that the developed stochastic non-linear mixed integer problem is strictly NP-Hard.

The main motivation of this paper has been related to a real-world steel company in which crude steel was the raw material provided by the suppliers. Different types of steel commodities

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are transported in this case study toward the depots (cross-dock). Metal manufacturing facility are customers of these depots to perform further processing and satisfy the demand of end users. According to the Vahdani, Tavakkoli-Moghaddam, Modarres, and Baboli (2012) the arrivals process and service times in this problem can be assumed to follow Poisson and Exponential distribution, respectively. In other words, the motivation of this paper is to introduce other aspects of uncertainty involved in supply chain problems. Hence, we take into account uncertain demand and service time that follow Poisson and Exponential distributions, respectively. It means that a queuing approach can be used to model opened cross-dock in the steady-state condition and then the problem can be formulated based on queuing theory.

The rest of this paper is organized as follows. The next section is allocated to the literature review. In Section 3 the problem is defined. Section 4 contains the mathematical formulation of the problem. The solution algorithms are described in Section 5. The multi-objective metrics used to design and to evaluate the performance of the solution algorithms are introduced in Section 6. The way the parameters of the algorithms are calibrated is discussed in Section 7. The algorithms are statistically compared in Section 8. Finally, the conclusion and some recommendations for future research come in Section 9.

2. Literature review

Some of the applications of queuing systems include emergency medical service systems (de Souza, Morabito, Chiyoshi, & Iannoni, 2015), construction processes (Akhavian & Behzadan, 2014), wireless networks (Huang, Liu, Yan, & Li, 2014), etc. Bhaskar and Lallement (2010) investigated a two-input three-stage supply chain problem within a queuing framework. Their proposed model aimed to calculate minimum response time to deliver goods to final destination. He, Hu, Wu, and Wang (2013) proposed a multi-echelon queuing network for transporting emergency goods by decreasing wasting times and accelerating transportation. Teimoury, Modarres, Khondabi, and Fathi (2012) developed a multi-echelon multi-product SCN model, in which the first stage was assumed to produce semi-finished products to supply needs of the second stage. Their proposed model aimed to minimize total expected costs including costs of semi-finished products, holding costs of semi-finished products, fixed costs of establishing storage for semi-finished products, delay, and transportation costs. Jain and Raghavan (2009) provided two queuing models for inventory planning with batch ordering in a multi-echelon SCN. Their first model aimed to determine optimal warehouse inventory that minimizes the total costs including backorder, ordering, and transportation cost. In their second model, a probabilistic service level constraint was imposed to prevent balking customers. Vahdani et al. (2012) designed a closed-loop supply chain reliable network under uncertainty to minimize both the total and the expected transportation costs resulted by facility failures. They used a queuing approach to model a probabilistic constraint optimization problem and solved it using fuzzy multi-objective optimization methods.

Cárdenas-Barrón and Treviño-Garza (2014) developed a mixed integer linear programming model for a multi-product multi-period three-echelon supply chain network. Their proposed model aimed to minimize total costs including transportation costs, supplier material costs, and manufacturing costs. They solved the problem using the CPLEX software. Wang and Lee (2015) proposed a bi-objective stochastic model for two and three echelon supply chain networks. Their aim was to maximize the total profit. They used the CPLEX software to find exact solutions of some small size problems. They also presented a revised ant colony algorithm to solve large-scale problems. Sarrafha, Rahmati, Niaki, and Zaretalab (2015) developed a bi-objective mixed integer nonlinear programming model for four echelon supply chain network including suppliers, factories, distribution centers, and retailers. They assumed a flow-shop scheduling model in the manufacturing layer of the SCN and shortage in form of backorder to make the model closer to reality. The first objective of their proposed model aimed to minimize the total supply chain costs including setup costs, procurement and transportation costs, production costs, inventory holding costs, purchasing costs, and backorder costs. The second objective was to minimize the total time including average tardiness of the products received by distribution centers. Since their proposed problem was strictly NP-Hard, three meta-heuristic algorithms called multi-objective biogeography based optimization algorithm (MOBBO), multi-objective simulated annealing algorithm (MOSA), and non-dominated sorting genetic algorithm (NSGA-II) were utilized to solve it. Pasandideh, Niaki, and Asadi (2015) developed a stochastic bi-objective mixed integer non-linear model for a multi-product multi-period three-echelon SCN including manufacturing plants, distribution centers, and customers. The first and the second objective of their model aimed to minimize average and variance of the total costs, respectively. They utilized two meta-heuristic genetic-based algorithms called NSGA-II and NRGA to solve the problem.

As global optimal solutions for most of small-size supply chain problems can be found in reasonable time, many researchers proposed different exact methods to solve them. Perron, Hansen, Le Digabel, and Mladenović (2010) developed a bilinear model for a multi-echelon global SCN. They used a linear relaxation method to reduce complexity of the proposed model. They presented an exact method called the branch and cut algorithm for solving small-size problems along with two other variable neighborhood search (VNS)-based heuristics to solve large scale problems. Pishvaee, Razmi, and Torabi (2014) presented a mixed integer multi-objective programming model for a medical supply chain network under uncertainty. Their model aimed to optimize three conflicting objectives including minimization of the total costs, minimization of the environmental effects, and maximization of social responsibilities. They defined several constraints and binary variables to convert the nonlinear model into a linear one and used an accelerated benders decomposition algorithm to solve the problem. Lemmens, Decouttere, Vandaele, and Bernuzzi (2016) performed a comprehensive study on published works for model-based SCN design. The aim of their investigation was to identify the applicability of these models to design the key supply chains such as vaccine supply chains. In addition, they provided an overview on how to consider the uncertainty in SCNs, especially those related to tender procurement, disease epidemics, demand uncertainty, and lead- time changeability.

Khatami, Mahootchi, and Farahani (2015) proposed a stochastic mixed integer programming model for a closed loop multi-echelon SCN. Their model aimed to minimize the present value of the total costs including fixed location and allocation costs, transportation costs, disposal costs, and inventory processing costs. They used the benders decomposition algorithm to solve the problem. Amin and Zhang (2013) developed a stochastic bi-objective mixed integer programming model for a closed looped multi-echelon SCN. The first objective of their model aimed to minimize the total costs including fixed costs, transportation costs, production costs, and recovery costs. The second objective was to maximize green environmental aspects such as using clean technologies and environmental friendly materials in SCNs. They used two methods called the epsilon constraint algorithm and the weighted sum method to find the exact solution of the problem.

Several recent developments have also led to an increased focus on supply chain disruption management. The sources of disruption