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System Dynamics modelling of a production and inventory system for remanufacturing to evaluate system improvement strategies

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A R T I C L E I N F O

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A B S T R A C T

Remanufacturing activity views the reverse supply chain of reclaimed goods as integral to the traditional supply chain to the consumer. At the end of the useful life of products, a reverse supply process is activated in which unwanted materials and products are recovered from end users to recapture some of their value. Therefore, planning for the traditional supply chain of goods must take into account the recovered products. Two main processes that need to be considered are inventory control and production planning. In this paper, we model a production and inventory system for remanufacturing using a System Dynamics simulation modelling approach. The aim is to explore the dynamics of the remanufacturing process and to evaluate system improvement strategies. Specifically, the analysis focuses on the effects of capacity planning and lead times on the system which presents push and pull inventory policies driven mainly by the inventory coverage. The research findings reveal efficiency in the remanufacturing process with higher remanufacturing capacity if the quantity of remanufacturable returns and the remanufacturing lead time are increased and decreased respectively. Moreover, an increase of the production lead time has a higher effect on the system performance than an equivalent increase in the remanufacturing lead time. In addition, we provide a case study both to support these findings and to further validate the developed model.

1. Introduction

The growing recognition of the limited quantity of natural resources, which comprise the raw materials of production, energy, water, air supply and landfill sites, is pushing societies to employ corrective actions to create a sustainable world for future generations (Gungor and Grupta, 1999). Resources reduction alongside the use of renewable energy can form part of such corrective actions, and remanufacturing activity has an important role to play in resources reduction. Indeed, remanufacturing is the company process to recapture value from product returns whose parts and materials are reused for the production of as good as new products. Such a process uses 85% less energy than production, and reduces landfill, pollution and raw material usage (Gray and Charter, 2007).

A remanufacturing process has a broader importance for a company's activities than solely to fulfil environmental issues. The use of remanufacturing is increasing in the business world not only for environmental purposes but also for competitive reasons. Indeed, an efficient remanufacturing brings many benefits to a company (Roy, 2003). These include: (1) the reduction of operating costs through the recovery and reuse of products or components; (2) the reduction of disposal costs; (3) the improvement of distribution channels through a more efficient process for collecting obsolete, outdated or clearance items; (4) a more efficient aftermarket; (5) improvement in the value of the company brand through the recovery of products which will be reused to benefit sustainable purposes.

However, company costs could be increased by the adoption of remanufacturing activities (Inderfurth, 2005). Dealing effectively with returns can prove to be more expensive than anticipated, and companies with slim retail profit margins may feel they have too little to gain (Zieger, 2003). If the total cost incurred by returns process activities exceeds the total cost generated by the traditional forward supply chain, firms will have no financial incentive to implement a remanufacturing process (Prahinski and Kocabasoglu, 2006). For this reason, a company objective is to optimise an integrated reverse and forward supply chain system to minimise the total costs and maximise benefits. In particular, the objective of production and inventory management in remanufacturing processes is to control external components orders and the internal components recovery process to ensure a specific service level and to minimise total production and inventory costs. Additionally, there is a need to determine whether it may actually be cheaper to overhaul a return than to produce or buy a new one (Fleischmann et al., 1997).

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Several authors have conducted research on the remanufacturing system. They have focused mainly on: production and remanufacturing lead times (Inderfurth and van der Laan 2001; Kiesmuller 2003; Kiesmuller and Minner 2003; van der Laan et al., 1999); optimisation procedures for inventory levels and Economic Order Quantity (Kiesmuller and van der Laan 2001; Koh et al. 2002; Teunter 2001; van der Laan et al., 1996; van der Laan et al., 1996); comparisons between pull and push strategies (van der Laan and Salomon 1997; van der Laan et al. 1999; van der Laan and Teunter 2006); and capacity planning (Georgiadis et al., 2006; Kleber 2006; Vlachos et al., 2007).

Mindful that these problems add complexity to this field of research, in this paper, our main objective is to model the main factors that affect a production and inventory system in which production is integrated with the remanufacturing activity, and to investigate and evaluate effective control strategies for improving the performance of the system. To address this objective, a System Dynamics (SD) (Forrester, 1958, 1961) simulation model of a production and inventory system for remanufacturing is developed. As part of the development of the SD model, we identify the main factors, their influence relationships and the business/operational policies that affect the dynamic behaviour of the system. The remanufacturing process is modelled using such key factors as (1) integrated remanufacturing/production capacity, (2) lead times, (3) backorder and (4) inventory coverage. Several policies that affect the dynamic behaviour of the system are defined in the modelling process using such factors. These modelled policies are included in order to improve the efficiency of managing production/remanufacturing and inventory activities in the process.

Several studies have been successful in developing and simulating models of remanufacturing systems. The objective of these studies was mainly to analyse the effects of various environmental and operational activities on the defined measures of performance of the systems. The integration between the forward and the reverse supply chain activities was modelled with success in these studies. However, we believe that in terms of the operational management aspects, analysis, for example, of the shared capacity between production and remanufacturing and on lead times duration has been fairly limited. In particular, in terms of capacity planning, models have been developed that mainly analyse capacity expansion and contraction of collection and remanufacturing activities (Georgiadis and Vlachos 2004; Georgiadis et al., 2006). However, the implications of the constraints on capacity which must be shared between remanufacturing and production is another topic requiring further research (Kleber 2006).

A case study is used in our study to gain support for the findings as well as to further validate the developed model for production and inventory systems for remanufacturing. In particular, through the case study we are able to assess the findings obtained from the simulation analysis of the model. Moreover, some of the information and data collected from the company have been useful in selecting the variables and the relationships among them to be used in the model development. For these reasons, we collected as much data and information as possible of a company involved in remanufacturing activities. The company is CEVA Logistics Australia which provides the materials handling services and the materials management services for the returns and remanufacturing processes of phones/mobiles and several electronic products.

The modelling and simulation method adopted in this study is introduced in the next section. In Section 3, the SD simulation model of the production and inventory system for remanufacturing is developed. The validation process of the obtained model is presented in Section 4 and the simulation of scenarios focusing on various levels of the main system parameters is developed in Section 5. A case study in support of the research findings is provided in Section 6, and finally our conclusion is given.

2. Modelling and simulation method

In terms of the modelling and simulation method, in this study we use System Dynamics (SD). SD is a methodology and computer simulation modelling technique used for understanding the dynamic behaviour of complex systems in order to analyse and solve complex problems with a focus on policy analysis and design. Originally developed by Professor Jay Forrester at the Massachusetts Institute of Technology in the 1950s, SD is currently being used for a wide range of applications in practice by academics, large companies, consulting agencies and government organisations (Sterman, 2000; Taylor, 2008).

The selection of an SD approach for this study was based on its ability to model systems with complex feedback structures using visual representation which can then be converted into mathematical formulas by software. The complex feedback structures are obtained by iterations of the physical and informational flows and managerial policies defined by the system variables. The SD model can then be simulated in order to reproduce the dynamic behaviour of the system, which in turn enables an evaluation of the system improvement strategies.

SD differs from other approaches such as analytic approaches. The former involves identifying influence relationships among the variables of a complex system in order to undertake a comparison between the reality and the dynamic behaviour of the model which represents the system in its totality. Moreover, SD is suitable for modelling and simulating systems that contain multiple nonlinear relationships and dynamic forces that render the use of an analytical approach to solving model equations not feasible (Angerhofer and Angelides, 2000; Coyle, 1996). For these reasons, we believe that such an approach is suitable for our study. Specifically, through a simulation approach it enables the modelling of factors, operations processes and company policies to consider in a production and inventory system for remanufacturing, as well as the evaluation of effective control strategies aimed at improving the performance of the system.

3. System modelling

All business and social systems contain a host of assets which can be viewed as stocks or accumulations of resources which change according to their physical inflows and outflows (Morecroft, 2007). This stock and flow structure of systems can be captured to create a System Dynamics simulation model in the form of a Stock and Flow Diagram (SFD).

The SFD of a single product production and inventory system for remanufacturing employed for our study is presented in Fig. 1. The diagram shows the variables used for the modelling of the system and the links or causal relationships among them. These relationships are used to establish the mathematical equations in order to run various simulations of the model and to analyse the dynamic behaviour of the system.

In Fig. 1, the rectangles represent stock variables that are accumulations of items, while the valves represent flow variables that are the physical flows of items feeding into or depleting the stocks. The physical flow of items is represented by a double line with arrows, while the flow of information (*i.e.* connexion among variables and their interrelationships to be used for mathematical formulations) is represented by a single line with arrows. Auxiliary variables shown in all upper case letters represent constants