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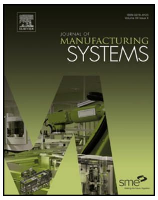

Technical Paper

Incorporating location and inventory decisions into a supply chain design problem with uncertain demands and lead times

Ali Diabat[a,*], Ehsan Dehghani[b], Armin Jabbarzadeh[b]

[a] *Department of Engineering Systems and Management, Masdar Institute of Science and Technology, Abu Dhabi, United Arab Emirates*
[b] *Department of Industrial Engineering, Iran University of Science and Technology (IUST), Tehran, Iran*

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ABSTRACT

This paper presents a joint location-inventory model for the network design of a supply chain with multiple Distribution Centers (DCs) and retailers. The developed model determines the number and location of DCs, the assignment of retailers to DCs, and the size and timing of orders for each DC. The uncertain natures of demands and replenishment lead times are incorporated into the model utilizing a queuing approach. To solve the presented model for large size problems, a hybrid solution algorithm based on simulated annealing and direct search method is adopted. The comparative analysis of the numerical results provides important modelling insights. Particularly, we demonstrate numerically that the cost savings obtained from the queuing approach can be significant.

1. Introduction

Fierce competition in today's global markets and the heightened expectations of customers have forced companies to focus on their supply chains [1]. It has been proven that effective management of the supply chain is crucial for business enterprises to reduce their costs and increase service levels [2–4]. In particular, supply chain network design is of paramount importance [5–7]. An appropriate network design strategy can contribute to decreasing the cost of a firm by 60% [8].

The design of supply chain networks has traditionally been considered as a strategic decision that involves determining the location and allocation of facilities [9–11]. Typically, in such a framework the tactical decisions of inventory are determined after the location decisions are made [12]. However, failure to take the related inventory costs into consideration when deciding the locations of facilities can result in sub-optimality, since strategic location decisions have a considerable impact on inventory costs [13–15]. In addition, it has been proven that operational aspects of lead times are required to be incorporated into strategic network design models [16]. Consequently, in recent years, there has been a strong move towards integration of strategic and tactical decisions through the development of joint location-inventory models [17].

Despite the fact that joint location-inventory models lead to improved management of the supply chain, integration of location and inventory decisions comes at the cost of higher model complexity [18]. This has led to the need for using simplistic and unrealistic assumptions in most of existing studies on location-inventory problems that may lead to inaccurate results. For instance, typically the replenishment lead time is assumed to be deterministic, whilst in real-world cases lead times are often uncertain due to different reasons such as stockouts at the supplier, transportation-infrastructure issues, customs inspections, and manufacturing or transit delays [19,20]. Likewise, most of location-inventory models tend to overlook shortage costs and the use Economic Order Quantity (EOQ) model to simplify the inventory formulations [17]. Nevertheless, supply chains may frequently face lost sales situations in practice [21,22].

This paper presents a joint location-inventory model consisting of multiple Distribution Centers (DCs) and retailers that aims to overcome the aforementioned limitations. The proposed model determines the number and location of DCs, the assignment of retailers to DCs, and the size and timing of orders for each DC. The objective of the model is to minimize the total supply chain cost including the location cost of DCs, the transportation cost for product shipment between DCs and retailers, the inventory cost of DCs and the lost sales costs associated with unserved retailers' demands. The uncertain natures of the lead times and demands are addressed in the proposed model utilizing queuing theory. To solve the nonlinear model for large sized problem, we use a simulated annealing approach in which a direct search method is embedded.

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* Corresponding author. Tel.: +9712 810 9101; fax: +9712 810 9901.
E-mail address: adiabat@masdar.ac.ae (A. Diabat).

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The performances of the proposed model and solution method are investigated in a number of numerical experiments and the results are discussed in detail.

The rest of the paper is organized as follows. Section 2 reviews the literature on location-inventory problems as well as the modelling efforts for tackling inventory problems using queuing techniques. Section 3 defines the problem in detail and formulates the integrated model, which is followed by solution methods in Section 4 and the computational experiments in Section 5. Finally, concluding remarks and potential future research directions are presented in Section 6.

2. Literature review

This section provides a brief review of the modelling efforts in the area of joint location-inventory problems. For comprehensive reviews on integrated supply chain network design models and joint location- inventory problems, please see [23–25].

The study by Baumol and Wolfe [26] is amongst the earliest works incorporating inventory costs into location models. The authors developed an uncapacitated facility location problem, for which they provided a solution method leading to local optimums. Eppen [27] investigated the risk pooling effect and demonstrated that the cost of a centralized inventory is smaller than the sum of the costs of decentralized inventories in each facility. A jointed location-inventory problem was presented by Barahona and Jensen [28], where Dantzig-Wolfe decomposition method and sub-gradient optimization were used to solve the model within 4% of optimality. Erlebacher and Meller [29] introduced a location-inventory problem and developed heuristic procedures to solve the model. Nozick and Turnquist [30] considered an integrated supply chain model in order to design efficient logistics systems. The model was applied in the distribution of finished vehicles by an automotive manufacturer.

Daskin, Coullard and Shen [17] formulated a location-inventory problem as a non-linear integer-programming model and proposed a Lagrangian relaxation for finding quality solutions. Shen, Coullard and Daskin [31] studied this problem as a set-covering integer programming model and developed a column generation algorithm. A faster solution approach for the same problem was proposed by Shu, Teo and Shen [32]. Shen and Qi [13] extended the problem by incorporating routing decisions into the model. Diabat and Theodorou [18] presented a two-echelon inventory problem with multiple retailers and utilized a piecewise linearization to transform this initially non-convex problem into a convex discrete optimization formulation.

Capacitated versions of joint location-inventory problem have been addressed by [33–40]. Amiri [33] formulated the distribution network design problem in a supply chain system that involved locating production plants and distribution warehouses. Unlike most previous studies, their research allowed multiple levels of capacities available to the warehouses and plants. Miranda and Garrido [35] and Ozsen, Daskin and Coullard [36] furthermore presented stochastic inventory and facility location models incorporating certain realistic capacity constraints that previous studies had ignored. For example, their model included stochastic constraints for the space availability of stocks. Likewise, Diabat, Aouam and Ozsen [40] considered a joint location-inventory problem involving a single supplier and multiple retailers facing stochastic demand. The authors proposed a genetic algorithm as an alternative technique for solving the capacitated facility location problem with risk pooling.

Miranda and Garrido [41] presented a two-step heuristic algorithm to optimize inventory service levels in a two-stage supply chain. The first step optimizes service levels and the second step addresses location and inventory decisions. Liu, Zhou and Zhang [37] studied a location problem assigning online demands to the capacitated regional warehouses serving in-store demands in a multi-channel supply chain. Their model explicitly considered the trade-off between the risk pooling effect and the transportation cost in a two-echelon inventory/logistics system.

More recently, Berman, Krass and Tajbakhsh [42] analyzed a stochastic integrated location-inventory problem, where each DC used a periodic-review inventory policy. Diabat, Richard and Codrington [43] developed a multi-echelon joint inventory-location model determining the location of warehouses and inventory policies at the warehouses and retailers. The model was formulated as a non-linear mixed-integer program, and was solved using a Lagrangian relaxation-based approach. An integrated location-inventory problem was also investigated by Tsao [44] in which a novel continuous approximation modelling procedure was presented. Wu and Zhang [45] developed a cutting plane approach based on polymatroid inequalities for a supply chain network design under uncertainty.

Nekooghadirli, Tavakkoli-Moghaddam, Ghezavati and Javanmard [46] studied a multi-period and multi-product supply chain network design and assumed probabilistic travelling time among customers. They proposed four meta-heuristics algorithms to solve this problem and compared their performances. Further, Diabat, Battaïa and Nazzal [47] and Alhaj, Svetinovic and Diabat [48] extended the joint location-inventory problem by incorporating the reduction of carbon emissions. They also accounted for uncertainty by including new variables that reflect the probability of different demand scenarios. Al-Salem, Diabat, Dalalah and Alrefaei [39] and Abdallah, Diabat and Simchi-Levi [49] addressed closed-loop joint location-inventory problems and formulated them as mixed integer non-linear models. Sadjadi, Makui, Dehghani and Pourmohammad [50] examined a stochastic location-inventory problem for a three-level supply chain network, while assuming each DC manages its inventory using (S-1, S) policy. Since the present paper utilizes a queuing approach for modelling the inventory levels at DCs, we briefly review some of the efforts for the formulation of on-hand inventories using queuing theory. Queuing approaches have been powerful tools for modelling the inventory levels, especially when demands arrive one by one and the on-hand inventory decreases by one at the time of service completion [51]. Employing a queuing approach, Goh, Greenberg and Matsuo [52] investigated perishable inventory systems with two types of demands. Cheung and Yuan [53], moreover, applied a classical GI/M/1 queuing technique to evaluate an unlimited horizon inventory policy with a periodic order guarantee.

In order to examine the impacts of demand variability on the performance of stochastic inventory systems, Jemaı¨ and Karaesmen [54] analyzed a make-to-stock queue with general demand arrival times operated according to a base-stock policy. Jain [55] developed a scheduling problem in a make-to-stock queue with two different variable demands. They compared three scheduling arrangements considering inventory cost performance. Additionally, Hennet and Arda [56] employed a queuing approach for formulating an inventory policy in the supply chain context. Using queuing theory, Teimoury, Modarres, Ghasemzadeh and Fathi [21] studied an (s,Q) inventory system with lost sales and exponentially distributed lead times. The authors developed a computationally efficient algorithm for determining optimal values for safety stock in a multi-item capacitated warehouse. Saffari, Asmussen and Haji [51] considered an M/M/1 queuing system with inventory under (r,Q) policy, in which demands occur according to a Poisson process. The authors derived the stationary distributions of the joint queue length and on-hand inventory when lead times were random variables. Otten, Krenzler and Daduna [57] analyzed a two-echelon