Decision Support Systems 54 (2013) 1548–1557

Contents lists available at SciVerse ScienceDirect

Decision Support Systems

journal homepage: www.elsevier.com/locate/dss

Optimization of a stochastic remanufacturing network with an exchange option

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ARTICLE INFO

Available online 5 June 2012

Keywords:
Network design
Queueing
Remanufacturing
Contracting

ABSTRACT

An international manufacturer of industrial equipment offers its customers a remanufacturing service consisting of a refurbishment of the most critical part in order to rejuvenate the equipment. Offering remanufacturing services is in line with a servitization strategy. We develop a strategic decision support tool to optimize the required remanufacturing network. Investment decisions have to be made, not only concerning the number and locations of remanufacturing facilities, but also concerning the appropriate capacity and inventory levels to guarantee specific service levels. These network decisions are influenced by the way remanufacturing services are offered. We consider two service delivery strategies, either a quick exchange of the used part by an available remanufactured one or re-installing the original part after it has been remanufactured. Given the high level of uncertainty, we build a stochastic, profit maximizing model to simultaneously determine the optimal network design and the optimal service delivery strategy for a multi-product, multi-level network for repairable service parts. The rapid modeling formulation with a non-linear objective function subject to non-linear constraints is solved by the differential evolution algorithm. We conduct the analysis for fast and slow moving part types. The model can be easily extended to more general settings, while the case-study provides valuable insights for practitioners.

1. Introduction

The large installed base of equipment provides original equipment manufacturers with an opportunity to develop a profitable remanufacturing business. The launch of more extensive warranties and overhaul services relies on remanufacturing activities and fits the current servitization trend in the industrial equipment industry [4,19,5]. Consequently, an increasing number of companies like Bosch and HP are intensifying their remanufacturing activities [10]. Our case-study company is an international manufacturer in the compressed air and generator industry with a renewed focus on remanufacturing. Due to confidentiality reasons the company is referred to as AirGen and financial specifications are omitted.

In order to set up a remanufacturing network, AirGen's management has to decide upon the number and locations of facilities. In addition, appropriate capacity and inventory levels have to be set in order to fulfill the service level agreements (SLA). Furthermore, contractual arrangements made with customers (e.g. regarding the ownership of parts) and the selected service delivery method have an impact on the optimal remanufacturing network design. The goal of our research is to build a model that supports this complex decision making process at the strategic management level.

2. Problem description

AirGen's remanufacturing service consists of a refurbishment of the most critical part of the equipment: they clean, rebear and restore the part to an as-good-as-new condition which will extend the lifetime of the equipment. Prior to these refurbishment activities taking place in a remanufacturing facility, an AirGen field technician travels to the customer site to disconnect the worn-out part. Two service delivery strategies are offered. Under a refurbishment with exchange, in short referred to as an "exchange" strategy, the technician replaces the part by an already refurbished one. Contrary, if a refurbishment without the exchange option is selected, or shortly a "refurbishment" strategy, the customer has to wait until its own part is refurbished and the field technician re-visits the site to install the part. With the exchange strategy, AirGen has to deliver a part from stock to replace the worn-out part. This inventory of as-good-as-new parts is replenished either by newly produced parts or by refurbished parts from previous customers. The inventory can be held at the remanufacturing facilities or at a centralized distribution center (DC). There are five locations for opening a remanufacturing facility, while their current production plant and DC are not to be relocated. Fig. 1 represents the potential network structure.

Customers are geographically dispersed but can be clustered into five customer regions corresponding to the five potential remanufacturing facility locations. Preferences for the two service delivery strategies are reflected in different demand and price levels between the customer regions. AirGen wants the model to determine the most profitable mix of both service contracts. Although different part types

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doi:10.1016/j.dss.2012.05.057

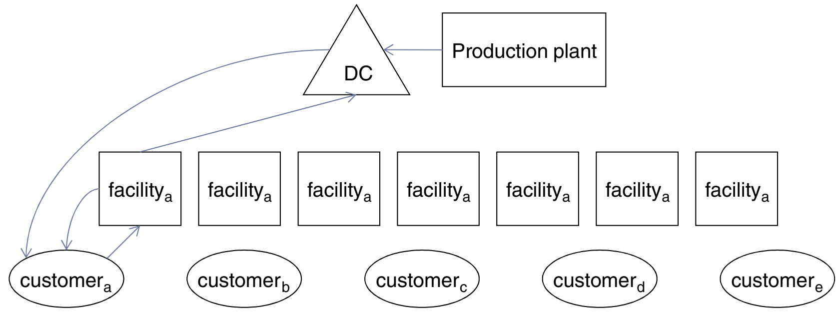

Fig. 1. Case study network.

can be refurbished, we group them in two categories to keep the problem traceable: a slow and a fast mover part category. Nevertheless, the model itself is capable of dealing with more than two categories.

Designing a remanufacturing network involves three related strategic sub-problems: a facility location, a capacity and an inventory sub-problem. The first decision to be made is where to open remanufacturing facilities. The second decision deals with the number of operators that should be employed at each facility. The third investment decision sets the appropriate inventory level(s) subject to a given SLA, which differs between the refurbishment and exchange service delivery strategies. In contrast to the refurbishment strategy, the exchange strategy requires an investment in inventory of as-good-as-new parts. Not only the level, but also the location of this inventory may be different for fast and slow moving parts. In general, fast moving parts benefit from more decentralized stock locations, while the opposite holds for slow moving parts. Pooling the risk of these highly uncertain items into one central hub can compensate for additional transportation costs. Given the specific characteristics of remanufacturing, we deal with a continuous review one-for-one replenishment inventory sub-problem.

Our focus is on interrelated strategic decisions concerning the network structure: the main questions to answer are the type of service delivery strategy and the number/locations of the remanufacturing facilities. However, these decisions are heavily influenced by the optimal capacity levels at the facilities and the required inventory levels: e.g. cost savings in transportation costs (facility location) may be canceled out by higher operator costs or higher inventory costs. Therefore, it is required to solve the tree sub-problems simultaneously. Tactical and operational decisions such as optimal routing of technicians, transportation batching, work scheduling at the refurbishment centers, etc. are not considered. Consequently, the planning horizon spans multiple years. This integrated approach that leads to outperforming network design solutions in combination with steady state queueing relationships that model lead times and inventory levels is the main research contribution of this paper.

Since all decisions with respect to facilities, capacities, inventories and service delivery strategies influence each other, we propose an integrated solution approach. The complicating factor of uncertainty in demand, processing and transportation times is also taken into account. We formulate a mixed integer non-linear model that integrates queueing relationships and maximizes profit. This rapid modeling approach is solved by a differential evolution search algorithm (see Section 4.7). The focus on the design of a remanufacturing network evidently contributes to the objective of designing sustainable after-market supply chains. After presenting the related literature in the next section, Section 4 clarifies the model. Section 5 presents the results of the case study at AirGen. We conclude in Section 6.

3. Related literature

One of the major contributions of this paper lies in its multi-disciplinary approach as we integrate facility location, capacity and inventory decisions at the strategic level. Therefore, our work is related to three distinct research streams: facility location, queueing and spare part inventory management literature. Each of these disciplines contains a vast amount of literature. In this section, we do not want to be exhaustive but review the major contributions in each of the three research fields in order to position our research.

The first relevant literature stream is that of the facility location problem (see for example Melo et al. [17] for an extensive overview). Many authors have demonstrated that integrating facility location and inventory decisions can be very rewarding [6,25]. Next to designing a cost efficient supply network, customer service objectives should be taken into consideration, as in the work of Zuo-Jun Max and Daskin [35], Nozick and Turnquist [20] or Mak and Shen [16]. Although both Nozick and Turnquist [20] and Mak and Shen [16] consider stochastic replenishment times, they do not optimize the capacity levels.

The second literature stream deals with queueing networks. Queueing networks are often modeled by using the parametric decomposition approach. The queueing network is decomposed into separate building blocks (i.e. individual workstations or in our case individual facilities in a multi-echelon network). Besides the steady-state waiting time distributions of separate blocks, we have to link the separate blocks by means of linking equations. As such, a linking equation literally links the results obtained at the separate building blocks to obtain the performance of the network as a whole. We refer the reader to Buzacott and Shanthikumar [2], Hopp and Spearman [11], Whitt [32] and [33] for excellent reviews. Using steady state equations as part of an optimization problem can be labeled as a rapid modeling approach [23,24]. These analytical expressions enable us not only to quickly build a mathematical model that represents a production system with realistic dimension, but also to evaluate instantly the performance of this system, allowing us to do a computation intensive optimization process. The use of analytical expressions is in contrast to a simulation technique. This method can also be combined with an optimization process as in Willis and Jones [34], but this would be more time consuming.

Lastly, the spare part inventory literature has paid special attention to multi-echelon repairable networks due to both the applicability and complexity of these networks. In his seminal work, Sher-Brooke [26] formulates a technique to find the base stock level that minimizes the expected number of back-orders in a two echelon parts network with ample repair capacity. This METRIC model has been adapted by many authors to make it applicable to more realistic settings. Muckstadt [18] extends the model to the MOD-METRIC that allows multi-indenture parts. The VARI-METRIC model that is based on the work of Graves [8] and further improved by Sherbrooke [27], allows for a higher variability in the distribution of the back-orders. A highly restrictive assumption of these multi-echelon models is the conjecture of infinite repair capacity. The research on multi-echelon capacitated repairable networks was started by Gross et al. [9]. Diaz and Fu [7] optimize the inventory levels for multiple items in a network with limited repair capacity, general repair times and a demand rate that depends on the repair backlog. The work of Sleptchenko et al. [28] is probably the first that simultaneously optimizes the repair