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Integrated spare parts logistics and operations planning for maintenance service providers

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A B S T R A C T

This paper considers the problem of coordinated spare-part logistics and operations planning for third-party maintenance providers. Due to the multi-indenture structure of the equipment, different types of components might randomly fail to perform at different points of time. The spare part logistics literature has been focused on spare part inventory management in an in-house maintenance context. In this article, a mathematical programming model is first developed to formulate the problem in the context of a third-party maintenance provider who is faced with strict due dates for the delivery of repaired equipment. The model seeks the optimal number of maintenance jobs that can be completed to deliver at each period, as well as the order quantity of spare parts so as to minimize the procurement, inventory, and equipment late delivery costs, while taking into account the spare part supply lead-time. Next, we model the spare part demand uncertainty as a non-stationary stochastic process in each period in the planning horizon. The deterministic model is then reformulated as a multi-stage stochastic program with recourse. We also discuss the complexity of the stochastic model and propose a preprocessing approach to reduce its size for large instances. Numerical results demonstrate how the proposed model links the spare part logistics and equipment delivery decisions under spare part demand uncertainty.

1. Introduction

1.1. Context and motivation

For advanced technical systems such as medical equipment, aircraft engine and electronic devices, high system availability is essential. As these systems are subject to failures, appropriate maintenance planning is necessary. In such systems, a failed item is forwarded to a maintenance service provider to be repaired if local repair is technically impossible, i.e. if the local repair shop does not have appropriate equipment or skills. Moreover, such products usually consist of other subassemblies due to their multi-indenture structure. If a product fails, the failure can be caused by the failure of one or more of its subassemblies. In this case, the assembly is disassembled and the failed subassembly is sent further for subassembly repair. In this context, it is important to choose optimal spare part stock levels in the network, such that target system availability is attained at minimal inventory investment.

Such spare part logistics networks are featured as multi-echelon networks that differ from other materials supply chains in several ways: the number and diversity of spare parts is usually large; item failure rates (demand) and repair times are extremely sporadic and difficult to forecast; the prices of individual parts may be very high; and the effect of spare part shortage is usually financially remarkable (Kennedya et al., 2002).

The present study is motivated by the challenges encountered by industries offering aircraft maintenance to the airlines. Such industries are faced with stringent standards in addition to strict due date for the delivery of repaired aircraft. They are dealing with a huge number of components available in the aircraft body and engine that might fail to perform at any given point of time. As a consequence, starting from a single item demanded by the customer, a variety of maintenance services and spare parts might be required. The latter considerably complicates the management and control of spare part inventory. Taking a conservative strategy, where high amounts of demand for different elements are predicted, might guarantee a high service level. On the other hand, the latter is a costly solution, particularly for expensive parts. It might also lead to the obsolescence of spare parts over time. These particular challenges for spare parts logistics in this

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industry, in addition to high penalties for the late delivery of aircraft, have drawn the attention of managers in integrating the spare part logistics decisions with the equipment delivery decisions rather addressing locally the spare part inventory management problem.

1.2. Literature review

A review of spare parts inventory models can be found in Kennedya et al. (2002). They also discussed the unique features of maintenance inventories comparing to other types of inventories, such as work-in process or finished products.

Huiskonen (2001) investigated the effect of criticality, specificity, demand pattern, and value of spare parts on spare part logistics network structure and control principles. The author concluded that safety stocking becomes necessary for all critical parts for which lead times are longer than the time to tolerate a stock out situation in case of failure. Furthermore, for more standard parts the part suppliers must be responsible for hold stocks. Finally, in case of low volume parts, a cooperative stocking pool can be created by a few relatively closely located users.

The literature on spare parts logistics optimization in an in-house context is scarce and can be categorized into two main research streams: (i) inventory modeling of spare parts logistics systems (see for example, Sherbrooke (1968, 1986), Muckstadt (1973), Chelbi and Ait-Kadi (2001), Sleptchenko et al. (2003, 2005), Vaughan (2005), Veenstra et al. (2006), Hua et al. (2009)), and (ii) integrated design and inventory management of service parts logistics (see for example, Candas and Kutanoglu (2007) and Kutanoglu and Lohiya (2008)).

Early works on the optimization of repairable spare parts stock level date back to 60's. The basic reference in this area is Sherbrooke (1968) who developed the METRIC class of models for determining the optimal stock level of recoverable items in a two-echelon inventory system including a base and a depot with the objective of minimizing the total expected base-level backorders subject to an investment constraint. Muckstadt (1973) extended the METRIC model into the MOD-METRIC model by considering the multi-indenture structure of parts. In the MOD-METRIC class of models, two levels of parts including an assembly and its components are permitted to be considered. Later, Sherbrooke (1968) proposed the VARI-METRIC class of models for the multi-indenture, multi-echelon stock level optimization of recoverable items. The latter was an improved approximation of METRIC and MOD-METRIC models by considering the delay in the repair of a higher indenture item caused by backorders on the item's lower indenture components.

Chelbi and Ait-Kadi (2001) developed a mathematical model to find the joint optimal periodic replacement and spare part provisioning strategy in the case of one type of equipment or a set of identical equipment. The objective of the model is to minimize the expected cost of spare part replenishment and inventory while assuming that the system lifetime distribution and the probability distribution of the spare part demand is known. Sleptchenko et al. (2003) proposed a procedure for simultaneous optimization of inventory levels and repair capacity in spare parts networks. They investigated a multi-echelon network and a multi-indenture product structure. Their methodology is a modification of VERI-METRIC procedure for determining near-optimal spare parts inventory level in multi-class, multi-server queuing systems representing repair shops.

Sleptchenko et al. (2003) examined the effect of repair priorities in reducing stock investment by the aid of several heuristics. They concluded that a proper priority setting may lead to a significant reduction in the inventory investment required to attain target system availability. Vaughan (2005) proposed a stochastic dynamic programming model in order to obtain an efficient spare part ordering policy while addressing two sources of demand for spare parts, namely, preventive maintenance and random failure of equipment. The nature of the ordering policy was then characterized numerically for different combination of parameter levels. The proposed ordering policy is applicable in the case of indoor plant maintenance and equipment. With a specific focus on Dutch dredging industry, Veenstra et al. (2006) proposed a simulation-based methodology to study the effect of different maintenance policies, such as predictive and condition-based maintenance, on spare part supply chain in terms of stock keeping, order fulfillment, and productivity of equipment. Hua et al. (2009) proposed a mean-value lot-sizing model in order to obtain spare part replenishment periods and order up-to-levels by considering multiple-period replenishment lead time and a non-stationary behavior for the demand of spare parts. The proposed model leads to a static-dynamic strategy that makes the replenishment and order quantity decisions over the planning horizon, however, it implements only the decisions of the first replenishment period. By adopting a rolling horizon approach, the multi-period problem is updated as better demand forecasts are available and inventory levels are revised.

Candas and Kutanoglu (2007) introduced an optimization model that reflects the interdependency between spare part logistics network design and inventory stocking decisions, such as stock levels and their corresponding fill rates. They also investigated the effect of demand levels, service level and costs on the total cost of the network. Kutanoglu and Lohiya (2008) proposed an optimization-based model for the integrated inventory and transportation for a single echelon, multi facility service parts logistics system. Fabry and Schmitz-Urban (2010) proposed an open IT-platform for maintenance supply chain coordination (MSC), where all MSC participants are integrated from end-customer via maintenance service provider, spare part retailer, spare part producer, and logistics service provider. Within their proposed approach, mobile devise technologies are assimilated to enable the semi-automatic generation of spare parts orders. Their goal is to provide a nearly real-time order processing and to reduce the order-to-deliver time for spare parts.

Since in this article we investigate spare part logistics problem from client (e.g., airline) and the maintenance provider viewpoints, some recent contributions on repairable parts inventory models that consider the system in a decentralized framework are also reviewed in what follows. The abovementioned models try to satisfy simultaneously the customer's desired performance (maximizing system availability) and the service provider's requirements (resource planning).

Kim et al. (2007) proposed analyzed the implications of performance-based contracts between the maintenance services buyers and suppliers in capital-intensive industries such as aerospace and defense. The authors introduced a multi-task principal-agent model where the customer (principal) faces a product availability requirement. It then offers contracts contingent on availability to a number of suppliers (agents) of the key subsystems used in the product. The agents in turn set spare-part inventory investments. They demonstrated that when channel members are risk averse, the best contract involves a combination of fixed-payment, a cost sharing incentive, and a performance incentive. Mirzahosseinian and Piplani (2011) modeled the closed-loop inventory system of repairable part systems that operate under a performance-based logistics contract as an M/M/m queue. Their proposed model revealed that improving the base stock level by the part supplier has little impact on the availability of the system. Rather, the supplier should improve the reliability of the components as well as the efficiency of the facility so that the availability of the system is improved. Jin and Wang (2012)