MULTI-ECHELON INVENTORY MANAGEMENT - CURRENT STATE OF ART ANALYSIS AND PROPOSED FUTURE RESEARCH DIRECTIONS

JURCZYK Krzysztof[1], WOŹNIAK Wojciech[2]

AGH University of Science and Technology, Krakow, Poland, EU
[1]kjurczyk@zarz.agh.edu.pl, [2]wojciech.wozniak.293@zarz.agh.edu.pl

Abstract

In the paper spare parts inventory management issues in the multi-echelon structures are discussed. Differences between spare parts and finished products inventories have been pointed out and discussed as well as differences between single-echelon and multi-echelon inventory optimization and structure. Current state of art analysis has been prepared as well as proposed future research directions.

Keywords: Inventory control, multi-echelon distribution systems, spare parts management

1. INTRODUCTION

As main functions of inventory management smoothing out irregularities in production flows and protecting against fluctuations in demands, lead times, differences in quality levels, differences in machine production rates or any other characteristics can be mentioned [1]. Therefore, the objective of inventory management can be considered as fulfilling the customer's needs by stocking the right quantity of the products at the right time such that the total associated costs and investments in them are minimal [2]. Those statements can refer to work-in-process (WIP) or finished products inventories. However in service parts inventory management there can be identified some crucial differences. Spare parts can be defined as items kept in case other items of the same type are lost, broken or worn out [3], so their role can be considered as assisting a maintenance staff in keeping equipment in operating condition [1]. This statement indicates that the spare parts inventory management is a very important and sophisticated process because of its prevailing nature, magnitude and complexity [4].

Another issue related to inventory management and considered in this article are differences between single-echelon and multi-echelon systems. In single-echelon distribution system there is a management focus on determining the appropriate level of inventory for an item separately for every single supply chain level - the material flows coming out or entering the considered level are negligible [5]. In a multi-echelon inventory structure however, there is a need for determining the size of the orders for each echelon during each period so as to maximize a final customer service level and products availability and in the same time minimize total associated inventory costs across the entire network [6, 7].

The aim of this article is to present and discuss current state of art referring to inventory management in these two, mentioned and shortly characterized above, specific fields - there has been discussed spare parts inventory management issues as well as multi-echelon inventory problems.

2. MULTI-ECHELON INVENTORY MANAGEMENT

The problem of multi-echelon inventory control has been investigated by many researchers. One of the earliest works in this area were Clark's and Scarf's considerations on determining optimal purchasing quantities in a multi-installation model [8]. The authors, as one of the firsts pointed out that the assumption that a time lag is independent of the size of the order placed are not tenable in multi-echelon inventory management practice. The proposed Clark-Scarf model is the best-known technique for determining safety stocks in a multi-echelon inventory system [9]. Later on, S.A. Bessler and A.F. Veinott Jr. have devoted their work to search for the optimal policy for a dynamic multi-echelon inventory model [10]. The authors have developed the model dedicated for single-echelon inventory problem with negotiable lead times. Another work, devoted to the dynamic analysis of multi-echelon supply systems was presented by J.F. Burns and B.D. Sivazlian [11]. Few years earlier, S.C. Aggarwal has presented a schematic diagram for inventory models taking their dynamics as the main criterion of classification [12]. Similar study devoted to classification of inventory systems was presented by R.H. Hollier and P. Vrat [13]. The authors decided to select such classification criteria as distribution channel structure, external company environment, inventory replenishment policy and inventory associated costs.

A.J. Clark and H. Scarf considered a finite time horizon in their model [8]. Their researches have been extended to the infinite-horizon case few years later by A. Federgruen and P. Zipkin [14]. P. van Beek has made an analysis of a multi-echelon inventory system comparing several alternatives for the way in which goods are forwarded from factory, via stores to the customers [15]. W.H.M. Zijm has provided a framework for the planning and control of the materials flow in a multi-item integrated production system [16]. The prime objective of this study was to achieve a pre-specified customer service level at minimum overall costs. Later on, M.C. van der Heijden et al. have analysed stock allocation policies in general multi-echelon distribution systems, where it is allowed to hold stock at all levels in the network in order to achieving differentiated target customer service level [17]. In another paper, the same author, has determined a simple inventory control rule for multi-echelon distribution systems under periodic review without lot sizing [18].

A dynamic multi-echelon inventory problem with nonstationary demands was studied by T. Iida [19]. The author proved that near-myopic replenishment policies are sufficiently close to optimal one not only in the single-location nonstationary inventory problem but also in the multi-echelon inventory problem. The research objective has been achieved by Markov decision process formulation for the decomposed serial inventory problem. Markov decision process technique has been used by the other researchers. F.Y. Chen et al. analysed the multi-echelon inventory control system with a periodic-review or lot-size reorder point replenishment policy for each location. The authors showed that each location's inventory positions are stationary and the stationary distribution is uniform and independent of any other's [20]. Optimal replenishment policies for multi-echelon inventory problems with Markov-modulated demand has been discussed earlier by F. Chen and J.-S. Song [21]. Optimal replenishment policies and approximations for a serial multi-echelon inventory system with time-correlated demand have been studied also by L. Dong and H.L. Lee, who provided a simple lower-bound approximation to the inventory levels and an upper bound approximation to the total system cost for the basic Clark-Scarf model [22].

S. Axsäter suggested and evaluated an approximate method for optimization of a two-echelon inventory system with continuous review and compound Poisson demand [23]. The proposed method was of interest in case of relatively large demands. In another work, the same author has provided a simple approximate technique for optimization of the reorder points in a quite general two-echelon distribution inventory system with batch-ordering [24]. The author has concluded that the proposed technique can be generalized to more than two echelons. M. Seifbarghy and M.R.A. Jokar also considered a two-echelon inventory system consisted of one central warehouse and many identical retailers [25]. The authors have developed an approximate cost function for a two-echelon inventory system where unsatisfied demand was lost and the control policy was continuous review. Similar studies were presented by R.M. Hill et al. [26] and S. Mitra [27]. Later on, S. Axsäter et al. have proposed three heuristics for handling direct upstream demand in two-echelon distribution inventory systems [28].

A. Ben-Tal et al. considered the problem of minimizing the overall cost of a supply chain over a possible long horizon under demand uncertainty [29]. M.-F. Yang an Y. Lin proposed a serial multi-echelon integrated just-in-time (JIT) model based on uncertain delivery lead time and quality unreliability consideration [30]. In another papers, the implications of considering power demand pattern and backorders in the one-warehouse N-retailer problem are addressed [31], and a multi-echelon inventory management framework for stochastic and fuzzy supply chains has been proposed [32]. A.T. Gümüs and A.F. Güneri, had also proposed a literature review on multi-echelon inventory management in supply chains with uncertain demand and lead times [33]. Another work, proposed by K.-J. Wang et al. deals with optimizing inventory policy for products with time-sensitive deteriorating rates in a multi-echelon supply chain [34]. Proposed study empirically investigated how different deterioration rates in each echelon affected performances of individuals and integrated inventory policies. The authors have proved that joint cost function is convex to deteriorating rates of products. Similar study, where multi-echelon supply chain management for deteriorating items with partial backordering under inflationary environment was analysed was proposed by A. Shastri et al. [35].

A multi-echelon inventory system with supplier selection and order allocation under stochastic demand was introduced by C. Guo and X. Li [36]. The objective of the proposed model was to select suppliers and to determine the optimal inventory policy that coordinates stock levels between each echelon of the distribution system while properly allocating orders among selected suppliers to maximize the expected profit. A continuous review system was considered, but the authors noted that future work may consider a periodic review system. In another paper, L.E. Cárdenas-Barrón and S.S. Sana introduced a production-inventory model for a two-echelon supply chain when demand is dependent on sales teams' initiatives [37]. In another study [38], O.H.D. Isaksson and R.W. Seifert have investigated quantifying the bullwhip effect using two-echelon data. Finally, N. Ekanayake et al. have presented a comparison of single-echelon and. multi-echelon inventory systems using multi-objective stochastic modelling [7].

At the end of this paragraph it should be written that spare parts inventory management issues in multi-echelon structures has been intentionally neglected - they will be discussed in the next paragraph.

3. SPARE PARTS INVENTORY MANAGEMENT IN MULTI-ECHELON STUCTURES

Numerous researchers have contributed to the development of spare parts inventory management systems. One of the earliest works in this area was Sherbrooke's METRIC (multi-echelon technique for recoverable item control) model for repairable items [39]. The author considered the minimization of the total expected backorders at the depots in two-echelon spare parts inventory system, where item demand was compound Poisson with a mean value estimated by a Bayesian procedure. The researcher noted that, for high-cost and low-demand items the most appropriate inventory control policy is continuous review according to the (s-l, S) rule. The generalization of Sherbrooke's model was presented later by J.A. Muckstadt [40]. Presented the MOD-METRIC model allowed for an inclusion of multi-indentures, i.e., hierarchical parts structures. Similar model, but for a single base was developed earlier by C.C. Sherbrooke [41]. Once again, C. C. Sherbrooke improved Muckstadt's MOD-METRIC model in 1986 [42]. Presented VARI-METRIC model did not understate expected backorders and did not overstate the expected availability of repairable items as pre-existing models. To achieve such quality of the VARI-METRIC model, the Grave's approximation had been used [43].

These standard analytical models have been improved further. Y. Wang et al. analysed a two-echelon system for repairable items with a central repair depot and multiple inventory stocking centres [44]. The model extended former works by allowing depot replenishment lead times to be stocking-centre-dependent. J. Andersson and P. Melchiors, using METRIC-approximation as a framework, analysed a one warehouse several retailers inventory system and proposed a heuristic for finding cost effective base-stock policies [45]. A. Sleptchenko et al. considered multi-echelon, multi-indenture supply systems for repairable service parts with finite repair capacity [46]. The VARI-METRIC method has been modified and used - the authors have proved 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. M. Kalchschmidt et al. described an integrated system for managing inventories in a multi-echelon spare parts supply chain, in which customers of different size laid at the same level of the supply chain [47]. In another study, H.Ch. Lau et al. considered time-varying operations to repair items with no-indenture [48]. The authors studied a multi-echelon repairable item inventory system under the phenomenon called passivation. An efficient approximation model to compute time-varying availability has been proposed and validated. In another work, K.E. Caggiano et al. considered inventory optimization in a multi-echelon system subject to time-based service level constrains [49]. In the paper, a practical method for computing channel fill rates in a multi-item, multi-echelon service parts distribution system has been described and validated.

M.H. Al-Rifai and M.D. Rossetti presented a two-echelon non-repairable spare parts inventory system that consisted of one warehouse and m identical retailers and implemented the reorder point, order quantity (R, Q) inventory policy [50]. The policy decision problem was formulated in order to minimizing the total annual inventory investment subject to average annual ordering frequency and expected number of backorder constraints. In order to solve the problem, the system was decomposed by echelon and location, expressions for the inventory policy parameters have been derived, an iterative heuristic optimization algorithm has been developed. Experimentation showed that the proposed optimization algorithm was an efficient and effective method for setting the policy parameters in large-scale inventory systems. A multi-item two-echelon spare parts inventory system in which the central warehouse operates under a (R, Q) policy was also considered by E. Topan et al. [51]. The objective of this study was to find the policy parameters minimizing expected system-wide inventory holding and fixed ordering subject to aggregate and individual response time constraints. Using an exact evaluation a very efficient and effective heuristic has been provided.

4. CONCLUSIONS AND PROPOSED FUTURE RESEARCH DIRECTIONS

The aim of this article was to present current state of art referring to multi-echelon inventory management. There has also been presented current literature on spare parts inventory management in multi-echelon structures. Analysing the pre-existing studies it should be noted that there are only few works, where authors analysed spare parts demand forecasting in multi-echelon distribution systems. It is necessary to extend those researches especially using non-conventional techniques.

ACKNOWLEDGEMENTS

This research has been conducted as a part of grant no. 15.11.200.329.

REFERENCES

[1] KENNEDY W.J., PATTERSON J.W., FREDENDALL L.D.: An overview of recent literature on spare parts inventories. International Journal of Production Economics, Vol. 76, Issue 22, 2002, pp. 201-215.

[2] GUDEHUS T., KOTZAB H.: Comprehensive Logistics. Springer-Verlag, Berlin Heidelberg, 2012.

[3] JURCZYK K., KARKULA M.: Selected aspects of spare parts inventory management. CLC'2013: Carpathian Logistics Congress, December 9th-12th 2013, Novotel Krakow City West, Cracow, Poland, Congress proceedings (reviewed version), TANGER Ltd., Ostrava, Czech Republic, 2014, pp. 318-323.

[4] ALTAY N., LITERRAL L.A. (Eds.): Service Parts Management. Demand Forecasting and Inventory Control. Springer-Verlag, London 2011.

[5] GHIANNI G., LAPORTE G., MUSMANNO R.: Introduction to Logistics Systems Planning and Control. John Wiley & Sons Ltd, Chichester 2004.

[6] ZHOU W.-Q., CHEN L., GE H.-M.: A multi-product multi-echelon inventory control model with joint replenishment strategy. Applied Mathematical Modelling, Vol. 37, Issue 4, 2013, pp. 2039-2050.

[7] EKANAYAKE N., JOSHI N., THEKDI S.A.: Comparison of single-echelon vs. multi-echelon inventory systems using multi-objective stochastic modelling. International Journal of Logistics Systems and Management, Vol. 23, No. 2, 2016, pp. 255-280.

[8] CLARK A.J., SCARF H.: Optimal Policies for a Multi-Echelon Inventory Problem. Management Science, Vol. 6, Issue 4, 1960, pp. 475-490.

[9] AXSÄTER S.: Inventory control. Springer International Publishing, 2015.

[10] BESSLER S. A., VEINOTT JR. A.F.: Optimal policy for a dynamic multi-echelon inventory model. Naval Research Logistics Quarterly, Vol. 13, Issue 4, 1966, pp. 355-389.

[11] BURNS J.F., SIVAZLIAN B.D.: Dynamic analysis of multi-echelon supply systems. Computers & Industrial Engineering, Vol. 2, Issue 4, 1978, pp. 181-193.

[12] AGGARWAL S.C.: A review of current inventory theory and its application. International Journal of Production Research, Vol. 12, Issue 4, 1974, pp. 443-482.

[13] HOLLIER R.H., VRAT P.: A proposal for classification of inventory systems. Omega, Vol. 6, Issue 3, 1978, pp. 277-279.

[14] FEDERGRUEN A., ZIPKIN P.: Computational Issues in an Infinite-Horizon, Multiechelon Inventory Model. Operations Research, Vol. 32, Issue 4, 1984, pp. 818-836.

[15] VAN BEEK P.: Modelling and analysis of a multi-echelon inventory system: a case study. European Journal of Operational Research, Vol. 6, Issue 4, 1981, pp. 380-385.

[16] ZIJM W.H.M.: Hierarchical production planning and multi-echelon inventory management. International Journal of Production Economics, Vol. 26, Issues 1-3, 1992, pp. 257-264.

[17] VAN DER HEIJDEN M.C., DIKS E.B., DE KOK A.G: Stock allocation in general multi-echelon distribution systems with (R, S) order-up-to-policies. International Journal of Production Economics, Vol. 49, Issue 2, 1997, pp. 157-174.

[18] VAN DER HEIJDEN M.C.: Supply rationing in multi-echelon divergent systems. European Journal of Operational Research, Vol. 101, Issue 3, 1997, pp. 532-549.

[19] IIDA T.: The infnite horizon non-stationary stochastic multi-echelon inventory problem and near-myopic policies. European Journal of Operational Research, Vol. 134, Issue 3, 2001, pp. 525-539.

[20] CHEN F.Y., FENG Y., SIMCHI-LEVI D.: Uniform distribution of inventory positions in two-echelon periodic review systems with batch-ordering policies and interdependent demands. European Journal of Operational Research, Vol. 140, Issue 3, 2002, pp. 648-654.

[21] CHEN F., SONG J.-S.: Optimal Policies for Multiechelon Inventory Problems with Markov-Modulated Demand. Operations Research, Vol. 49, Issue 2, 2001, pp. 226-234.

[22] DONG L., LEE H.L.: Optimal Policies and Approximations for a Serial Multiechelon Inventory System with Time-Correlated Demand. Operations Research, Vol. 51, Issue 6, 2003, pp. 969-980.

[23] AXSÄTER S.: Scaling down multi-echelon inventory problems. International Journal of Production Economics, Vol. 71, Issues 1-3, 2001, pp. 255-261.

[24] AXSÄTER S.: Approximate optimization of a two-level distribution inventory system. International Journal of Production Economics, Vol. 81-82, 2003, pp. 545-553.

[25] SEIFBARGHY M., JOKAR M.R.A.: Cost evaluation of a two-echelon inventory system with lost sales and approximately Poisson demand. International Journal of Production Economics, Vol. 102, Issue 2, 2006, pp. 244-254.

[26] HILL R.M., SEIFBARGHY M., SMITH D.K.: A two-echelon inventory model with lost sales. European Journal of Operational Research, Vol. 181, Issue 2, 2007, pp. 753-766.

[27] MITRA S.: Analysis of a two-echelon inventory system with returns. Omega, Vol. 37, Issue 1, 2009, pp. 106-115.

[28] AXSÄTER S., OLSSON F., TYDESJÖ P.: Heuristics for handling direct upstream demand in two-echelon distribution inventory systems. International Journal of Production Economics, Vol. 108, Issues 1-2, 2007, pp. 266-270.

[29] BEN-TAL A., GOLANY B., SHTERN S.: Robust multi-echelon multi-period inventory control. European Journal of Operational Research, Vol. 199, Issue 3, 2009, pp. 922-935.

[30] YANG M.-F., LIN Y.: Applying the linear particle swarm optimization to a serial multi-echelon inventory model. Expert Systems with Applications, Vol. 37, Issue 3, 2010, pp. 2599-2608.

[31] ABDUL-JALBAR B., GUTIÉRREZ J.M., SICILIA J.: A two-echelon inventory/distribution system with power demand pattern and backorders. International Journal of Production Economics, Vol. 122, Issue 2, 2009, pp. 519-524.

[32] GÜMÜS A.T., GÜNERI A.F.: A multi-echelon inventory management framework for stochastic and fuzzy supply chains. Expert Systems with Applications, Vol. 36, Issue 3, Part 1, 2009, pp. 5565-5575.

[33] GÜMÜS A.T., GÜNERI A.F.: A Multi-echelon inventory management in supply chains with uncertain demand and lead times: literature review from an operational research perspective. Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, Vol. 221, Issue 10, 2007, pp. 1553-1570.

[34] WANG K.J., LIN Y.S., YU J.C.P.: Optimizing inventory policy for products with time-sensitive deteriorating rates in a multi-echelon supply chain. International Journal of Production Economics, Vol. 130, Issue 1, 2011, pp. 66-76.

[35] SHASTRI A., SINGH S.R., YADAV D., GUPTA S.: Multi-Echelon Supply Chain Management for Deteriorating items with Partial Backordering under Inflationary Environment. Procedia Technology, Vol. 10, 2013, pp. 320-329.

[36] GUO C., LI X.: A multi-echelon inventory system with supplier selection and order allocation under stochastic demand. International Journal of Production Economics, Vol. 151, 2014, pp. 37-47.

[37] CÁRDENAS-BARRÓN L.E., SANA S.S.: A production-inventory model for a two-echelon supply chain when demand is dependent on sales teams′ initiatives. International Journal of Production Economics, Vol. 155, 2014, pp. 249-258.

[38] ISAKSSON O.H.D., SEIFERT R.W.: Quantifying the bullwhip effect using two-echelon data: A cross-industry empirical investigation. International Journal of Production Economics, Vol. 171, Part 3, 2016, pp. 311-320.

[39] SHERBROOKE C.C.: METRIC: a multi-echelon technique for recoverable item control. Operations Research, Vol. 16, Issue 1, 1968, pp. 122-141.

[40] MUCKSTADT J.A., A Model for a Multi-Item, Multi-Echelon, Multi-Indenture Inventory System. Management Science, Vol. 20, Issue 4,1973, pp. 472-481.

[41] SHERBROOKE C.C.: An Evaluation for the Number of Operationally Ready Aircraft in a Multilevel Supply System. Operations Research, Vol. 19, Issue 3, 1971, pp. 618-635.

[42] SHERBROOKE C.C.: VARI-METRIC: improved approximations for multi-indenture, multi-echelon availability models. Operations Research, Vol. 34, Issue 2, 1986, pp. 311-319.

[43] GRAVES S.C.: A multi-echelon inventory model for a repairable item with one-for-one replenishment. Management Science, Vol. 31, Issue 10, 1985, pp. 1247-1256.

[44] WANG Y., COHEN M.A., ZHENG S.-Y.: A two-echelon repairable inventory system with stocking center dependent depot replenishment lead times. Management Science, Vol. 46, Issue 11, 2000, pp. 1441-1453.

[45] ANDERSSON J., MELCHIORS P.: A two-echelon inventory model with lost sales. International Journal of Production Economics, Vol. 69, Issue 3, 2001, pp. 307-315.

[46] SLEPTCHENKO A., VAN DER HEIJDEN M.C., VAN HARTEN A.: Effects of finite repair capacity in multi-echelon, multi-indenture service part supply systems. International Journal of Production Economics, Vol. 79, Issue 3, 2002, pp. 209-230.

[47] KALCHSCHMIDT M., ZOTTERI G., VERGANTI R.: Inventory management in a multi-echelon spare parts supply chain. International Journal of Production Economics, Vol. 81-82, 2003, pp. 397-413.

[48] LAU H.C., SONG H., SEE C.T., CHENG S.Y.: Evaluation of time-varying availability in multi-echelon spare parts systems with passivation. European Journal of Operational Research, Vol 170, Issue 1, 2006, pp. 91-105.

[49] CAGGIANO K.E., JACKSON P.L., MUCKSTADT J.A., RAPPOLD J.A.: Efficient computation of time-based customer service levels in a multi-item, multi-echelon supply chain: a practical approach for inventory optimization. European Journal of Operational Research, Vol. 199, Issue 3, 2009, pp. 744-749.

[50] AL-RIFAI M.H., ROSSETTI M.D.: An efficient heuristic optimization algorithm for a two-echelon (R, Q) inventory system. International Journal of Production Economics, Vol. 109, Issues 1-2, 2007, pp. 195-213.

[51] TOPAN E., BAYINDIR Z.P., TAN T.: Heuristics for multi-item two-echelon spare parts inventory control subject to aggregate and individual service measures. European Journal of Operational Research, Vol. 256, Issue 1, 2017, pp. 126-138.