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Network and contract optimization for maintenance services with remanufacturing

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ABSTRACT

Implementing comprehensive service contracts and sustainable supply chains are two recent trends that create the opportunity to develop maintenance contracts with an uptime guarantee for the customer and a remanufacturing process for removed parts. This involves management decisions on the design of the contract (price, uptime guarantee and overhaul interval) and the logistics network (facility locations, capacities and inventories with given service level). These two decision levels are interrelated: the number of contracts is a function of price and machine uptime, while this uptime is affected by the overhaul interval and network responsiveness. Steady-state queueing equations explicitly model the stochastic nature of the problem, e.g. the impact of resource utilization levels on lead time of the remanufacturing process. This approach results in a non-linear mixed integer model, which is solved by a differential evolution algorithm to find the maximum profit that simultaneously optimizes both problems. A real-life application reveals that price sensitivity is a critical determinant and that measures must be taken to tackle the problem of moral hazard.

1. Introduction

For most equipment such as trains, elevators, oil-platforms or airplanes, maintenance costs are several times higher than the purchasing cost of the equipment. As customers focus on lifecycle cost and machine uptime, original equipment manufacturers (OEM) are responding with more comprehensive after sales service contracts. These contracts, also referred to as a full responsibility contracts (FRC), stipulate that the OEM guarantees to perform all preventive and corrective maintenance, and to deliver the required parts and components with given service level.

Offering FRC impacts the pricing strategy as well as the operations management decision process. The contract design of FRC is determined by a yearly fixed fee and a guaranteed machine uptime (or machine availability) [1,2]. Clearly, pricing and uptime decisions are related: customers are often willing to pay a premium for fast service [3]. High machine availability can only be delivered when sufficient resources (field technicians and parts) are available to repair machines quickly. Hence, the uptime in the contract is influenced by capacity and inventory decisions, which are handled in the logistics network design (see further below). In addition, the uptime is also affected by the maintenance policy, more in particular by the decision on the time between machine overhauls. There is a complex trade-off: more preventive maintenance may limit the number of failures (uptime increase), but machines are unavailable during this maintenance time (uptime decrease). Managing the overhaul interval is also critical for manpower requirements: more frequent maintenance visits cause a need for more field technicians who perform the service of machine overhauls, but for less field technicians who perform the repair of machine failures. Failures are commonly modeled according to a Power Law process from reliability theory [4]. This is the contract design problem.

Another complicating decision-making factor is that nowadays OEMs often extend their business with a remanufacturing process for parts removed during maintenance in order to save resources and reduce costs or to access new customer markets. It is important that a sufficient amount of already remanufactured parts is available in stock and that the network is responsive enough to re-supply this stock. Management decisions related to these operations include the location and capacity of remanufacturing centers, and the location and amount of safety stock to satisfy a given service level. This is the logistics network design problem.

These two distinct strategic decision levels (contract design and logistics network design) cannot be separated because of the interrelated nature of their problems. More specifically, the lead time creates interdependencies. A fundamental queueing relationship states

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that lead time increases nonlinearly in both mean and variance with resource utilization, which is system's workload relative to its capacity [5]. Let us illustrate this point. The utilization level of field technicians (those who repair a failed machine) and their associated waiting times clearly impacts the uptime guarantee in the maintenance contract. Similarly, the remanufacturing capacity impacts the lead time and consequently the required amount of spare parts inventory (through the demand during lead time).

By modeling the dynamics in the system with queueing relationships, the lead time is endogenously determined. Furthermore, we want the contract volume to be a function of price and uptime, and customer's sensitivity for these values. Thus demand for contracts has also an endogenous character. We consider the endogenous treatment of lead time and contract volume as the major methodological contribution of this paper.

Our research is inspired by the full responsibility contract strategy at a leading manufacturer of industrial equipment, which we refer to as AirGen. Although they are successfully selling multi-year service contracts, they only have recently started to include uptime guarantees in these contracts. Nevertheless, due to many complex interrelationships, it is generally unclear how the service contract design (price, uptime guarantee and maintenance policy) influences the logistics network design (location and capacity of facilities, flow assignments and inventory levels), as well as which factors influence the optimal parameter values of these two strategic decision levels (contract and network). Therefore, there is a need for a mathematical model that captures all the complex relationships between these two design levels in order to understand what kind of consequences the new strategy (including uptime guarantees in service contracts and adding a remanufacturing process for removed parts) has on several dimensions: maintenance and pricing policies, contract types and volumes, and capacity and inventory investments.

Given the importance of lead times to achieve the uptime guarantee in the contract design and to determine the inventory level in the logistics network design, we use an advanced queueing model with steady state relationships to estimate the profit that the OEM can expect from this new strategy. Steady state equations are typically used in queueing models to analyze stochastic systems. The underlying probabilities for state transitions, influenced by various sources of variability in the system, determine the outcome of the queueing model, i.e. performance measures like delays, lead times and work-in-process in terms of an average and a variance. We refer to Section 4 to clarify how the stochastic nature of our problem is introduced in the mathematical model. Since these relationships are analytical in nature, an algorithm can search for the optimal profit. Similar to Lieckens et al. [6], we use the differential evolution method. The model includes costs for facilities, labor, transportation, processing, disposal and inventory. The revenues are generated through the sales of service contracts.

Based on the results from the model applied to the AirGen case, we want to answer the following research questions on the design of service contracts and logistics networks:

1. What are critical parameters for setting the price and the uptime guarantee?
2. What is the impact of adverse selection and moral hazard?
3. What is the impact of labor costs?
4. What is the impact of inventory costs (centralization vs. decentralization)?

To summarize, the goal of this research is to investigate the consequences of selling comprehensive contracts in aftermarket services with remanufacturing of removed parts. We take into account the interplay between market dynamics, pricing, maintenance policy and network profit optimization in a business environment that is typically stochastic in nature. Based on queueing relationships and reliability theory, an analytical model is built that simultaneously sets the parameters in both contract design (price, uptime guarantee and overhaul interval) and logistics network design (facility location, remanufacturing and technical field capacity, and inventory of remanufactured parts with given service level). The model enables us to quantify the impact of these network investment decisions on machine uptime. This uptime, together with the price, will influence demand and hence the workload. Since both problems are clearly connected with complex interrelationships, we prefer to optimize the integrated model. It contains a contract sub-model for setting contract parameters and volume, and the logistics network sub-model for the investment decisions. Concurrent design decisions will lead to an overall efficient strategy for this research problem.

In Section 2, we provide an overview of relevant literature, followed by a detailed description of the AirGen case study in Section 3. In Section 4, we develop the contract sub-model and the logistics network sub-model. We also introduce the profit maximizing objective function and the selection of the search algorithm. Section 5 is devoted to our extensive computational experiment. We report on the major findings and insights. We conclude in Section 6.

2. Literature overview

The multi-disciplinary approach of integrating network and contract design problems is the major methodological contribution of this paper. Therefore, our work has links with several distinct streams in the literature: location analysis, queueing theory and spare part inventory management for the logistics network design model on the one hand, and reliability theory, maintenance policy and pricing strategy for the contract model on the other hand. The purpose of this section is to position our research with respect to these research fields.

Melo et al. [7] provide an extensive literature overview on the facility location problem. Many authors see the benefit of combining location and inventory decisions (e.g. [8,9]), some authors treat replenishment times as stochastic and subject to customer service objectives (e.g. [42,10]), but an integrated approach that also considers the capacity levels is less developed.

Relevant literature with respect to queueing networks can be found in Buzacott and Shanthikumar [11], Hopp and Spearman [5], Whitt [12] and Whitt [13]. The decomposition of a queueing network into separate building blocks (i.e. facilities and field technicians in the AirGen case) with their steady-state waiting time distributions is followed by a linking step to obtain the overall system performance.

The spare part inventory research on multi-echelon networks with finite repair capacity was initiated by Gross et al. [14]. For multiple items with general repair times and a repair backlog dependent demand rate, Diaz and Fu [15] optimize the inventory levels. Sleptchenko et al. [16] start to optimize repair capacity and inventory decisions in a concurrent way. Caggiano et al. [17] also focus on capacity and inventory decisions in a multi-echelon network, but they use real time data to optimize resource allocation while the level of capacity and inventory is given. For a queueing based network model that finds the stock levels with maximum availability in a closed loop two-echelon repairable item system with repair facilities both at a number of local service centers and at a central location, we refer to Spanjers et al. [18]. The optimization is for a given fixed configuration of machines and servers and subject to a budget constraint.

As observed by Melo et al. [7], a profit maximizing objective is scarcely studied in reverse logistics networks. Recently, increased