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Analyzing supply chain robustness for OEMs from a life cycle perspective using life cycle simulation

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ABSTRACT

Long-term relationships between original equipment manufacturers (OEMs) and stakeholders in their supply chain and end-of-life process can be designed, while considering uncertainty in future environmental legislation changes. This study proposes a method to analyze the capability of OEMs to reconfigure their supply chain and end-of-life operations to achieve performance targets, which are defined in terms of environmental impacts and life cycle costs. Using life cycle simulation (LCS), the physical deterioration and the functional obsolescence of individual products are considered as stochastic elements in the analysis. The analyzed reconfiguration capability provides the OEM with robustness against uncertainty from a life cycle perspective.

1. Introduction

Original equipment manufacturers (OEMs) often need reconfiguration of their supply chain to follow environmental legislations such as the Directive on Waste Electrical and Electronic Equipment (WEEE, 2002) and the Restriction of Hazardous Substances Directive (RoHS, 2002). The reconfiguration at an operational level consists mainly of reallocation of component orders to OEM suppliers, which have been designed to optimize multiple performance criteria such as cost, delivery time, delivery performance (reliability), and quality (Wang et al., 2004). From a life cycle perspective, OEMs can reduce life cycle costs and environmental impacts (e.g., resource consumption, emission) by designing end-of-life operations to improve the logistics of used products and components (Umeda et al., 2000). In this study, the authors propose a method to evaluate the capability of an OEM to reconfigure its supply chain and end-of-life operations to achieve a performance target. The target is quantitatively described with environmental impacts and life cycle costs.

The aforementioned reconfiguration capability is crucial for OEMs to adapt themselves not only to environmental legislations, but also to strategic policies initiated by OEMs themselves. These policies are, for instance, based on the principle of extended producer responsibility (EPR). These policies are initiated in order to attract customers from an environmental perspective by differentiating themselves from competitors (Tojo, 2004). In either case, these legislations and policies include quantitative target descriptions (e.g., reduction of resource consumption by 20% in five years). Quantitative information in these descriptions is often uncertain when OEMs design their supply chain and end-of-life operations. Thus, reconfiguration capability partially represents robustness of OEMs against introductions and changes of these legislations and policies.

For the evaluation of the reconfiguration capability, various stochastic elements in a life cycle have to be considered. Besides demand fluctuation of products in a market, *physical deterioration* and *functional obsolescence* of products in a life cycle are considered as stochastic phenomena in this study. These phenomena influence the number of used products and components collected by OEMs. They also influence the operations of OEMs that control the logistics of new and used products and components.

In order to simulate these phenomena, life cycle simulation (LCS) (Shu et al., 1996; Umeda et al., 2000) is employed. LCS has been used for the design of life cycles (Tomiyama, 1997; Umeda, 2001), in which interrelations among the processes in a life cycle (e.g., production, transportation, utilization, maintenance, upgrade, and end-of-life operations) are analyzed. The analysis is necessary to evaluate the performance of a life cycle from economic and environmental perspectives.

Other studies about supply chain design considering end-of-life operations are called *reverse logistics* or *closed-loop supply*

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chains. These studies have been conducted mainly in the field of operational research, where distribution logistics, inventory control, and production planning have been the major interests of the researchers in this field (Fleischmann et al., 1997). Modeling methods used in these studies are diverse, and include mathematical programming (e.g., Fandel and Stammen, 2004; Chouinard et al., 2008), system dynamics (e.g., Georgiadis and Vlachos, 2004), material flow analysis (e.g., Kandelaars and van den Bergh, 1997), and queuing systems (e.g., Bayindir et al., 2006). These methods support supply chain design by using equations and inequality constraints that, for instance, represent product flows among the processes in a life cycle and the capacity of end-of-life processes, respectively. These methods also deal with the uncertainty in terms of demand fluctuation of products in a market and the rates of product collection and recovery. In this study, these methods are reviewed and compared with the modeling method used for LCS.

The present study is an extension of previous studies by the authors. In these studies, a method to evaluate the performances of an OEM's supply chain in terms of multiple criteria (costs, environmental impacts, delivery performance) using discrete event simulation has been proposed (Nagel et al., 2005). Furthermore, a method for an OEM to optimize its supply chain operations subject to the multiple performance criteria using a multi-objective genetic algorithm has been proposed (Komoto et al., 2005). In the present study, LCS is used to evaluate the performances of an OEM's supply chain operations considering end-of-life operations in terms of the multiple performance criteria. The optimized results of LCS indicate the performance of the OEM that can be achieved by reconfiguring these operations.

This paper is organized as follows. In Section 2, modeling methods that support supply chain design from a life cycle perspective are reviewed. In Section 3, a LCS model including supply chain operations, the simulation, optimization, and robustness evaluation procedure, are described. In Section 4, a case is introduced to demonstrate the proposed method. The objective of this case is to evaluate whether an OEM can obtain some economic and environmental performance targets with its current supply chain and end-of-life operations. The case is followed by discussions about the applicability of the method to industrial practice and its limitation. In Section 5, this study is summarized and concluded.

2. Related work

In this section, modeling methods that support supply chain design from a life cycle perspective are reviewed. The review focuses on the representation of the supply chain and end-of-life operations in these methods, and on the stochastic elements considered in these methods from a life cycle perspective.

2.1. Life cycle simulation

Life cycle simulation (LCS) is a quantitative technique to evaluate the performance of a life cycle (Umeda et al., 2000). LCS is based on the concept of probabilistic design of life cycles (Shu et al., 1996). LCS includes stochastic elements such as physical deterioration of individual products which will be briefly described. LCS is particularly useful in designing life cycles in which decisions regarding end-of-life operations depend on the state of individual products, and a certain range of uncertainty is assumed in some of the end-of-life operations (e.g., product collection rate) (Kobayashi, 2005; Kobayashi, 2006). As an example of practical use, LCS has been employed to analyze the life cycle of personal computers, in which the employed end-of-life operation was shifted from product reuse to component reuse for downgraded products (Kumazawa and Kobayashi, 2006).

Analysis of physical deterioration of products is crucial in product design, because one of the crucial tasks in product design is to optimize the module structure of products assuming the specific physical deterioration of each module component (Umeda et al., 2000). The physical deterioration causes uncertainty in the timing of product repair, component replacement, and product collection. To measure the impact of this uncertainty on the delivery of repaired products, the *rate of market fulfillment* (i.e., product delivery to meet the market demand) was proposed (Kondoh et al., 2005). The study of Kondoh et al. employed LCS, and it was concluded that appropriate selection of end-of-life operations to control the circulation could help improve the rate of market fulfillment. However, the study did not include decision making at the supply chain operations such as allocations of component orders to component suppliers.

Some studies about life cycle design using LCS have introduced the functional obsolescence of products as a stochastic element in a life cycle (e.g., Kato and Kimura, 2004). Nonetheless, these studies have not differentiated the functional obsolescence from the physical deterioration of products. In a previous work (Komoto and Tomiyama, 2008), the authors proposed to express this difference assuming that the functional state of a product (e.g., novelty) in a market can be measured relative to the technological state of the market, while the physical state of a product (e.g., wear) can be absolutely measured regardless of the market state. Under this assumption, a new product introduction into a market causes functional obsolescence of other products existing in the market, while the physical deterioration of individual products depends on their usage patterns (Komoto and Tomiyama, 2008).

Similar to LCS, life cycle costing (LCC) and life cycle assessment (LCA) are quantitative techniques to evaluate the performance of a life cycle economically and environmentally (e.g., Durairaj et al., 2002; Senthil et al., 2003). However, LCC and LCA do not explicitly consider the physical deterioration and functional obsolescence of products as stochastic elements in their life cycle. This is why these techniques calculate the life cycle performance by aggregating the performances of individual processes in the life cycle, which are deterministic and independently calculated. In comparison, LCS calculates the life cycle performance by aggregating the performances of individual processes (e.g., production, usage, repair), whose occurrences depend on stochastic state fluctuations (both physical and functional) of products in a market.

2.2. Reverse logistics and closed-loop supply chains

Studies about supply chain design considering end-of-life operations are called *reverse logistics* or *closed-loop supply chains*. These studies have been mainly conducted in the field of operational research, in which distribution logistics, inventory control, and production planning have been the major interests of the researchers (Fleischmann et al., 1997). The modeling methods employed in these studies have been based on stochastic mathematical programming, material flow analysis, system dynamics, and queuing systems as reviewed below.

Stochastic mathematical programming methods have been used to analyze the behavior of closed-loop supply chains (e.g., Fandel and Stammen, 2004; Chouinard et al., 2008). The mathematical models used in these methods deal with the uncertainty about market demand and the proportion of products to be collected, disassembled, and reused. Such models also deal with the capacity of production process and end-of-life operations as model