Sustainable Product and Supply Chain Design Decisions under Uncertainties

Ming-Chuan Chiu1# and Li-Wei Teng1

1 Department of Industrial Engineering and Engineering Management, National Tsing-Hua University, Hsinchu, Taiwan
# Corresponding Author / E-mail: mcchiu@ie.nthu.edu.tw, TEL: 03-5742699

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Nowadays enterprises are forced to consider broader aspects while designing and manufacturing products. The scarcity of natural resources as well as stern environmental regulations have obliged enterprises to develop new products that can satisfy profit, people, and planet during its life cycle. In the last decade, many research efforts have incorporated supply chain and sustainability into product design. However, most of the studies provided deterministic based methodologies. Enterprises who intend to improve sustainability under various uncertainties couldn’t find an appropriate method. The method based on fuzzy set theory is proposed in this study to tackle the uncertainty of supply chain and highlight the sustainable design concepts considering product disassemblability, closed loop supply chain performance, and carbon footprint. A scooter company case study is presented to demonstrate the advantage of this methodology. Because the risk of impreciseness of data could be reduced, decision-makers only have to provide suitable regions to express the costs and lead-time instead of exact numbers. This method can support decision-makers to make the most sustainable decisions which contain both product and the closed loop supply chain design based on the concern of lead-time, cost, and carbon footprint. As a result, sustainable product and supply chain design under uncertainties can be addressed at the product design stage.

1. Introduction

The shortage of energy resources and raw materials as well as the increasing variation of customer needs have become the main stress of manufacturers. Owing to the trend of globalization, the management of manufacturing capacity and quality become more troublesome because some of components might be outsourced. Therefore, performance evaluation of suppliers turns into one of the most critical issues in supply chain management.

Moreover, the awareness of environmental protection, such as sustainable development and eco-consciousness, has drawn the attention of citizens worldwide. As a result, more and more countries applied strict regulations for imported products, such as WEEE, RoHS and EuP/ErP. These standards have strong impacts on the exporter since the limitation would influence the design of products. Although changing product design would increase the costs, the product can be reused at the time product life is ended. The recycled product can be disassembled and remanufactured so that the manufacturer can attain some profits from recycling. Therefore, manufacturers can achieve higher profit by increasing the recyclability of the product.

Many previous researches have studied disassemblability and recyclability of products at the design stage, but the design of supply chain was seldom considered simultaneously. Therefore, some of the supply chain execution costs were ignored or underestimated. Accordingly, many researchers that solely focused on the supply chain design, including the selection of suppliers and the decision of outsourcing but seldom jointly considered product design. To address this issue, this study aims to integrate product recyclability and supply chain performance at product design stage.

Close-loop supply chain, which is also known as green supply chain, investigates configuration of supply chain network through product life cycle from raw material to end-of-life recycling. In this research, we address the sustainability of product as well as supply chain under uncertainties. Therefore, the proposed method can provide decision support functions for manufacturers both in product and supply chain design related decisions.
2. Literature Review

Modular product design is advantages in terms of design, production, logistics, and support of after service.1,2 “Modularization” was first mentioned in the literature in the 60 s, which means to group components of products in a module for practical production purposes. Modularization is an approach to organize complex designs and process operations more efficiently by decomposing complex systems into simpler portions.3 Gershenson et al.4,5 reviewed literature and provided an overview of module definition and modularization methods.

In order to group components into a module, classifying the components of a product becomes a critical issue. Stone and Wood6 introduced a design language, which is known as functional basis. A black box model is generated to describe functions of a product and proper components are classified into modules.7 Lambert8 applied integer programming to optimize disassembly processes and Tseng et al.9 utilized disassembly indexes and component connector line to modularize a product. However, supply chain and ecological problems at product design stage are not considered.

Supply chain management has become the competitive advantage of a company.10 Due to increasing global competition and the shortening of product life cycle, the enterprise has no choice but to consider and improve its supply chain at the product design stage so as to maintain competitiveness. Ülkü and Schmidt11 examined the suggested link between product architecture and supply chain configuration. They presented a model and suggested that the choice of product architecture should consider not only supply chain structure but also firm, market, and product characteristics. ElMaraghy and Mahmoudi12 developed an integer linear decision support model to determine the optimal location of global supply chain nodes with the objective of minimizing total cost. The model also considers the currency exchange rate at various sides so that optimal modular product structure can be identified. This model combines the product design modular configuration problem and the supply chain design configuration problem. Chiu and Okudan13 presented a methodology which considered product and supply chain design decisions at the product design stage. The methodology can find the optimal design alternative that can simultaneously integrated product and supply chain design decisions. Nepal et al.14 developed a multi-objective methodology with fuzzy approach in supply chain design problems. The proposed method enables decision makers to find the optimal supply chain structures with respect to the product. However, there are lots of random factors existing in supply chain (e.g., lead-time, price variation). In most of the previous research, these random factors are not taken into account so that the result might be impractical for actual situation. Recently, ecological problems have drawn lots of attention. More and more researchers started to investigate the close-loop supply chain in order to reduce the environmental impacts resulting from discarded products.

It is no doubt that the uncertain factors in supply chain cannot be avoided in practical perspective. For instance, production capacity, transit time, forecast, etc., or some situation that cannot be expressed by exact statistics, like customer satisfaction level and accept degree of cost among vendors. Utilizing the fuzzy set theory Zadeh15 can conduct these uncertain troubles in an effective way. Amid et al.16 proposed the fuzzy linear multi-goal programming from suppliers in supply chain to figure out proper solutions if the input of information is not accurate enough. Chen et al.17 employed the multi-objective fuzzy decision to locate the best warehousing and distribution center in the supply chain network, which considers multi-product, multi-class, and multi-planning cycle of production and distribution network, and use the two phase method to require a better solution. Xu et al.18 presented the multi-objective supply chain networks optimal model and its application under the random fuzzy environment. The practice is turning the uncertain factors into definite statistics, substitutes which to math modules by utilizing expectations computing sub and opportunities computing sub, and then, use genetic algorithms find out its answer.

Since the late 1990s, various sustainable design methods and techniques have been developed in response to the awareness of environmental protection.19-20 In recent years, manufacturing industries are obliged to minimize the negative impact on the environment and communities. Along with the increased concern to the social, environmental, and other important issues, new methodologies should be able to achieve win-win situation for both plant and planet.21 Park et al.22 studied energy consumption reduction technology in manufacturing sector by reviewing various policies, standards, and researches. Some studies23-25 applied CAD techniques to design and evaluate sustainable product and system. In operation and maintenance (O&M) perspective, a prognosis-informed stochastic decision-making framework is proposed with concurrent consideration of economic benefits and environmental impacts.26

So far, some researchers have considered sustainable product and supply chain simultaneously but only a few of them addressed the uncertainty issues. In this research, we propose a methodology which takes stochasticity of both sustainable product and supply chain design into account at product design stage.

3. Methodology

To consider the sustainability of product and supply chain design decisions at the product design stage, this study integrates both original forward and reverse logistics into the closed-loop supply chain (as shown in Fig. 1). In the forward logistics, raw materials are made into components, which will finally turn into the complete products and send to customers. After their lifespan terminates, products will enter the system of reverse logistics, where these products are preceded to the procedures of cleaning, testing, disassembly, and classifying. The reusable materials, components, and modules will be recycled, while the rest is going to be discarded.

The procedure of the proposed method is shown in Fig. 2. Firstly, collecting customer needs and expectations are the primary sources of the product design and this research will transform customer requirements into product functions. Then, design concepts are developed systematically by using function basis model. Secondly, a database is built to connect these conceptual product design ideas. Design for disassembly (DfDA) methods is incorporated to define feasible product assembly/disassembly procedures in different stages of supply chain using structure of the AND/OR graph and transition matrix.22 Thirdly, fuzzy theory is applied to quantify the uncertainty conditions of supply chain performance into fuzzy functions. The proposed method which