Operational Supply Chain Planning Method for Integrating Spare Parts Supply Chains and Intelligent Maintenance Systems

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Abstract A lack of spare parts and ineffective maintenance lead to low service levels and high production costs. Intelligent maintenance systems (IMS) have been intensively considered for supporting a better performance of maintenance service. For achieving high supply chain performance, it is also necessary that the information provided by IMS is integrated into the operational planning of the spare parts supply chain. Thus, this paper proposes a procedure for the integration of the spare parts supply chain operational decision level and the IMS. A framework comprising a heuristic approach along with a simulation model and a mathematical model is proposed.

Keywords Spare parts · Supply chain · Intelligent maintenance systems · Planning and scheduling

Introduction

Insufficient maintenance services and lack of spare parts can lead to negative effects in complex production systems. Proper maintenance and the availability of needed spare parts directly influence the production systems effectiveness and efficiency. In this context, one of the most used maintenance approaches is the predictive approach. It aims to forecast the lifetime of components based on classical statistical

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H. Kotzab et al. (eds.), *Dynamics in Logistics*,
Lecture Notes in Logistics, DOI 10.1007/978-3-319-23512-7_44

models, thus allowing their replacement before a failure occurs. However, sporadic spare parts' demand and the wide variety of system components do not allow for generating accurate predictions. In order to solve this problem, the adoption of intelligent maintenance systems (IMS) was suggested in the literature (Djurdjanovic et al. 2003). IMS are embedded diagnostic/prognostic systems that can forecast failures, supporting the optimization of maintenance processes. The IMS monitors a machine's or a part's gradual degradation status and, through these inputs, can estimate the probability rate and date of breakdowns.

In order to achieve higher levels of effectiveness (i.e., adequate level of maintenance services and spare parts' availability) and efficiency (i.e., low costs of maintenance service and spare parts' provision), it is also necessary that the information provided by the IMS is integrated with the planning activities of the spare parts supply chain (Espíndola et al. 2012). Thereof, the information becomes available and, consequently, it is possible to achieve more accurate supply chain plans. This paper will propose a tailored operational supply chain planning method for the integration of the spare parts supply chain and IMS. First, a generic spare parts supply chain structure considering classical approaches and in contrast with an IMS will be presented. Second, the existing literature related to spare parts and supply chain planning and scheduling will be reviewed. Third, based on the literature search and review, an operational supply chain method for integrating spare parts supply chains and IMS will be proposed. The paper ends by stating specific conclusions and proposing next steps for further research.

Spare Parts Supply Chain and IMS

According to Muckstadt (2005), it is possible to describe the general taxonomy of service parts inventory systems. To repair the failed equipment, a repair technician normally performs a diagnosis and if needed, the broken part can be replaced for a new one. The technical staff receives the ordered parts from the local stock of the service centers, which are responsible for feeding this demand. The service centers subsequently are resupplied from the responsible regional warehouse. Consequently, the regional warehouse is also replenished, but it receives its products from the central warehouse according to the previously planned stock replenishment polices. The central warehouse likewise receives replenishment stocks from the production (Muckstadt 2005). Moreover, the material flow is directed from the manufacturer to the costumers and a logistics service provider normally provides the transport of the goods. The information flow is a reverse path of the material flow. It crosses the supply chain backwards from the costumer to the manufacturer, consisting of customer orders, sales forecasts, internal orders for warehouse replenishment, production orders, as well as purchasing orders to the suppliers, etc. (Stadler and Kilger 2008). Furthermore, the information flow is also given in the vertical direction; downward flows coordinate subordinate plans by obtained results of the higher levels (Stadler and Kilger 2008). In this context, many spare parts supply chain's structure designs are possible, some systems have more echelons, and others have fewer. It mostly depends on strategic decisions based on control characteristics of serviceable parts such as criticality of the product, specificity of the components, demand pattern, value of the parts, joint geographic and product hierarchies (Muckstadt 2005).

Regarding the spare parts supply chain management, for improved planning activities in each supply chain's domain, the decision levels can be split in three interdependent components: strategic, tactical, and operational. Strategic are long-term decisions (over several years) and they typically concern the design and structure of the supply chain. Tactical are mid-term decisions (months up to one year) regarding to rough regular operations for the flows and resources (Stadler and Kilger 2008). Operational spare parts' planning corresponds to the short-term (days up to one month) decision-making time horizon. Here, the interconnections to the tactical planning layer have to be considered. The main focus of this approach lies on short-term production, inventory, transport, and maintenance planning and scheduling. The goal is the best utilization of existing structures (e.g., communication, buildings, transportation, and machines) restricted by the tactical decisions.

In the literature, it was not found a reasonable description of a spare parts supply chain containing an intelligent maintenance system. However, from these studies one can assume that the structure, the processes, and the flows of this specific supply chain will be different from a final product's one. First, the demand appears by providing forecasted failure information through an IMS in manufacturing devices and machines. The forecasted failure information is sent to an integration layer, responsible to integrate shop floor devices and machines to the spare parts supply chain entities. The suppliers and manufacturers receive the information, through specific information system mechanisms of an integration layer. The information layer receive the notification about *which*, *when,* and *where* the part will fail and share it to the specific decision levels. Furthermore, before the breakdown happens, the technical staff receives the required parts from the stock suppliers, which is responsible for feeding this demand. Thus, in order to reach adequate processes effectiveness, and efficiency, spare parts supply chain actors also have to cope with the IMS approach. The development of improved spare parts *planning* methods, integrating IMS information, is essential for the supply chain's performance. The main spare parts supply chain operational level tasks in a spare parts supply chain with IMS can be seen in Fig. 1.

With respect to Fig. 1, while the tactical level is resupplied with information about the actual condition of processes and machines and consequently forecasts the monthly aggregated potential failures, the short-term sales planning particularizes these forecasts in weekly and daily quantities for single spare parts. At the same time, the daily inventory management and transport quantities for single products are controlled and managed; taking into account previously agreed (in contract) lead times and service levels. Another important task of the inventory domain is the parts, categorization for creating a manageable number of spare part groups (Jouni et al. 2011). In order to carry the daily ordered goods, it is necessary to plan the detailed transportation capacities (e.g., available trucks) and the route

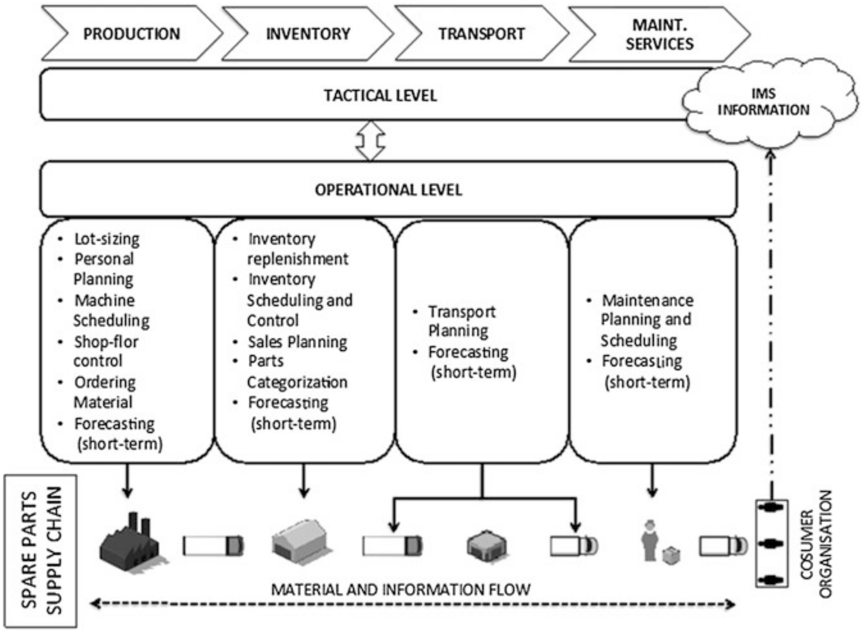

Fig. 1 Operational planning of main tasks in the spare parts supply chain

planning for optimizing the trade-offs between time, services, and costs. Therefore, the production (shop floor control, determination of lot-sizes, and their sequences on the machines, personnel scheduling) needs to be scheduled and controlled. All of these tasks are connected by information flows that also may be organized and processed by the operational level.

The service personal is another important task in the operational decision level (e.g., personal scheduling and maintenance scheduling). The planning of maintenance follows the elimination of downtimes and near zero breakdown times (Djurdjanovic et al. 2003). The maintenance scheduling regards an optimization of time and costs (e.g., through mathematical models); taking also into account the previously agreed lead times and service levels.

Spare Parts Supply Chain Planning Methods and Concepts

Spare parts logistics comprises different areas, such as service management, inventory control, production and transportation planning, as well as supply chain management, etc. However, the target of this chapter is not to review all these aspects, but to *review methods, which could be tailored to the integrated planning of operational decisions in the spare parts supply chain, regarding specific service* *level and costs*. Some tactical methods are also reviewed, because the discussion of those methods and concepts are relevant, as some of them might also be applied for the short-term decisions, by redefining variables and a new planning horizon. A classification of spare parts supply chain planning methods is presented below. This classification is based on the results obtained by the proposed search and review methodology[1] and authors' interpretation.

Spare Parts Inventory Management in Multi-echelon Supply Chains

The majority of planning methods, which have being implemented in the spare parts supply chains, according to the conducted research, is focused on *inventory management and control* (12 works). "Due to the sporadic need of a spare part, a vast inventory level in different places is required" (Kutanoglu et al. 2009). As a consequence, an extensive costumer's service must be developed. One of the most current network problems is where to place spare parts in a multi-echelon inventory system. For dealing with this issue, Sherbrook developed a landmark mathematical model, METRIC (A Multi-Echelon Technique for Recovered Item Control); "since that time many extensions and modifications in his model have been proposed" (Muckstadt 2005). One of these extensions is the VARI-METRIC (Improved Approximations for Multiple-Indenture and Multi-Echelon Availability Models) model (Sherbrook 1986). The VARI-METRIC system objectives describe the logistics relationships between assembly and subassemblies and compute stock levels for each component and inventory echelon that minimize backorder costs of reparable parts. Sleptchenko et al. (2002) shows that the used assumption of infinite capacity, of the VARI-METRIC, can seriously affect the stock allocation, if the repair capacity utilization is high (see Sleptchenko et al. 2002). As a result, the authors suggested modifications with the assumption of finite repair capacity. Furthermore, Sleptchenko et al. (2004) suggested a further extension to the VARI-METRIC by using repair priorities to reduce stock investment in spare part networks (see Sleptchenko et al. 2004). Another important issue in this area was pointed out by Sherbrook et al. (1992), Krannenburg and van Houtum (2009) and Tiacci and Saetta (2011). They presented the reducing of mean spare parts supply delay by using *lateral transshipments policies*. This subject has been intensively studied in the multi-echelon spare parts inventory system literature. By lateral transshipment high stock levels can be moved to other facilities, which have low

[1]The first keyword chosen for the review were "*spare parts supply chain*". After obtaining the results, the literature was filtered in order of relevance, considering works with the keywords "*spare parts*" and "*supply chain*". Firstly, 3.218 references were obtained. Nevertheless, many of them were not suitable to the proposed subject; by that, 23 articles have been chosen and they serve as basis for the literature review. The works date from 1978 to 2013.

stock levels, in the same echelon, for reducing supply chain delays through better parts distribution inside the inventory network systems.

Synetos and Keyes (2008) Jouni et al. (2011) and Bachetti and Saccani (2012) research the effects of *parts categorization in the spare parts inventory management*. The classification of components is necessary to establish service requirements for different parts classes because it gives greater accuracy to forecast and stock control processes. Bachetti and Saccanni (2012) performed a literature review about the categorization methods and found out that most of the papers used multi-criteria categorization methods. The most applied techniques (quantitative and qualitative) were ABC and AHP (Analytic Hierarchic Process).

Last but not least, Kalschmidt et al. (2003) presented the results of a case study, where an integrated system for managing inventories in a multi-echelon structure was supposed. The paper shows how combining *demand information and inventory management* can guarantee a substantial improvement of performance. The performance was measured taking into account the "*inventory* level/service *level*" trade-off curves for four different scenarios.

Spare Parts Supply Chain Optimization and Planning

In the present literature review, the *Spare Parts Optimization* is covered with 11 works. These papers generally consist of mathematical models and software aiming to find the optimum balance between costs and benefits such as service levels, delivery times, etc. It is a well-known area for *planning and scheduling spare parts and maintenance processes* as showed in the works of Dekker and Scarf (1997) and Garg and Deshmukh (2006).

According to Mula et al. (2010), the vast majority of the studies reviewed about mathematical programming for supply chain production and transport planning opted mixed integer linear programming models (MILP). Regarding to present an *integrated planning method* of different domains in a spare parts supply chain Goel et al. (2003) and Kutanoglu and Lohiya (2008) worked in the same direction. Goel et al. (2003) developed a new mathematical model for planning the design, production, and maintenance in multipurpose process plants. The aim is to create a schedule for suggesting maintenance policies that optimizes the balance between benefits and costs. Kotanoglu and Lohiya (2008) present a model to minimize costs and ensure service level in an integrated inventory and transportation problem.

Furthermore, Tysseland (2009) analyzed how the spare parts optimization process was conducted in the Norwegian defense procurement projects. The Norwegian defense was recommended to start using the *multi-echelon, multi-item, and multi-indenture optimization software tool* (OPUS10). In this context, Wu and Hsu (2008) pointed out the possibility to calculate an optimum BOM (bill of material) configuration through OPUS10. However, it might be, according to the authors, formidably time-consuming. With the aim of remedy, the time-consuming problem, they proposed a GA-neural network approach to solve the BOM configuration design. Extending the same approach in a new work, Wu et al. (2010) solved a design problem for spare parts logistics system encompassing part vendors and transport modes selection. Two approaches and five algorithms were proposed to find a near-optimal logistics network and an optimal combination for part vendor and transportation modes selection (see Wu et al. 2010).

Sarker and Haque (2000) proposed a *system optimization of maintenance and spare parts provision*. A model has been developed for a manufacturing system with preventive maintenance, continuous review inventory policy, and stochastic item failure. The paper showed, in its specific case, that a jointly optimal policy (regarding continuous review inventory and preventive maintenance interval per unit time) determines better cost effective results than combinations of separately and sequentially optimized policies. Zamperini and Freimer (2005) analyzed optimization procedures through simulation. They performed an analysis of the optimization method for inventory management VARI-METRIC, in the context of the American Cost-Guard fleet. The study illustrated the benefits of using simulation to validate other optimization methods. Last but not least, Chen and Popova (2002) and Barata et al. (2002) used Monte Carlo simulation to minimize the service costs and modeling deteriorating systems.

Operational Spare Parts Supply Chains Planning Whit IMS

The research mentioned above generally discuss the rather unexplored problem of managing multi-echelon, multi-item, and multi-modal supply chains with high demand uncertainties. In order to find solutions for this problem, the spare parts literature has focused major attention on forecasting lumpy demand (e.g., statistical classical approaches, CBM, etc.) and also on inventory management and control for multi-echelon supply chains (METRIC models, parts categorization, etc.). Minor attention has been devoted for planning integration and information exchange. Recent investigations show that a supply chain's domain integration (e.g., production, inventory, transport, and maintenance) can lead to additional information and reliability, which can enhance the performance of planning methods and consequently the whole supply chain (Chen and Popova 2002; Goel et al. 2003; Kutanoglu 2009; Wu et al. 2010). Most of these works use mathematical programming models as integration method.

The aim of suggesting a methodology for the operational planning of spare parts supply chains, considering information provided by IMS is to improve the supply chain's performance by minimizing costs while ensuring service level regarding the delivery of the orders in a predefined time. In this way, scientific studies as Chen and Popova (2002), Goel et al. (2003), Kutanoglu (2009), and Wu et al. (2010) showed that it is possible to plan and schedule multi-echelon supply chains with high demand uncertainties through an integrated planning, using optimization methods. Furthermore, Zamperini and Freimer (2005) illustrated the benefits of using simulation to validate optimization methods. In that work, the simulation

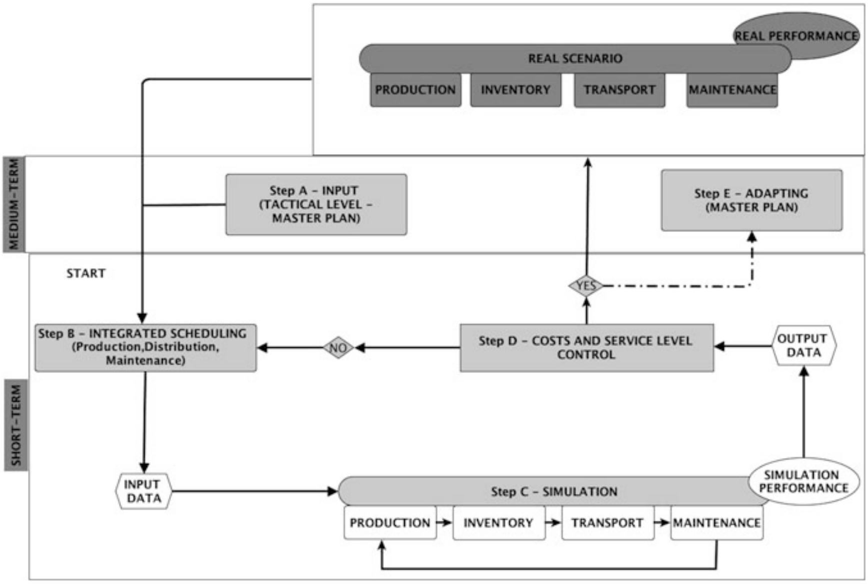

Fig. 2 Framework for spare parts supply chain with IMS

allowed examining the efficient frontier for maximizing spare parts availability while minimizing total costs in the U.S. coast guard.

Based on these scientific works and considering the present research problem, a heuristic is suggested for supporting the integrating process and, consequently, improving the planning and scheduling of spare parts supply chain along with an IMS. Figure 2 sketches the concept of the framework, which aims to find a feasible solution by minimizing costs while ensuring service levels.

An introduction of a scheduling entity along the supply chain will be proposed, which can perform the integrated scheduling for "production-distribution-maintenance" (Step B), using mathematical programming. The scheduling will be based on the capabilities, forecasts, order delivery dates, etc., provided by the master plan on the tactical level (Step A). After that, the obtained scheduling will be taken as model input, a sensitivity analysis, using a simulation-based model, will support the evaluation and the validation of the scheduling results (Step C). The simulation can resemble the behavior of complex systems and enables the estimation of their performance by taking into account stochastic variables (Banks 2009). Through this method, it is possible to integrate chain's actors in a dynamic way and to study their behavior. In Step D, the simulation output data has to be checked, whether satisfactory costs and service levels are met. Changes (e.g., a new scheduling) can be suggested in the real scenario and the tactical master plan can be adapted (Step E). Furthermore, if the simulation outputs indicate undesirable results, Step B would need to be rerun, i.e., a new schedule would need to be created and reevaluated (Step C). This interactive and iterative scheme would provide the capability of dynamically integrating spare parts supply chains and IMS.

Conclusion

According to the literature, the integration of spare parts supply chain with information provided by IMS can provide better performance, because the planning and scheduling of the supply chain can consider the actual condition of production components. This approach is a good alternative for the problem of sporadic/lumpy demand of spare parts. Nevertheless, it still imposes enormous challenges for the logistics management. It is necessary that the information provided by IMS is available for production, inventory, transport, and service management domains, so that they can plan their activities. The literature review showed that most of current research concentrates their efforts in the areas of inventory management and spare parts supply chain optimization, using mathematical models. Nevertheless, identified analytical methods are not suitable to the proposed integration case. Therefore, a framework is suggested in the present paper, in order to improve the operational performance by minimizing costs while ensuring service level, in terms of delivering orders in time. The framework is composed by a heuristic approach along with simulation and mathematical models. The framework will be further developed and applied to a test case and a real-world case study.

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