Multi-echelon inventory management in supply chains with uncertain demand and lead times: literature review from an operational research perspective

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Abstract: Historically, the echelons of the supply chain, warehouse, distributors, retailers, etc., have been managed independently, buffered by large inventories. Increasing competitive pressures and market globalization are forcing firms to develop supply chains that can quickly respond to customer needs. To remain competitive and decrease inventory, these firms must use multi-echelon inventory management interactively, while reducing operating costs and improving customer service. The current paper reviews the literature, addressing multi-echelon inventory management in supply chains from 1996 to 2005. The behaviour of the papers against demand and lead-time uncertainty is the key analysis point of the literature review presented here and it is conducted from an operational research point of view. Finally, directions for future research are suggested.

Keywords: supply chain, multi-echelon inventory management, demand uncertainty, lead-time uncertainty

1 INTRODUCTION

Supply chain management (SCM) is an integrative approach for planning and control of materials and information flows with suppliers and customers, as well as between different functions within a company [**1**]. This area has drawn considerable attention in recent years and is seen as a tool that provides competitive power [**2**]. SCM is a set of approaches to integrate suppliers, manufacturers, warehouses, and stores efficiently, so that merchandise is produced and distributed at right quantities, to the right locations, and at the right time, in order to minimize system-wide costs while satisfying service-level requirements [**2**, **3**]. So the supply chain consists of various members or stages. A supply chain is a dynamic, stochastic, and complex system that might involve hundreds of participants [**2**].

Inventory usually represents from 20 to 60 per cent of the total assets of manufacturing firms. Therefore, inventory management policies prove critical in determining the profit of such firms [**4**]. Inventory management is, to a greater extent, relevant when a whole supply chain (SC), namely a network of procurement, transformation, and delivering firms, is considered. Inventory management is indeed a major issue in SCM, i.e. an approach that addresses SC issues under an integrated perspective [**2**, **5**].

Inventories exist throughout the SC in various forms for various reasons [**6**]. The lack of a coordinated inventory management throughout the SC often causes the bullwhip effect, namely an amplification of demand variability moving towards the upstream stages. This causes excessive inventory investments, lost revenues, misguided capacity plans, ineffective transportation, missed production schedules, and poor customer service [**5**].

Many scholars have studied these problems, as well as emphasized the need of integration among SC stages, to make the chain effectively and efficiently satisfy customer requests (e.g. reference [**7**]). Beside the integration issue, uncertainty has to be dealt with in order to define an effective SC inventory policy. In addition to the uncertainty on supply (e.g. lead times)

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and demand, information delays associated with the manufacturing and distribution processes characterize SCs [**5**].

Inventory management in multi-echelon SCs is an important issue, because there are many elements that have to coordinate with each other. They must also arrange their inventories to coordinate. There are many factors that complicate successfull inventory management, e.g. uncertain demands, lead times, production times, product prices, costs, etc., especially the uncertainty in demand and lead times where the inventory cannot be managed between echelons optimally.

In the current paper, a detailed literature review is presented, addressing multi-echelon inventory management in SCs from 1996 to 2005. Here, the behaviour of the papers against demand and lead time uncertainty is emphasized. First, echelon concept and multi-echelon inventory management in SCs are defined. Then, the literature review conducted from an operational research point of view between 1996 and 2005, is presented. Finally, directions for future research are suggested.

2 MULTI-ECHELON INVENTORY MANAGEMENT IN SUPPLY CHAINS

Most manufacturing enterprises are organized into networks of manufacturing and distribution sites that procure raw material, process them into finished goods, and distribute the finish goods to customers. The terms 'multi-echelon' or 'multilevel' production/distribution networks are also synonymous with such networks (or SC), when an item moves through more than one step before reaching the final customer. Inventories exist throughout the SC in various forms for various reasons. At any manufacturing point, they may exist as raw materials, work in progress, or finished goods. They exist at the distribution warehouses, and they exist in-transit, or 'in the pipeline', on each path linking these facilities [**6**].

Manufacturers procure raw material from suppliers and process them into finished goods, sell the finished goods to distributors, and then to retail and/or customers. When an item moves through more than one stage before reaching the final customer, it forms a 'multi-echelon' inventory system [**8**]. The echelon stock of a stockpoint equals all stock at this stockpoint, plus in-transit to or on-hand at any of its downstream stockpoints, minus the backorders at its downstream stockpoints [**9**].

The analysis of multi-echelon inventory systems that pervades the business world has a long history [**10**]. Multi-echelon inventory systems are widely employed to distribute products to customers over extensive geographical areas. Given the importance of these systems, many researchers have studied their operating characteristics under a variety of conditions and assumptions [**11**]. Since the development of the economic order quantity (EOQ) formula by Harris (1913), researchers and practitioners have been actively concerned with the analysis and modelling of inventory systems under different operating parameters and modelling assumptions [**2**]. Research on multi-echelon inventory models has gained importance over the last decade mainly because integrated control of SCs consisting of several processing and distribution stages has become feasible through modern information technology [**8**, **9**, **12**]. Clark and Scarf [**13**] were the first to study the two-echelon inventory model [**8**, **9**, **10**, **14–17**]. They proved the optimality of a base-stock policy for the pure-serial inventory system and developed an efficient decomposing method to compute the optimal base-stock ordering policy. Bessler and Veinott [**18**] extended the Clark and Scarf [**13**] model to include general arborescent structures. The depot–warehouse problem described above was addressed by Eppen and Schrage [**19**] who analysed a model with a stockless central depot [**20**]. They derived a closed-form expression for the order-up-to-level under the equal fractile allocation assumption. Several authors have also considered this problem in various forms [**11**, **14–17**, **20–30**]. Owing to the complexity and intractability of the multi-echelon problem, Hadley and Whitin [**31**] recommend the adoption of single-location, single-echelon models for the inventory systems [**10**].

Sherbrooke [**32**] considered an ordering policy of a two-echelon model for warehouse and retailer. It is assumed that stockouts at the retailers are completely backlogged [**8**]. Also, Sherbrooke [**32**] constructed the METRIC (multi-echelon technique for recoverable item control) model, which identifies the stock levels that minimize the expected number of backorders at the lower-echelon subject to a budget constraint. This model is the first multi-echelon inventory model for managing the inventory of service parts [**6**, **10**, **33**]. Thereafter, a large set of models, which generally seek to identify optimal lot sizes and safety stocks in a multi-echelon framework, were produced by many researchers [**27**, **34–37**]). In addition to analytical models, simulation models have also been developed to capture the complex interactions of the multi-echelon inventory problems [**10**, **38–41**]. Figure 1 shows a multi-echelon system consisting of a number of suppliers, plants, warehouses, distribution centres, and customers [**27**, **42**, **43**].

So far literature has devoted major attention to the forecasting of lumpy demand, and to the development of stock policies for multi-echelon SCs [**13**]. Inventory control policy for multi-echelon systems with stochastic demand has been a widely researched

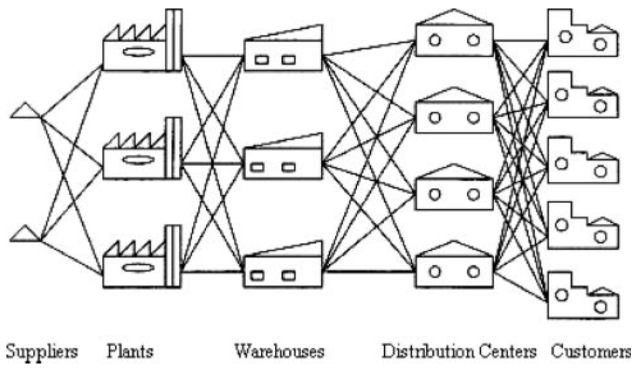

Fig. 1 A multi-echelon inventory system

area. More recent papers have been covered by Silver and Pyke [**44**]. The advantage of centralized planning, available in periodic review policies, can be obtained in continuous review policies, by defining the reorder levels of different stages, in terms of echelon stock rather than installation stock [**45**].

3 LITERATURE REVIEW: FROM 1996 TO 2005

In this section, a detailed literature review, conducted from an operational research point of view, is presented. It addresses multi-echelon inventory management in SCs, from 1996 to 2005. The selection criteria of the papers that are reviewed are: using operational research techniques to overcome multi-echelon inventory management problems, and being demand and lead time sensitive (there are uncertain demand and lead times). Here, the behaviour of the papers against demand and lead time uncertainty is emphasized.

The papers reviewed here are categorized into groups on the basis of the research techniques in which they are used. These techniques can be grouped as:

(a) mathematic modelling (only);
(b) mathematic modelling and other techniques (in the same paper);
(c) METRIC modelling;
(d) Markov decision process;
(e) simulation (only);
(f) Stackelberg game;
(g) literature review;
(h) other techniques (vari-METRIC method, heuristics, scenario analysis, fuzzy logic, etc.).

While the research techniques are common for papers that are grouped according to their research techniques, the number of echelons they consider, inventory/system policies, demand and lead time assumptions, the objectives, and the solutions' exactness may be different. Therefore these factors are also analysed.

3.1 Mathematic modelling technique

Rau *et al.* [**8**], Diks and de Kok [**9**], Dong and Lee [**16**], Mitra and Chatterjee [**45**], Hariga [**46**], Chen [**47**], Axsater and Zhang [**48**], Nozick and Turnquist [**49**], and So and Zheng [**50**] use a mathematic modelling technique in their studies to manage multi-echelon inventory in SCs. Diks and de Kok's study [**9**] considers a divergent multi-echelon inventory system, such as a distribution system or a production system, and assumes that the order arrives after a fixed lead time. Hariga [**46**], presents a stochastic model for a single-period production system composed of several assembly/processing and storage facilities in series. Chen [**47**], Axsater and Zhang [**48**], and Nozick and Turnquist [**49**] consider a two-stage inventory system in their papers. Axsater and Zhang [**48**] and Nozick and Turnquist [**49**] assume that the retailers face stationary and independent Poisson demand. Mitra and Chatterjee [**45**] examine De Bodt and Graves' model (1985), which they developed in their paper 'Continuous-review policies for a multi-echelon inventory problem with stochastic demand', for fast-moving items from the implementation point of view. The proposed modification of the model can be extended to multi-stage serial and two-echelon assembly systems. In Rau *et al.*'s [**8**] model, shortage is not allowed, lead time is assumed to be negligible, and demand rate and production rate is deterministic and constant. So and Zheng [**50**] used an analytical model to analyse two important factors that can contribute to the high degree of order-quantity variability experienced by semiconductor manufacturers: supplier's lead time and forecast demand updating. They assume that the external demands faced by the retailer are correlated between two successive time periods and that the retailer uses the latest demand information to update its future demand forecasts. Furthermore, they assume that the supplier's delivery lead times are variable and are affected by the retailer's order quantities. Dong and Lee's paper [**16**] revisits the serial multi-echelon inventory system of Clark and Scarf [**13**] and develops three key results. First, they provide a simple lower-bound approximation to the optimal echelon inventory levels and an upper bound to the total system cost for the basic model of Clark and Scarf [**13**]. Second, they show that the structure of the optimal stocking policy of Clark and Scarf [**13**] holds under time-correlated demand processing using a Martingale model of forecast evolution. Third, they extend the approximation to the time-correlated demand process and study, in particular for an autoregressive demand model, the impact of lead times, and autocorrelation on the performance of the serial inventory system.

After reviewing the literature about multi-echelon inventory management in SCs using mathematic modelling technique, it can be said that, in summary, these papers consider two, three, or *N*-echelon systems with stochastic or deterministic demand. They assume lead times to be fixed, zero, constant, deterministic, or negligible. They gain exact or approximate solutions.

3.2 Mathematic modelling and other techniques together

Routroy and Kodali [**2**], Ganeshan [**6**], Bollapragada *et al.* [**14**], van der Heijden [**20**], Verrijdt and de Kok [**28**], Parker and Kapuscinski [**30**], Seferlis and Giannelos [**41**], Axsater [**43**], Forsberg [**51**], Graves [**52**], Mohebbi and Posner [**53**], Dekker *et al.* [**54**], Korugan and Gupta [**55**], van der Heijden *et al.* [**56**], Andersson and Marklund [**57**], Cachon and Fisher [**58**], Axsater [**59**], Axsater [**60**], Tsiakis *et al.* [**61**], Moinzadeh [**62**], Tang and Grubbström [**63**], Chiu and Huang [**64**], Mitra and Chatterjee [**65**], Chen and Lee [**66**], Jalbar *et al.* [**67**], Seifbarghy and Jokar [**68**], and Han and Damrongwongsiri [**69**] used mathematic modelling and other research techniques in their papers.

Forsberg [**51**], Graves [**52**], Verrijdt and de Kok [**28**], Bollapragada *et al.* [**14**], Dekker *et al.* [**54**], Korugan and Gupta [**55**], van der Heijden *et al.* [**56**], van der Heijden [**20**], Andersson and Marklund [**57**], Axsater [**59**], Axsater [**60**], Mitra and Chatterjee [**65**], Seferlis and Giannelos [**41**], Seifbarghy and Jokar [**68**], Moinzadeh [**62**], and Axsater [**43**] consider a two-stage inventory system with stochastic demand in their papers, while Mohebbi and Posner [**53**] consider only a single-echelon system with stochastic demand. Tang and Grubbström [**63**] assume the demand to be constant and deterministic. In all these papers, mathematic modelling and simulation techniques are used together in the same paper. Ganeshan [**6**] considers a three-echelon inventory system with stochastic demand and lead times. Forsberg [**51**] and Verrijdt and de Kok [**28**] assume that lead times are constant, and Mohebbi and Posner [**53**] assume stochastic lead times, while Graves [**52**] assumes deterministic ones, and Bollapragada *et al.* [**14**] assumes fixed lead times. Verrijdt and de Kok [**28**] present two adjustment methods that improve the service performance considerably in certain cases. Another important contribution of the current paper is the generalization of the concept of imbalance. The work by Bollapragada *et al.* [**14**] is a generalization of earlier work by Eppen and Schrage [**19**], to allow for non-identical warehouses.

Dekker *et al.* [**54**] analyse the effect of the break-quantity rule on the inventory costs. The break-quantity rule is to deliver large orders from the warehouse, and small orders from the nearest retailer, where a so-called break quantity determines whether an order is small or large. In most *l*-warehouse–*N*-retailers distribution systems, it is assumed that all customer demand takes place at the retailers [**19**, **22**, **24**, **70**, **71**]. However, it was shown by Dekker *et al.* [**72**] that delivering large orders from the warehouse can lead to a considerable reduction in the retailer's inventory costs. In Dekker *et al.* [**54**] the results of Dekker *et al.* [**72**] were extended by also including the inventory costs at the warehouse. The study by Mohebbi and Posner's [**53**] contains a cost analysis in the context of a continuous-review inventory system with replenishment orders and lost sales. The policy considered in the paper by van der Heijden *et al.* [**56**] is an echelon stock, periodic review, order-up-to (R,S) policy, under both stochastic demand and lead times.

Andersson and Marklund's [**57**] approach is based on an approximate cost-evaluation technique. Axsater [**59**] presents a method for exact evaluation of control policies that provides the complete probability distributions of the retailer inventory levels. Mitra and Chatterjee [**65**] examine the effect of utilizing demand information in a multi-echelon system. Seferlis and Giannelos [**41**] present an optimization-based control approach that applies multivariable model-predictive control principles to the entire network. The inventory system under Seifbarghy and Jokar's [**68**] consideration uses continuous review inventory policy (R,Q) and assumes constant lead times. In Moinzadeh's paper [**62**], each retailer places their order to the supplier according to the well-known 'Q,R' policy. It is assumed that the supplier has online information about the demand, as well as inventory activities of the product at each retailer, and uses this information when making order/replenishment decisions. Tang and Grubbström's [**63**] general formulae are developed for solving the optimal planned lead times with the objective of minimizing total stockout and inventory holding costs. Axsater [**43**] assumes that the system is controlled by continuous review installation stock (R,Q) policies with given batch quantities and presents a simple technique for approximate optimization of the reorder points.

Cachon and Fisher [**58**] and Tsiakis *et al.* [**61**] use mathematical modelling and scenario analysis in their studies. Cachon and Fisher [**58**] consider a two-echelon inventory system with stochastic demand, while Tsiakis *et al.* [**61**] consider a four-echelon inventory system with time-invariant demand, differently from most studies. Cachon and Fisher [**58**] study the value of sharing demand and inventory data in a two-echelon inventory system, while Tsiakis *et al.*'s [**61**] objective is the minimization of the total annualized cost of the network

Chiu and Huang [**64**] use mathematical modelling and simulated annealing algorithm in their studies and consider an *N*-echelon serial SC. Their paper proposes a multi-echelon integrated just-in-time inventory (MEIJITI) model with random-delivery lead times for a serial SC in which members exchange information to make purchase, production, and delivery decisions jointly.

Parker and Kapuscinski [**30**] use mathematical modelling and Markov decision processes in their paper, and consider a two-echelon inventor system with stochastic demand. Extending the Clark and Scarf [**13**] model to include installations with production capacity limits, they demonstrate that a modified echelon base-stock policy is optimal in a two-stage system when there is a smaller capacity at the downstream facility.

A multi-product, multi-stage, and multi-period production and distribution planning model is proposed in Chen and Lee [**66**] to tackle the compromised sales prices and the total profit problem of a multi-echelon SC network with uncertain sales prices. They use mathematical modelling (mixed integer non-linear programming) and fuzzy optimization in their study.

Jalbar *et al.* [**67**] use mathematical modelling, Schwarz heuristic, Graves and Schwarz procedure, Muckstadt and Roundy approach, and O(N log N) heuristic in their paper, and consider a two-echelon inventory system with one-warehouse and *N*-retailers. The goal is to determine single-cycle policies that minimize the average cost per unit time, that is, the sum of the average holding and set-up costs per unit time at the retailers and at the warehouse.

In Routroy and Kodali's paper [**2**] mathematical modelling and differential evolution algorithms are used. A three-echelon inventory system is considered consisting of a retailer, a warehouse, and a manufacturer.

Han and Damrongwongsiri's [**69**] purpose is establishing a strategic resource allocation model to capture and encapsulate the complexity of the modern global SC management problem. A mathematical model is constructed to describe the stochastic multi-period two-echelon inventory with the many-to-many demand–supplier network problem. Genetic algorithm (GA) is applied to derive near optimal solutions through a two-stage optimization process. Demand in each period can be represented by the probability distribution, such as normal distribution or exponential distribution.

Most of the papers reviewed here use simulation with mathematical modelling. They consider intensively two-echelon inventory system with stochastic demand, 1, 3, or *N*-echelon systems are rarely considered. They gain exact or approximate solutions.

Scenario analysis, simulated annealing algorithm, Markov decision process, fuzzy optimization, heuristics, differential evolution algorithm, and GAs are used in addition to mathematical modelling in some of these papers. These techniques, however, are not used commonly in more than in a few papers, as they consider mostly two-echelon systems, but there are papers considering two-, three-, four-, or *N*-echelons. They usually assume stochastic demand and constant, fuzzy, or negligible lead times. With the exception of Parker and Kapuscinski [**30**] they obtain approximate solutions.

3.3 METRIC modelling technique

Moinzadeh and Aggarwal [**11**] use METRIC modelling and simulation techniques in their study, while Andersson and Melchiors [**42**] and Wang *et al.* [**73**] use METRIC modelling only. The three of them consider a two-echelon inventory system with stochastic demand, and obtain approximate solutions.

Moinzadeh and Aggarwal [**11**] study a (S-1,S)-type multi-echelon inventory system where all the stocking locations have the option to replenish their inventory through either a normal or a more expensive emergency resupply channel. Wang *et al.* [**73**] study the impact of such centre-dependent depot-replenishment lead times (DRLTs) on system performance. Andersson and Melchiors [**42**] evaluate and optimize S-1,S-policies for a two-echelon inventory system consisting of one central warehouse and an arbitrary number of retailers.

3.4 Markov decision process technique

Iida [**74**], Chen and Song [**75**], Chen *et al.* [**76**], and Minner *et al.* [**77**] use the Markov decision process in their studies, while Chiang and Monahan [**10**] use Markov decision process and scenario analysis, and Johansen [**78**] uses Markov decision process, simulation, and Erlang's loss formula together. Iida [**74**] and Chen and Song [**75**] consider an *N*-echelon inventory system, but under stochastic demand in the first study and Markov-modulated demand in the second one, respectively. Chen *et al.* [**76**], Minner *et al.* [**77**], and Chiang and Monahan [**10**] consider a two-echelon inventory system with stochastic demand. Johansen [**78**] considers a single-item inventory system and a sequential supply system with stochastic demand.

The main purpose of Iida's [**74**] paper is to show that near-myopic policies are acceptable for a multi-echelon inventory problem. It is assumed that lead times at each echelon are constant. Chen and Song's [**75**] objective is to minimize the long-run average costs in the system. In the system by Chen *et al.* [**76**], each location employs a periodic-review (R,nQ), or lot-size reorder point inventory policy. They show that each location's inventory positions are stationary and the stationary distribution is uniform and independent of any other. In the study by Minner *et al.* [**77**], the impact of manufacturing flexibility on inventory investments in a distribution network consisting of a central depot and a number of local stockpoints is investigated. Chiang and Monahan [**10**] present a two-echelon dual-channel inventory model in which stocks are kept in both a manufacturer warehouse (upper echelon) and a retail store (lower echelon), and the product is available in two supply channels: a traditional retail store and an internet-enabled direct channel. Johansen's [**78**] system is assumed to be controlled by a base-stock policy. The independent and stochastically dependent lead times are compared.

To sum up, these papers consider two- or *N*-echelon inventory systems, with generally stochastic demand, except for one study that considers Markov-modulated demand [**75**]. They generally assume constant lead time, but two of them accept it to be stochastic. They gain exact or approximate solutions.

3.5 Simulation

Tee and Rossetti [**15**], Ng *et al.* [**79**], Martel [**80**], Kiesmüller *et al.* [**81**], and Liberopoulos and Koukoumialos [**82**] use simulation as a research technique in their studies about multi-echelon inventory management. Tee and Rossetti [**15**] examine the robustness of a standard model of multi-echelon inventory systems, specifically the models discussed in Axsater [**59**]. They, and Liberopoulos and Koukoumialos [**82**] consider a two-echelon inventory system, while Ng *et al.* [**79**], Martel [**80**], and Kiesmüller *et al.* [**81**] consider *N*-echelon systems.

Tee and Rossetti's [**15**] study evaluates the behaviour of a (R,Q) multi-echelon inventory model in predicting the total system cost under a non-stationary Poisson demand process. Also, here, it is assumed that the transport lead times are one day for all situations. Ng *et al.* [**79**] use different inventory policies at the echelon level, and the demand and lead times are uncertain. Martel [**80**] develops rolling, planning, horizon policies to manage material flows in multi-echelon supply–distribution networks with relatively general stochastic-demand processes and procurement, transportation, inventory, and shortage cost structures under (S-1,S) policy. Kiesmüller *et al.* [**81**] assume that all stock points are controlled by continuous review (s,nQ) installation stock policies with stochastic transportation times and compound renewal demand. Liberopoulos and Koukoumialos [**82**] numerically investigate trade-offs between near-optimal base-stock levels, numbers of kanbans, and planned supply lead times in base-stock policies and hybrid base-stock/kanban policies with advance demand information used for the control of multi-stage production/inventory systems.

In summary, all papers that are reviewed here gain approximate results. They usually present generalized models with *N*-echelon, and solve a small example as two- or three-echelon. They assume demand and lead times to be stocastic, uncertain, constant, or deterministic.

3.6 Stackelberg game

Axsater [**83**] and Lau and Lau [**84**] utilize the Stackelberg game in their papers. In Axsater's paper [**83**] a cost stucture is provided that can be used to decentralize control of a multi-echelon inventory system consisting of a central depot and several retailers. It is assumed that the demand of retailers is derived from independent Poisson processes. Lau and Lau's paper [**84**] applies different demand-curve functions to a simple inventory/pricing model, and shows that while the common-wisdom implication is valid for a single-echelon system, assuming different demand curve functions can lead to very different results in a multi-echelon system.

3.7 Literature review technique

Minner [**1**] and Thomas and Griffin [**29**] review the literature about multi-echelon inventory management in SCs.

Minner [**1**] reviews inventory models with multiple supply options and discusses their contribution to SCM in his paper. Further, related inventory problems from the fields of reverse logistics and multi-echelon systems are presented. Within the context of review, the studies that make deterministic and stochastic demand and lead time assumptions are placed.

Thomas and Griffin [**29**] review the literature addressing coordinated planning between two or more stages of the SC, placing particular emphasis on models that would lend themselves to a total SC model.

3.8 Other techniques

In multi-echelon inventory management there are some other research techniques used in literature, such as heuristics, vari-METRIC method, fuzzy sets, model predictive control, scenario analysis, statistical analysis, and GAs. These methods are used rarely and only by a few authors.

Yoo *et al.* [**85**] and Jalbar *et al.* [**86**] use heuristics to multi-echelon inventory management in SCs. Yoo *et al.* [**85**] utilize from a heuristic method in their study, and they have made their experiment with various demand distributions, forecast error distributions, and lead times. Jalbar *et al.* [**86**] use Raundy procedure and O(N log N) heuristics in their paper, and assume that customer demand arrives at each retailer at a constant rate and lead times are negligible.

Liang and Huang [**87**] and Köchel and Nielander [**88**] use GA. Additionally, Liang and Huang [**87**] use an agent-based system, beer game, and statistical analysis to strengthen the solution methodology. Similarly, Köchel and Nielander [**88**] use simulation for the same purpose. Liang and Huang's study [**87**] develops a multi-agent system to simulate a SC, where agents operate these entities with different inventory systems. The demand is forecasted with a GA and the ordering quantity is offered at each echelon incorporating the perspective of 'systems thinking'. Köchel and Nielander [**88**] propose the simulation optimization approach where a simulator is combined with an appropriate optimization tool. Here, the analyses are made according to zero and random lead-time situations, and infinite or finite (Poisson or arbitrary process) and constant- or random-demand characteristics situations.

In Sleptchenko *et al.*'s work [**89**] the vari-METRIC method is used in multi-echelon, multi-indenture supply systems for repairable service parts with finite repair capacity. It is assumed here that demands occur according to stationary Poisson processes, independent of the number of items under repair.

Giannoccaro *et al.*'s paper [**5**] presents a methodology to define a SC inventory-management policy, which is based on the concept of echelon-stock and fuzzy-set theory. In particular, the echelon-stock concept is adopted to manage the SC inventory in an integrated manner, whereas fuzzy-set theory is used properly to model the uncertainty associated with both market demand and inventory costs. Finally, by adopting simulation, the performance of the three-stage SC is assessed and shown to be superior to that which the adoption of a local inventory management policy would guarantee. In this study, lead times are assumed to be deterministic and constant.

Kalchschmidt *et al.*'s work [**12**] describes an integrated system for managing inventories in a multi-echelon spare parts SC, in which customers of different sizes lay at the same level of the SC. Here, an algorithmic solution is provided through probabilistic forecasting and inventory management.

The translation of the SC problem into a formulation amenable to model predictive control (MPC) implementation is initially developed for a single-product, two-node example. Insights gained from this problem are used to develop a partially decentralized MPC implementation for a six-node, two-product, three-echelon demand network problem developed by Intel Corporation that consists of interconnected assembly/test, warehouse, and retailer entities in Braun *et al.*'s paper [**90**]. Lead times are estimated by facility personnel.

A multi-product, multi-stage, and multi-period scheduling model is proposed by Chen and Lee [**91**] to deal with multiple incommensurable goals for a multi-echelon SC network with uncertain market demands and product prices. The uncertain market demands are modelled as a number of discrete scenarios with known probabilities, and the fuzzy sets are used for describing the sellers' and buyers' incompatible preference on product prices.

The paper by Chandra and Grabis [**92**] quantifies the bullwhip effect in the case of serially correlated external demand, if autoregressive models are applied to obtain multiple steps demand forecasts. Here, under autoregressive demand, inventory management of a two-echelon SC consisting of a retailer and a distributor is considered. It is assumed that the lead time is deterministic.

The papers using the other techniques consider (one-, two-, three-, four-, five-, or *N*-echelon systems) assume stochastic, constant, fuzzy, or deterministic demand and lead times. All of them obtain approximate solutions.

4 FINDINGS OF THE LITERATURE REVIEW

Limited echelons of a multi-echelon inventory system is usually considered in the literature. They rarely generalize their models to *N*-echelon. Similarly, they usually consider serial systems, instead of a tree conformation.

The authors generally assume demand and lead times to be stochastic, deterministic, constant, or negligible. There are only a few studies that find these variables with heuristics, fuzzy logic, and GAs. These techniques are not examined adequately yet in inventory management in multi-echelon SC.

In addition, the papers present mostly approximate models. There are a small amount of papers that give exact solutions. The summary of literature review addressing multi-echelon inventory management in SC can be seen from Table 1.

5 CONCLUSION AND DISCUSSION

In the current paper, a detailed literature review, conducted from an operational research point of view, is presented, addressing multi-echelon inventory management in supply chains from 1996 to 2005. Here, the behaviour of the papers, against demand and lead time uncertainty, is emphasized. First, echelon concept and multi-echelon inventory management in SCs are defined. Then, the literature review between 1996 to 2005 is presented.

The summary of literature review is given as: the most used research technique is simulation. Also, analytic, mathematic, and stochastic modelling techniques are commonly used in literature. Recently, heuristics as fuzzy logic and GAs have gradually started to be used.

Table 1 The summary of literature review addressing multi-echelon inventory management in supply chains

Author, year	Research technique	Number of echelons	Inventory system/policy	Demand assumption	Lead-time assumption	Exact/approximate solution	Objective
Forsberg (1996)	Mathematical modelling and simulation	2 – one warehouse, *N* different retailers	Continuous review (R,Q)* policies	Stochastic – Poisson	Constant	Exact	To show how exactly to evaluate holding and shortage costs for a two-level inventory system
Graves (1996)	Mathematical modelling and simulation	2 – one central warehouse, several retailers	Order-up-to policy	Stochastic	Deterministic	Approximate	To develop a new model for studying multi-echelon inventory systems with stochastic demand
Verrijdt and de Kok (1996)	Mathematical modelling and simulation	2 – one central depot, a number of end stock points	Order-up-to policy	Stochastic	Constant	Approximate	To present two adjustment methods that improve the service performance considerably in certain cases and to generalize the concept of imbalance
Thomas and Griffin (1996)	Literature review	2 or more stages	–	–	–	–	To review the literature addressing coordinated planning between two or more stages of the supply chain
Yoo *et al.* (1997)	A heuristic method	2 – one central distribution centre, *N* regional distribution centres	Reorder point policy and fixed-order interval policy	Probabilistic	Constant	Approximate	To propose an improved DRP method to schedule multi-echelon distribution network
Moinzadeh and Aggarwal (1997)	METRIC modelling and simulation	2 – a warehouse and *M* retail centres	(S-1,S)*-type inventory system	Random and stochastic – Poisson	Deterministic	Approximate	To propose and test an order/expediting policy that uses the information about the remaining lead times of the orders
Mohebbi and Posner (1998)	Mathematical modelling and simulation	1 – two or more suppliers	Continuous review inventory system – an (s, Q)* policy	Stochastic – compound Poisson	Stochastic – exponentially distributed	Exact	To present an exact treatment of sole versus dual sourcing problem in the context of a lost sales inventory system
Bollapragada *et al.* (1998)	Mathematical modelling and simulation	2 – a single depot that supplies several warehouses	Base stock policy–optimal allocation policy at the depot	Stochastic	Fixed	Approximate	To generalize the earlier work by Eppen and Schrage, to allow for non-identical warehouses
Dekker *et al.* (1998)	Mathematical modelling and simulation	2 – one warehouse, *N* retailers	Not specified	Stochastic – normally distributed	Stochastic – normally distributed	Exact	To provide insight into the effect of the break quantity rule on the inventory holding costs
Diks and de Kok (1998)	Mathematical modelling	Divergent *N*-echelon	Periodic review order-up-to policy	i.i.d.$^{+}$	Fixed	Exact	To minimize the expected holding and penalty costs per period
Hariga (1998)	Mathematical modelling	*N*-echelon	A composite strategy of the assemble to order and assemble in advance policies	Stochastic – different demand distributions	Not specified	Approximate	To present a stochastic model for a single-period production system composed of several assembly/processing and storage facilities in series

Korugan and Gupta (1998)	Mathematical modelling and simulation	2 – a warehouse and *N*-retailers, and a warehouse and *M*-customers	A continuous (Q,r)* inventory policy	Demand rate is probabilistic	Not specified	Approximate	To model a two-echelon inventory system by usage of an open queueing network with finite buffers
Ganeshan (1999)	Mathematical modelling and simulation	3 – a multiple retailers, one warehouse and multiple suppliers	A near-optimal (s,Q)*-type inventory policy	Stochastic	Stochastic	Approximate	To present a near-optimal (s,Q)-type inventory-logistics cost-minimizing model for a production/distribution network
Chen (1999)	Mathematical modelling	2 – customer demand arises at stage 1, stage 1 replenishes its inventory from stage 2, and stage 2 orders from an outside supplier	(R,Q)* policy	Deterministic	Zero	Approximate	To minimize the (long-run average) total cost in the system
Van der Heijden *et al.* (1999)	Mathematical modelling and simulation	2 – and then extended for *N*-echelons	Periodic review, order-up-to (R,S)* policy	Stochastic	Stochastic	Approximate	To develop an algorithm to analyse multi-echelon divergent networks with integral (R,S) inventory control under both stochastic demand and lead times
Van der Heijden (1999)	Mathematical modelling and simulation	2 – a central depot and multiple (non-identical) local warehouses	Order-up-to (R,S)* policy	Stochastic and stationary in time	Constant and deterministic	Approximate	To present a computational method to derive the control parameters in a two-echelon distribution system with different shipment frequencies at both levels
Axsater and Zhang (1999)	Mathematical modelling	2 – a central warehouse and a number of identical retailers	Warehouse uses a regular installation stock batch-ordering policy	Stochastic – stationary and independent Poisson demand	Constant	Exact	To show how the costs can be evaluated, and compare the policy both to an installation stock and to an echelon stock policy
Andersson and Marklund (2000)	Mathematical modelling and simulation	2 – one central warehouse and *N*-non-identical retailers	An installation stock (R,Q)* policy	Stochastic – normally distributed demand	Stochastic	Approximate	To analyse a conceptually quite simple model for highly decentralized control of a two-level distribution system
Wang *et al.* (2000)	METRIC modelling	2 – a central repair depot and multiple inventory stocking centres	Continuous-review, one-for-one policy	Stochastic – Poisson	i.i.d.$^{+}$	Approximate	To find impact of such centre-dependent depot replenishment lead times on system performance
Cachon and Fisher (2000)	Mathematical modelling and scenario analysis	2 – one supplier, *N*-identical retailers	A (R_r, nQ_r)* reorder point policy	Stationary stochastic consumer demand	Constant	Approximate	To study the value of sharing information and develop a simulation-based lower bound over all feasible policies
Axsater (2000)	Mathematical modelling and simulation	2 – one central warehouse and *N*-retailers	Continuous review installation stock (R,Q)* policies	Stochastic – independent compound Poisson demand	Constant	Exact	To present a method for exact evaluation of control policies that provides the complete probability distributions of the retailer inventory levels

Table 1 (Continued)

Author, year	Research technique	Number of echelons	Inventory system/policy	Demand assumption	Lead-time assumption	Exact/approximate solution	Objective
Iida (2001)	Markov decision process	*N*-Echelon serial inventory system	Near-myopic policy	Stochastic – nonstationary	Constant	Approximate	To show that near-myopic policies are acceptable for multi-echelon inventory problem
Axsater (2001a)	Stackelberg game	2 – a central warehouse and a number of retailers	S policies or (R,Q)* policies	Stochastic – derived from independent Poisson processes	Constant	Approximate	To provide a cost structure that can be used for decentralized control of a multi-echelon inventory system
Axsater (2001b)	Mathematical modelling and simulation	2 – echelon distribution inventory system	Continuous review (R,Q)* policies	Stochastic	Constant	Approximate	To suggest and evaluate an approximate method for optimization of a two-echelon inventory system
Chen and Song (2001)	Markov decision process	*N*-echelon serial inventory system	State dependent (s,S)* policy	Markov – modulated demand	Constant	Exact	To minimize the long-run average costs in the system
Nozick and Turnquist (2001)	Mathematical modelling	2 – a multi-product inventory system	Not specified	Stochastic – Poisson	Not specified	Exact	To present a model for optimizing the location of inventory for individual products and integration location analysis for distribution centres
Andersson and Melchiors (2001)	METRIC modelling	2 – one central warehouse and an arbitrary number of retailers	(S-1,S)* policies with continuous review	Stochastic – compound Poisson demand	Constant	Approximate	To evaluate and optimize (S-1,S)-policies by a heuristic method for a one warehouse, multiple retailers inventory system
Tsiakis *et al.* (2001)	Mathematical modelling (MILP) and scenario analysis	4 – a number of manufacturing sites, warehouses, and distribution centres and customer zones	Not specified	Time-invariant demand (but possibly uncertain)	Not specified	Approximate	To minimize the total annualized cost of the network, taking into account both infrastructure and operating costs
Chen *et al.* (2002)	Markov decision process	2 – one supplier and multiple retailers	A periodic-review (R,nQ)*, or lot-size reorder point inventory policy	Stochastic, interdependent demands	Constant	Exact	To show that each location's inventory positions are stationary and the stationary distribution is uniform and independent of any other's
Sleptchenko *et al.* (2002)	VARI-METRIC method	Multi-echelon, multi-indenture supply systems	(S-1,S)* inventory policy	Stochastic – stationary Poisson processes	Dependent repair lead times	Approximate	To show that the commonly used assumption of infinite capacity may seriously affect system performance and stock allocation decisions if the repair shop utilization is relatively high
Moinzadeh (2002)	Mathematical modelling and simulation	2 – one supplier and *M* identical retailers	(Q,R)* policy	Stochastic – random, but stationary	Constant	Exact	To propose a replenishment policy for the supplier and then to provide an exact analysis of the operating measures

Tee and Rossetti (2002)	Simulation	2 – one-warehouse, multiple retailer system	(R,Q)* inventory policies	Stochastic – non-stationary Poisson demand process	One day for all situations	Approximate	To examine the robustness of a standard model of multi-echelon inventory systems, specifically the models discussed in Axsater (2000)
Rau *et al.* (2003)	Mathematical modelling	3 – single supplier, single producer, and single retailer	Not specified	Demand rate is deterministic and constant	Negligible	Exact	To develop a multi-echelon inventory model for a deteriorating item and to derive an optimal joint total cost from an integrated perspective among the supplier, the producer, and the buyer
Minner (2003)	Literature review	–	–	–	–	–	To review the literature on inventory models with multiple suppliers and to discuss their potential contribution to SCM issues
Giannoccaro *et al.* (2003)	Simulation and fuzzy set theory	*N* – stage serial system	Echelon periodic-review control policy	Fuzzy	Assumed to be deterministic and constant	Approximate	To present a methodology defining a supply chain inventory management policy, which is based on the concept of echelon stock and fuzzy set theory
So and Zheng (2003)	Mathematical modelling	2 – a retailer and a supplier	Order-up-to policy	Stochastic – independent and identically distributed	Variable and affected by the retailer's order quantities	Approximate	To analyse two important factors that can contribute to the high degree of order quantity variability experienced by semiconductor manufacturers: supplier's lead time and forecast demand updating
Kalchschmidt *et al.* (2003)	An algorithmic solution is provided through probabilistic forecasting and inventory management	1 and 2 – central warehouse serves on one side, a one-echelon chain, and a two-echelon supply chain	Order-up-to policy	Stochastic – variable and lumpy	Not specified	Approximate	To describe an integrated system for managing inventories in a multi-echelon spare parts supply chain, in which customers of different size lay at the same level of the supply chain
Tang and Grubbström (2003)	Mathematical modelling and simulation	2 – level assembly system	Lot-for-lot policy	Constant and deterministic	Stochastic	Approximate	To minimize total stockout and inventory holding costs
Ng *et al.* (2003)	Simulation	*N*-echelon supply chains	Different inventory policies at the echelon level	Uncertain	Uncertain	Approximate	The development of a simulation workbench for modelling and analysing multi-echelon supply chains
Martel (2003)	Simulation	*N*- and three-echelon for numerical example	(S-1,S)* policy	Stochastic	A pre-planned integer number	Approximate	To develop rolling planning horizon policies to manage material flows in multi-echelon supply–distribution networks

Table 1 (Continued)

Author, year	Research technique	Number of echelons	Inventory system/policy	Demand assumption	Lead-time assumption	Exact/ approximate solution	Objective
Dong and Lee (2003)	Mathematical modelling	*M*-echelon serial periodic review inventory system and three echelons for numerical example	An echelon base-stock inventory policy, order-up-to S policy	An autoregressive demand model; assumed to be i.i.d.$^{+}$	Variable to see the impact of lead times and autocorrelation on the performance of the system	Approximate	To extend the approximation to the time correlated demand process of Clark and Scarf (1960) [**13**]
Lau and Lau (2003)	Stackelberg game	1 – an integrated firm 2 – the manufacturer and the retailer 3 – the manufacturer, the wholesaler and the retailer	Not specified	Different demand-curve functions (linear, iso-elastic, exponential, and algebraic)	Not specified	Approximate	To apply different demand-curve functions to a simple inventory/pricing model and show the different results gained
Axsater (2003)	Mathematical modelling and simulation	2 – a central warehouse and a number of retailers	Continuous review installation stock (R,Q)* policies with given batch quantities	Stochastic	Constant and stochastic	Approximate	To present a simple technique for approximate optimization of the reorder points
Minner *et al.* (2003)	Markov decision process	2 – a central depot and a number of local stockpoints	Periodic review echelon-order-up-to policies	Stochastic	Constant, may be different for different retailers	Approximate	To investigate the impact of manufacturing flexibility on inventory investments in a distribution network consisting of a central depot and a number of local stockpoints
Braun *et al.* (2003)	Model predictive control (MPC) and simulation	Six-node, two-product, three-echelon demand network	Not specified	Deterministic	Estimated by facility personnel	Approximate	To develop a partially decentralized MPC implementation
Chiu and Huang (2003)	Mathematical modelling (MINLP) and simulated annealing algorithm	A serial *N*-echelon supply chain in which each echelon contains only one member	A time buffer and emergency borrowing policies	Demand rate of member 1 is known and constant, and of member *i* is related to production rate	A non-negative random variable following a probability distribution	Approximate	To propose a multi-echelon integrated just-in-time inventory (MEIJITI) model with random delivery lead times for a serial supply chain

Mitra and Chatterjee (2004a)	Mathematical modelling	2 – stage 1 is facing demand and is supplied by stage 2, which in turn is supplied by an outside source	Continuous review (R,Q)* system under nested and echelon stock-based policy	Stochastic	Joint and deterministic	Approximate	To examine De Bodt and Graves' model (1985), which they developed in their paper 'Continuous-review policies for a multi-echelon inventory problem with stochastic demand', and suggest a modification
Mitra and Chatterjee (2004b)	Mathematical modelling and simulation	2 – one-warehouse two-retailer	Periodic-review inventory policy	Stochastic – stationary, independent and normally distributed	Deterministic	Approximate	To examine the effect of utilizing demand information in a multi-echelon system
Parker and Kapuscinski (2004)	Mathematical modelling (dynamic programming) and Markov decision process	2 – stage system	A modified echelon base-stock (MEBS) policy	Stochastic and independent from period	Integer and lead time model follows the MEBS policy	Exact	To demonstrate optimal policies for capacitated serial multi-echelon production/inventory systems
Chen and Lee (2004a)	Discrete scenario based approach, fuzzy logic and mathematic modelling (MINLP)	A multi-product, multi-stage, and multi-period scheduling system	Not specified	Stochastic – different scenarios of demand are forecasted with known probabilities	Fuzzy	Compensatory	To deal with multiple incommensurable goals for a multi-echelon supply chain network with uncertain market demands and product prices
Chen and Lee (2004b)	Mathematical modelling (MINLP) and fuzzy optimization	A multi-product, multi-stage, and multi-period model	Not specified	Uncertain and stochastic	Deterministic	Approximate	To tackle the compromised sales prices and the total profit problem of a multi-echelon supply chain network with uncertain sales prices
Kiesmüller *et al.* (2004)	Simulation	*N*-echelon and two- and three-echelons for numerical example	Continuous review (s,nQ)* installation stock policy	Stochastic – compound renewal demand	Stochastic	Approximate	To derive analytical approximations for performance characteristics of a divergent multi-echelon distribution network
Seferlis and Giannelos (2004)	Mathematical modelling and simulation	4 – two production nodes, two-warehouse nodes, four-distribution centres, and 16 retailer nodes	A decentralized safety inventory control policy	Both stochastic and deterministic demand variations	Not specified	Approximate	To treat process uncertainty within the deterministic supply chain network model, a rolling-horizon, model-predictive control approach is suggested
Chiang and Monahan (2005)	Markov decision process and scenario analysis	2 – a manufacturer warehouse and a retail store	One-for-one replenishment inventory control policy	Stochastic	Stochastic – independent exponential random variables	Exact	To analyse the impact of customers' search rates on the channel performance and to present a two-echelon dual-channel inventory model

Table 1 (Continued)

Author, year	Research technique	Number of echelons	Inventory system/policy	Demand assumption	Lead-time assumption	Exact/approximate solution	Objective
Jalbar *et al.* (2005a)	Mathematical modelling, Schwarz heuristic, Graves and Schwarz procedure, Muckstadt and Roundy approach, and O(N log N) heuristic	2 – one-warehouse and *N*-retailers	Single-cycle-policies	Demand rates are assumed to be known and constant	Negligible	Approximate	To determine single-cycle policies that minimize the average cost per unit time
Jalbar *et al.* (2005b)	Raundy procedure and O(N log N) heuristic	2 – one-warehouse and *N*-retailers	Nested policy	Arrives at each retailer at a constant rate	Negligible	Approximate	To propose a heuristic process to compute near-optimal policies
Johansen (2005)	Markov decision process, simulation and Erlang's loss formula	Single-item inventory system and a sequential supply system	Base-stock policy	Stochastic – Poisson	Stochastic – Erlangian	Approximate	To study how to compute the optimal base-stock for a lost sales inventory model with a sequential supply system and Erlangian lead times
Chandra and Grabis (2005)	Simulation and statistical analysis	2 – A retailer and a distributor	An order-up policy and MRP	Autoregressive demand	Deterministic	Approximate	To quantify the bullwhip effect in the case of serially correlated external demand
Liberopoulos and Koukoumialos (2005)	Simulation	Single-stage and two-stage production/inventory systems	Base-stock policy and hybrid-base stock/kanban policy	Arrives randomly with constant demand lead time	A fixed lead-time parameter and analytically obtained	Approximate	To investigate trade offs between near-optimal base stock levels, numbers of kanbans, and planned supply lead times in base stock policies, and hybrid base stock/kanban policies

Liang and Huang (2005)	Agent-based system, genetic algorithm, beer game, and statistical analysis	4 – supplier (P system), manufacturer (Q system), distributor (P system) and retailer (optional system)	(P Q P O) inventory policy-periodic review (P), continuous review (Q), and optional (O) systems	Demand is forecasted with a genetic algorithm	The lead-time data are collected by the control agents	Approximate	To develop a multi-agent system to simulate a supply chain
Seifbarghy and Jokar (2005)	Mathematical modelling (deterministic) and simulation	2 – one central warehouse and many identical retailers	Continuous review inventory policy (R,Q)*	Stochastic – independent Poisson demands	Constant	Approximate	To develop an approximate cost function to find optimal reorder points for given batch sizes in all installations
Routroy and Kodali (2005)	Mathematical modelling and differential evolution algorithm	3 – a retailer, a warehouse and a manufacturer	A continuous review policy (Q,r)*	Stochastic – normally distributed	Constant	Approximate	To minimize the total system wide cost, i.e. supply chain inventory capital, supply chain ordering/set-up cost, and supply chain inventory stock out cost
Köchel and Nielander (2005)	Simulation and genetic algorithms	5 – factory depot, central stock, district warehouse, branch store, and retailer outlet	Continuous-review, order-point, order-quantity strategy (s,Q)*	Stochastic – Poisson, constant or random	Zero or random	Approximate	To show that simulation optimization successfully can be applied to define optimal policies in very general multi-echelon inventory systems
Han and Damrongwongsiri (2005)	Mathematical modelling and genetic algorithms	2 – I number of warehouses and J number of markets	A (t,S)* control policy	Stochastic – represented by the probability distribution, (normal or exponential)	There is no lead time	Approximate	To establish a strategic resource allocation model to capture and encapsulate the complexity of the modern global supply chain management problem

*(Q,r), (Q,R), (R,Q), (R,nQ), (s,Q), (s,nQ) an order for Q or nQ is placed whenever the stock level falls to reorder point of r, R, or s (s,S), (S-1,S) the stock level equals S (order-up-to level) and each demand immediately generates an order for a replacement item (R,S) every R period the central authority issues a replenishment order that raises the echelon inventory position to the level S (t,S) the inventory will be replenished according to scheduling period, t, to the inventory ordering level, S

$^{+}$i.i.d. = independent and identically distributed

The number of echelons considered in studies are usually two or three. The solutions are rarely generalized to *N*-echelons. If inventory system/policy is examined, then it can be seen that continuous review policies are used mostly.

To overcome demand- and lead-time uncertainties there are different assumptions in different studies, but generally they are determined according to various probability distributions. There are also some assumptions such as deterministic, constant, negligible, zero, etc.

If the solutions' certainty is examined, then it can be seen that there are commonly approximate solutions and rarely exact solutions. Herein, the effects of several variable and uncertain factors of multi-echelon inventory management can not be omitted.

Generally, there are various assumptions to remove the uncertainties, especially concerned with demand and lead times. There are many variables that change according to problem type, sector studied, product, research method, number of echelons, etc., in multi-echelon inventory management. Hence there is a search to find optimal combinations under these uncertain and variable conditions. For further researches, it can be suggested to take advantage of several techniques, such as artificial neural networks, fuzzy logic, genetic algorithms, etc., that give more realistic results and consider real-world situations to remove uncertainties for multi-echelon inventory management in SCs. Also, as research directs, the assumption of being identical for retailers or other installations can be omitted. The supply network studied can be extended to an *N*-echelon-tree structure, the models developed can be tried for different SCs to show their availability of utilization, the product variability can be increased in the chain, and user-friendly and dynamic software can be presented to real-life application convenience containing the developed models and calculations.

REFERENCES

1 **Minner, S.** Multiple-supplier inventory models in supply chain management: a review. *Int. J. Prod. Econ.*, 2003, **81–82**, 265–279.

2 **Routroy, S.** and **Kodali, R.** Differential evolution algorithm for supply chain inventory planning. *J. Mfg Technol. Mgmt*, 2005, **16**(1), 7–17.

3 **Simchi-Levi, D., Kaminsky, P.,** and **Simchi-Levi, E.** *Designing and managing the supply chain*, 2000 (Irwin McGraw-Hill, Boston, MA).

4 **Arnold, J. R. T.** *Introduction to materials management*, 1998 (Prentice Hall, USA).

5 **Giannoccaro, I., Pontrandolfo, P.,** and **Scozzi, B.** A fuzzy echelon approach for inventory management in supply chains. *Eur. J. Opl Res.*, 2003, **149**, 185–196.

6 **Ganeshan, R.** Managing supply chain inventories: a multiple retailer, one warehouse, multiple supplier model. *Int. J. Prod. Econ.*, 1999, **59**, 341–354.

7 **Towill, D. R.** Industrial dynamics modeling of supply chains. *Logistics Inf. Mgmt*, 1996, **9**, 43–56.

8 **Rau, H., Wu, M.-Y.,** and **Wee, H.-M.** Integrated inventory model for deteriorating items under a multi-echelon supply chain environment. *Int. J. Prod. Econ.*, 2003, **86**, 155–168.

9 **Diks, E. B.** and **de Kok, A. G.** Optimal control of a divergent multi-echelon inventory system. *Eur. J. Opl Res.*, 1998, **111**, 75–97.

10 **Chiang, W. K.** and **Monahan, G. E.** Managing inventories in a two-echelon dual-channel supply chain. *Eur. J. Opl Res.*, 2005, **162**, 325–341.

11 **Moinzadeh, K.** and **Aggarwal, P. K.** An information based multiechelon inventory system with emergency orders. *Ops Res.*, 1997, **45**(5), 694.

12 **Kalchschmidt, M., Zotteri, G.,** and **Verganti, R.** Inventory management in a multi-echelon spare parts supply chain. *Int. J. Prod. Econ.*, 2003, **81–82**, 397–413.

13 **Clark, A.** and **Scarf, H.** Optimal policies for a multi-echelon inventory problem. *Mgmt Sci.*, 1960, **6**, 475–490.

14 **Bollapragada, S., Akella, R.,** and **Srinivasan, R.** Centralized ordering and allocation policies in a two-echelon system with non-identical warehouses. *Eur. J. Opl Res.*, 1998, **106**, 74–81.

15 **Tee, Y. S.** and **Rossetti, M. D.** A robustness study of a multi-echelon inventory model via simulation. *Int. J. Prod. Econ.*, 2002, **80**, 265–277.

16 **Dong, L.** and **Lee, H. L.** Optimal policies and approximations for a serial multiechelon inventory system with time-correlated demand. *Ops Res.*, 2003, **51**(6), 969.

17 **van der Vorst, J. G. A. J., Beulens, A. J. M.,** and **van Beek, P.** Modelling and simulating multi-echelon food systems. *Eur. J. Opl Res.*, 2000, **122**, 354–366.

18 **Bessler, S. A.** and **Veinott, A. F.** Optimal policy for a dynamic multi-echelon inventory model. *Naval Res. Logistics Q.*, 1965, **13**(4), 355–389.

19 **Eppen, G.** and **Schrage, L.** Centralized ordering policies in a multi-warehouse system with lead times and random demand. *Multi-level production-inventory control systems: theory and practice* (Ed. L. B. Schwarz), 1981 (North-Holland, Amsterdam).

20 **van der Heijden, M. C.** Multi-echelon inventory control in divergent systems with shipping frequencies. *Eur. J. Opl Res.*, 1999, **116**, 331–351.

21 **Rosenbaum, B. A.** Service level relationships in a multi-echelon inventory system. *Mgmt Sci.*, 1981, **27**(8), 926–945.

22 **Federgruen, A.** and **Zipkin, P.** Computational issues in an infinite-horizon, multi-echelon inventory model. *Ops. Res.*, 1984, **32**, 818–836.

23 **Schwarz, L. B., Deuermeyer, B. L.,** and **Badinelli, R. D.** Fill rate optimization in a one-warehouse N-identical retailer distribution system. *Mgmt Sci.*, 1985, **31**(4), 488–498.

24 **Jackson, P. L.** Stock allocation in a two-echelon distribution system or "what to do until your ship comes in". *Mgmt Sci.*, 1988, **34**, 880–895.

25 **Jackson, P. L.** and **Muckstadt, J. A.** Risk pooling in a two-period, two-echelon inventory stocking and

allocation problem. *Naval Res. Logistic Q.*, 1989, **36**(1), l–26.

26 **Erkip, N., Hausman, W. H.,** and **Nahmias, S.** Optimal centralized ordering policies in multi-echelon inventory systems with correlated demands. *Mgmt Sci.*, 1990, **36**(3), 38l–392.

27 **Axsater, S.** Simple solution procedures for a class of two-echelon inventory problems. *Ops Res.*, 1990, **38**, 1, 64.

28 **Verrijdt, J. H. C. M.** and **de Kok, A. G.** Distribution planning for a divergent depotless two-echelon network under service constraints. *Eur. J. Opl Res.*, 1996, **89**, 341–354.

29 **Thomas, D. J.** and **Griffin, P. M.** Coordinated supply chain management. *Eur. J. Opl Res.*, 1996, **94**, 1–15.

30 **Parker, R. P.** and **Kapuscinski, R.** Optimal policies for a capacitated two-echelon inventory system. *Ops Res.*, 2004, **52**(5), 739.

31 **Hadley, G.** and **Whitin, T. M.** *Analysis of inventory systems*, 1963 (Prentice-Hall, Englewood Cliffs, NJ).

32 **Sherbrooke, C. C.** Metric: a multi-echelon technique for recoverable item control. *Ops Res.*, 1968, **16**, 122–141.

33 **Sherbrooke, C. C.** Optimal inventory modeling of systems-multi-echelon techniques, 1992 (John Wiley & Sons, New York).

34 **Moinzadeh, K.** and **Lee, H. L.** Batch size and stocking levels in multi-echel on repairable systems. *Mgmt Sci.*, 1986, **32**, 1567–1591.

35 **Svoronos, A.** and **Zipkin, P.** Estimating the performance of multi-level inventory systems. *Ops Res.*, 1988, **36**, 57–72.

36 **Nahmias, S.** and **Smith, S. A.** Optimizing inventory levels in a two-echelon retailer system with partial lost sales. *Mgmt Sci.*, 1994, **40**, 582–596.

37 **Aggarwal, P. K.** and **Moinzadeh, K.** Order expedition in multi-echelon production/distribution systems. *IIE Trans.*, 1994, **26**, 86–96.

38 **Pyke, D. F.** Priority repair and dispatch policies for repairable-item logistics systems. *Naval Res. Logistics*, 1990, **37**, 1–30.

39 **Dada, M.** A two-echelon inventory system with priority shipments. *Mgmt Sci.*, 1992, **38**, 1140–1153.

40 **Alfredsson, P.** and **Verrijdt, J.** Modeling emergency supply flexibility in a two-echelon inventory system. *Mgmt Sci.*, 1999, **45**, 1416–1431.

41 **Seferlis, P.** and **Giannelos, G. F.** A two-layered optimisation-based control strategy for multi-echelon supply chain networks. *Computers Chem. Engng*, 2004, **28**, 799–809.

42 **Andersson, J.** and **Melchiors, P.** A two-echelon inventory model with lost sales. *Int. J. Prod. Econ.*, 2001, **69**, 307–315.

43 **Axsater, S.** Approximate optimization of a two-level distribution inventory system. *Int. J. Prod. Econ.*, 2003, **81–82**, 545–553.

44 **Silver, E. A., Pyke, D. F.,** and **Peterson, R.** *Inventory management and production planning and scheduling*, third edition, 1998 (John Wiley, New York).

45 **Mitra, S.** and **Chatterjee, A. K.** Echelon stock based continuous review (R;Q) policy for fast moving items. *Omega*, 2004a, **32**, 161–166.

46 **Hariga, M.** A single-period, multi-echelon stochastic model under a mix of assemble to order and assemble in advance policies. *Naval Res. Logistics*, 1998, **45**, 599–614.

47 **Chen, F.** Worst-case analysis of (R;Q) policies in a two-stage serial inventory system with deterministic demand and backlogging. *Ops Res. Lett.*, 1999, **25**, 51–58.

48 **Axsater, S.** and **Zhang, W.-F.** A joint replenishment policy for multi-echelon inventory control. *Int. J. Prod. Econ.*, 1999, **59**, 243–250.

49 **Nozick, L. K.** and **Turnquist, M. A.** A two echelon inventory allocation and distribution center location analysis. *Transpn Res., Part E*, 2001, **37**, 425–441.

50 **So, K. C.** and **Zheng, X.** Impact of supplier's lead-time and forecast demand updating on retailer's order quantity variability in a two-level supply chain. *Int. J. Prod. Econ.*, 2003, **86**, 169–179.

51 **Forsberg, R.** Exact evaluation of (R, Q)-policies for two-level inventory systems with Poisson demand. *Eur. J. Opl Res.*, 1996, **96**, 130–138.

52 **Graves, S. C.** A Multiechelon inventory model with fixed replenisment intervals. *Mgt Sci.*, 1996, **32**(1), 1.

53 **Mohebbi, E.** and **Posner, M. J. M.** Sole versus dual sourcing in a continuous-review inventory system with lost sales. *Computers Ind. Engng*, 1998, **34**(2), 321–336.

54 **Dekker, R., Kleijn, M. J.,** and **de Kok, A. G.** The break quantity rule's effect on inventory costs in a 1-warehouse, N-retailers distribution system. *Int. J. Prod. Econ.*, 1998, **56–57**, 61–68.

55 **Korugan, A.** and **Gupta, S. M.** A multi-echelon inventory system with returns. *Computers Ind. Engng*, 1998, **35**(1–2), 145–148.

56 **van der Heijden, M. C., Diks, E.,** and **de Kok, T.** Inventory control in multi-echelon divergent systems with random lead times. *OR Spektrum*, 1999, **21**, 331–359.

57 **Andersson, J.** and **Marklund, J.** Decentralized inventory control in a two-level distribution system. *Eur. J. Opl Res.*, 2000, **127,** 483–506.

58 **Cachon, G. P.** and **Fisher, M.** Supply chain inventory management and the value of shared information. *Mgmt Sci.*, 2000, **46**(8), 1032–1048.

59 **Axsater, S.** Exact analysis of continuous review (R,Q) policies in two-echelon inventory systems with compound Poisson demand. *Ops Res.*, 2000, **48**(5), 686–696.

60 **Axsater, S.** Scaling down multi-echelon inventory problems. *Int. J. Prod. Econ.*, 2001(b), **71**, 255–261.

61 **Tsiakis, P., Shah, N.,** and **Pantelides, C. C.** Design of multi-echelon supply chain networks under demand uncertainty. *Ind. Engng. Chem. Res.*, 2001, **40**, 3585–3604.

62 **Moinzadeh, K.** A multiechelon inventory system with informaton exchange. *Mgmt Sci.*, 2002, **48**(3), 414.

63 **Tang, O.** and **Grubbström, R. W.** The detailed coordination problem in a two-level assembly system with stochastic lead times. *Int. J. Prod. Econ.*, 2003, **81–82**, 415–429.

64 **Chiu, H. N.** and **Huang, H. L.** A multi-echelon integrated JIT inventory model using the time buffer and emergency borrowing policies to deal with random delivery lead times. *Int. J. Prod. Res.*, 2003, **41**(13), 2911–2931.

65 **Mitra, S.** and **Chatterjee, A. K.** Leveraging information in multi-echelon inventory systems. *Eur. J. Opl Res.*, 2004(b), **152**, 263–280.
66 **Chen, C.-L.** and **Lee, W.-C.** Optimization of multi echelon supply chain networks with uncertain sales prices. *J. Chem. Engng Jap.*, 2004(b), **37**(7), 822–834.
67 **Jalbar, B. A., Gutierrez, J. M.,** and **Sicilia, J.** Single cycle policies for the one-warehouse N-retailer inventory/distribution system. *Omega*, 2005(a), in press.
68 **Seifbarghy, M.** and **Jokar, M. R. A.** Cost evaluation of a two-echelon inventory system with lost sales and approximately Poisson demand. *Int. J. Prod. Econ.*, 2005, in press.
69 **Han, C.** and **Damrongwongsiri, M.** Stochastic modeling of a two-echelon multiple sourcing supply chain system with genetic algorithm. *J. Mfg Technol. Mgmt*, 2005, **16**(1), 87–108.
70 **Axsater, S., Forsberg, R.,** and **Zhang, W.-F.** Approximating general multi-echelon inventory systems by Poisson models. *Int. J. Prod. Econ.*, 1994, **35**, 201–206.
71 **Jönsson, H.** and **Silver, E. A.** Analysis of a two-echelon inventory control system with complete redistribution. *Mgmt Sci.*, 1987, **33**, 215–227.
72 **Dekker, R., Frenk, J. B. G., Kleijn, M. J., de Kok, A. G.,** and **Piersma, N.** On the use of break quantities in multi-echelon distribution systems. *Inventory Modelling* (Ed. L. Bogataj), Lecture Notes of the International Postgraduate Summer School, vol. 1, Budapest, ISIR, 1995.
73 **Wang, Y., Cohen, M. A.,** and **Zheng, Y.-S.** A two-echelon repairable inventory system with stocking-center-dependent depot replenishment lead times. *Mgmt Sci.*, 2000, **46**(11), 1441–1453.
74 **Iida, T.** The infinite horizon non-stationary stochastic multi-echelon inventory problem and near-myopic policies. *Eur. J. Opl Res.*, 2001, **134**, 525–539.
75 **Chen, F.** and **Song, J. S.** Optimal policies for multi-echelon inventory problems with Markov-modulated demand. *Ops Res.*, 2001, **49**(2), 226.
76 **Chen, F. Y., Feng, Y.,** and **Simchi-Levi, D.** Uniform distribution of inventory positions in two-echelon periodic review systems with batch-ordering policies and interdependent demands. *Eur. J. Opl Res.*, 2002, **140**, 648–654.
77 **Minner, S., Diks, E. B.,** and **de Kok, A. G.** A two-echelon inventory system with supply lead time flexibility. *IIE Trans.*, 2003, **35**, 117–129.
78 **Johansen, S. G.** Base-stock policies for the lost sales inventory system with Poisson demand and Erlangian lead times. *Int. J. Prod. Econ.*, 2005, **93–94**, 429–437.
79 **Ng, W. K., Piplani, R.,** and **Viswanathan, S.** Simulation workbench for analysing multi-echelon supply chains. *Integrated Mfg Syst.*, 2003, **14**(5), 449.
80 **Martel, A.** Policies for multi-echelon supply; DRP systems with probabilistic time-varying demands. *ABI/INFORM Global*, 2003, **INFOR 41**(1), 71.
81 **Kiesmüller, G. P., de Kok, T. G., Smits, S. R.,** and **van Laarhoven, P. J. M.** Evaluation of divergent N-echelon (s,nQ)-policies under compound renewal demand. *OR Spectrum*, 2004, **26**, 547–577.
82 **Liberopoulos, G.** and **Koukoumialos, S.** Tradeoffs between base stock levels, numbers of Kanbans, and planned supply lead times in production/inventory systems with advance demand information. *Int. J. Prod. Econ.*, 2005, in press.
83 **Axsater, S.** A Framework for decentralized multi-echelon inventory control. *IIE Trans.*, 2001(a), **33**, 91–97.
84 **Lau, A. H. L.** and **Lau, H.-S.** Effects of a demand-curve's shape on the optimal solutions of a multi-echelon inventory/pricing model. *Eur. J. Opl Res.*, 2003, **147**, 530–548.
85 **Yoo, Y.-J., Kim, W.-S.,** and **Rhee, J. T.** Efficient inventory management in multi-echelon distribution systems. *Computers Ind. Engng*, 1997, **33**(3–4), 729–732.
86 **Jalbar, B. A., Gutierrez, J. M.,** and **Sicilia, J.** Integer-ratio policies for distribution/inventory systems. *Int. J. Prod. Econ.*, 2005(b), **93–94**, 407–415.
87 **Liang, W.-Y.** and **Huang, C. C.** Agent-based demand forecast in multi-echelon supply chain. *Decision Support Systems*, 2005, in press.
88 **Köchel, P.** and **Nielander, U.** Simulation-based optimisation of multi-echelon inventory systems. *Int. J. Prod. Econ.*, 2005, **93–94**, 505–513.
89 **Sleptchenko, A., van der Heijden, M. C.,** and **van Harten, A.** Effects of finite repair capacity in multi-echelon, multi-indenture service part supply systems. *Int. J. Prod. Econ.*, 2002, **79**, 209–230.
90 **Braun, M. W., Rivera, D. E., Flores, M. E., Carlyle, W. M.,** and **Kempf, K. G.** A model predictive control framework for robust management of multi-product, multi-echelon demand networks. *Ann. Rev. Control*, 2003, **27**, 229–245.
91 **Chen, C.-L.** and **Lee, W.-C.** Multi-objective optimization of multi-echelon supply chain networks with uncertain product demands and prices. *Computers Chem. Engng*, 2004(a), **28**, 1131–1144.
92 **Chandra, C.** and **Grabis, J.** Application of multi-steps forecasting for restraining the bullwhip effect improving inventory performance under autoregressive demand. *Eur. J. Opl Res.*, 2005, **166**, 337–350.