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Optimization of replenishment policies for decentralized and centralized capacitated supply chains under various demands ☆

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ABSTRACT

In this paper, the optimal replenishment policies of capacitated supply chains (SC) operating under two different control strategies (decentralized vs. centralized) and various demands are determined and insights useful to management are discussed. The details of the system used, including the underlying supply chain inventory model and the simulation-based optimization framework, are presented. The effectiveness and efficiency of the proposed optimization framework is illustrated by comparing it with brute force estimation of the true optimum on three selected scenarios. The entire study was carried out by following a design of experiment, covering ten demand patterns, four levels of capacity constraints, and two control strategies. The main and two-factor interaction effects were analyzed via ANOVA. Detailed analyses of the ordering patterns, cost distribution over the SC and internal service level were carried out to provide useful insights. For demand with high variation, capacity constraint may lead to significant changes in ordering patterns. Failing to detect those changes may lead to unnecessary cost increase. Overall it is beneficial to adopt centralized control and cost savings realized are dependent upon the demand patterns. An incentive mechanism is proposed to coordinate the decentralized system so that each player in the SC will be better off. Additional experiments were also carried out to investigate the effect of using different allocation rules by the distributor.

1. Introduction

It is well-known that in today's global economy the competition is among supply chains, instead of individual companies. Two major types of supply chains can be distinguished depending upon how decisions are made: decentralized if decisions are made by each member with no consideration given to the other and centralized if decisions are made centrally by considering all members together. Centralized supply chains are known to be more cost-effective than decentralized ones; but it normally requires a higher degree of integration. Researchers have been devising various coordination mechanisms for moving relatively inefficient decentralized supply chains toward more efficient centralized supply chains. Of interest in this study is the inventory decision because supply chain inventory is necessary to quickly respond to uncertain customer demand and to absorb shocks introduced by interruption on the supply side. Not to mention that inventory is also one of the most valuable assets for most supply chains.

Supply chain inventory management in general has been a topic of interest to many researchers as well as practitioners. Numerous studies have been carried out in particular concerning the optimization of supply chain inventory/replenishment polices. Supply chain inventory optimization studies can be distinguished by the fact whether they consider uncertainty or not. This paper focuses on the latter. From the solution methodology viewpoint, both analytical approaches such as Leung (2010) and (meta-)heuristic approaches such as Yang et al. (2012) have been used to optimize supply chain inventory/replenishment policies. Both approaches have their own pros and cons. Generally speaking, an analytical approach is able to guarantee global optimal solution if the underlying mathematical model is solvable. However, such model is often based on a number of assumptions. For inventory problems, each analytical model assumes either constant demand or stochastic demand following a specific distribution. The applicability of the model thus depends upon the validity of the assumption. On the other hand, (meta-)heuristic approaches do not guarantee finding the global solution. Nevertheless, often (meta-)heuristic approaches are able to find the global optimum or near-optimal solutions and they are able to solve mathematical models with fewer and more realistic assumptions, non-differential, nonconvex, and having no explicit form. Most importantly, (meta-)heuristic approaches can work with simulation models to mimic a more complicated

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system while analytical approaches cannot. The area of simulation optimization relies more on powerful meta-heuristics than traditional optimization methods (Fu, 2002).

A number of simulation-based models have been developed in the past and solved by various meta-heuristic algorithms for supply chain inventory optimization. Most models are stochastic, which include (Köchel and Nieländer, 2005; Kleijnen and Wan, 2007; Alrefaei and Diabat, 2009; Ramaekers, 2009; Keskin et al., 2010 and Köchel and Thiem, 2011). Other models, such as Dong and Leung (2009), Liao and Chang (2010), are deterministic. This study falls into the latter category. Several studies have been devoted to comparing the performance of a centralized SC inventory system with a decentralized one. These studies include (Baboli et al., 2011; Leung, 2010; Geng et al., 2010; Ye and Xu, 2010 and Saharidis et al., 2009). However, all these studies assume infinite capacity and the effects of capacity constraint are ignored. The same is true for the majority of other supply chain inventory optimization studies, except a few described in the next paragraph.

Based on game theory, Mahajan et al. (2002) analyzed a supply chain consisted of an uncapacitated/capacitated supplier distributing two independent products through multiple retailers. Jemai and Karaesmen (2007) investigated a two-stage supply chain consisted of a capacitated supplier and a retailer in the framework of Nash game. Sitompul et al. (2008) formulated the safety stock placement problem for an n-stage capacitated serial supply chain as a shortest path problem and proposed a solution procedure with the objective to maintain the required overall service level at the lowest cost. Karaman and Altiok (2009) developed a model based on decomposition approximations to study an n-stage serial supply chain consisted of a supplier, a plant with finite production rate, a distribution center, and a retailer. Their model was solved by an iterative optimization procedure with the objective to minimize total system cost. Toktaş-Palut and Ülengin (2011) modeled a 2-stage supply chain consisted of multiple suppliers and a manufacturer with limited production capacities as a queuing system. They developed both decentralized and centralized models and examined three different transfer payment contracts for the coordination of the supply chain. To the best of our knowledge, so far the study of Toktaş-Palut and Ülengin (2011) is the only one that considers both decentralized and centralized capacitated supply chains and their study focuses on the supplier side.

This paper considers a two-tier supply chain consisted of a distributor distributing a single product to multiple retailers for meeting end customer demands. Both decentralized and centralized models are developed (see Section 2.1 for more details) with finite planning horizon. A periodic review replenishment policy, specifically (s, S), is adopted by both the distributor and retailers. The distributor orders from a capacitated supplier and the retailers face varying deterministic customer demands. Unfulfilled demand is assumed lost to resemble the case in fast-moving retail market; customers who do not find what they want most likely will shop somewhere else. Both decentralized and centralized models are simulated for performance evaluation; and the optimal replenishment policies for all members of the supply chain are determined by a hybrid meta-heuristic algorithm recently developed by us (Duan et al., 2012). Essentially, our supply chain inventory optimization framework integrates a hybrid meta-heuristic optimization algorithm with supply chain inventory simulation models (see Section 2 for more details).

The proposed framework does not require any unrealistic assumption on demand. Ten different demand patterns are tested in this study. The developed framework allows us to (1) to determine near-optimal replenishment policies for each SC member under both decentralized and centralized control strategies; (2) to examine and quantify the effect of different demand patterns, supplier's capacity constraint and control strategies (centralized/decentralized) on the unit inventory cost; (3) to investigate the changes in various internal performance measures such as ordering patterns, cost distribution and internal service level, and (4) to develop an incentive mechanism for coordinating a decentralized supply chain. The majority of analytical models can only provide general information on system performance such as the overall system profit/cost based on restrictive assumptions. The proposed framework is advantageous over analytical models in its ability to produce additional detailed information to enable deeper investigation of the dynamics of internal system operations, thus gaining more useful insights for inventory managers to make better and more informative decisions. In summary, the main contribution of this paper is threefold: (1) to be the first that develops both centralized and decentralized models for a capacitated inventory system focusing on the retailers' side; (2) to investigate the interactions between capacity constraint, control strategy, and demand; and (3) to evaluate the performance of the supply chain in more details from different angles to provide some useful managerial insights.

The remainder of the paper is organized as follows. Section 2 describes the proposed framework in details. Section 3 verifies the framework and presents the testing results, followed by a discussion in Section 4. Finally, the paper is concluded in Section 5.

2. The proposed supply chain inventory optimization framework

The proposed framework is designed to find sufficiently good solutions for a decentralized or centralized supply chain inventory problem. For clarity, a brief definition is given below.

Decentralized control. All players of the SC make their replenishment decisions based on their local information independently. Players in the SC are treated as individual company in which they aim to minimize their own inventory cost regardless of the system cost.

Centralized control. Centralized decisions are made to minimize the overall SC inventory cost. It can be applied when the distributor and all retailers belong to the same enterprise. It can also be adopted for special configurations, e.g., vendor-managed inventory (VMI).

The overall structure of the proposed framework is depicted in Fig. 1. The hybrid meta-heuristic generates a trial solution and supplies this candidate solution to the SC simulation model to evaluate its objective function value. Based on the result provided by the evaluation module, the meta-heuristic optimizer then generates a new input set according to its intelligent searching mechanism. This cycle is repeated until a near-optimum solution is obtained. Such a simulation optimization formulation allows more realistic modeling of the inventory control system. In the following subsections, the SC inventory models studied are described first, followed by the hybrid meta-heuristic optimizer used.

2.1. Decentralized and centralized capacitated supply chain inventory models

Generally speaking, a supply chain inventory model can be adapted to different network configuration, replenishment policies, control strategies, etc. In this study, inventory models are tailored to a single-distributor multi-retailer supply chain system. The retailers can be identical or non-identical. It is assumed that all supply chain members adopt the (s, S) inventory