

Optimization of manufacturing systems under environmental considerations for a greenness-dependent demand[☆]



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ABSTRACT

In this work, we show that the optimization models for manufacturing systems should evolve to consider the environmental impacts of manufacturing activities and to integrate the environmental performance of finished products. In particular, the selection of manufacturing processes (technologies) and input items (components) should be revised with environmental consideration. With this scope in mind, we develop two optimization models where we consider the selection of production processes and the choice of input products. In the first model, a single product is offered by the firm and the demand of this product depends on its greenness. In the second model, the market is segmented between ordinary and green customers and the firm offers a different variety of the output product to each segment. In this case, both the demand and the price depend on the product greenness. In both models, the greenness of the output product is a decision variable that is simultaneously determined along with the other decisions. In addition, the models integrate environmental legislations. We conduct numerical experiments on a case study from the textile sector in order to show how the integration of the product greenness impacts on the system profit and decisions.

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1. Introduction

The environmental concerns are becoming increasingly important for firms as customer awareness towards the environment increases and environmental regulations become more stringent (Zhang and Xu, 2013; Bouchery et al., 2012; Mollenkopf et al., 2010). Thus, many classical decision problems in production management have been revisited with environmental considerations. In particular, decisions that have significant environmental impact such as the choice of the manufacturing processes for a given product and the selection of its components have received considerable attention in the literature. Many papers proposed optimization models to deal with this issue. Most of these models focused on the integration of environmental regulations imposed by governments and on the study of their impacts while the environmental behavior of customers has been widely ignored.

We believe that the optimization models that address environmental concerns in the field of production and supply chain management should evolve to take into account the customer awareness to

the environment. Indeed, with the emergence of environmental concerns, an increasing number of consumers are becoming interested in the environmental performance (greenness) of products. According to the surveys of the European Commission (2008, 2009), 83% of Europeans pay great attention to the impact of products on the environment when buying products. Many authors point out that the environmental attribute of a product has become one of the most important factors that affect the purchase decisions of many customers in today's consumer market (Krass et al., 2013; Tang and Zhou, 2012; Blengini and Shields, 2010; Young et al., 2010). Consequently, the structure of some markets is fundamentally changing. The demand of some products has become highly correlated to their environmental performance. In particular, a large number of works (Chen, 2001; Mahenc, 2008; Young et al., 2010) and real-world statistics (Eurobarometer, 2009, DHL, 2010) describe an increasing demand for the green products due to green market share gain.

Also, many works point out the correlation between the price of some products and their greenness level (Krass et al., 2013; Hassini et al., 2012; Brécard et al., 2009; Mahenc, 2008; Chen, 2001). In particular, they highlighted the cases when the price increases with the increase of the environmental performance. There are two main reasons that explain such a correlation: the marketing argument (Mahenc, 2008) and the greenness cost (Chen, 2001). Indeed, many companies use the greenness as a marketing argument to justify the high prices of some environmentally friendly products. Eurobarometer

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(2008) indicates that 75% of European customers are “ready to buy environmentally friendly products even if they cost a little bit more”, compared to 31% in 2005. Furthermore, many authors argue that a green product may be more costly than an ordinary product. According to [Chen \(2001\)](#), the high cost of green products is related to the costly R&D investment and to the high cost of green input items and green technologies. The high cost of green products can be also justified by the cost of obtaining green certifications ([Plantinga et al., 2000](#); [Veisten, 2007](#)).

Hence, there is a need to develop new models where we link the demand and/or price of products to their greenness level. This imposes many challenges.

- First, we have to define and quantify (measure) the greenness of a product. This is a complex issue that has been addressed from different perspectives in the literature and for which there are no yet well-established standards (see, for instance, [Chen, 2001](#); [Kobayashi, 2006](#); [Ljungberg, 2007](#); [Gehin et al., 2008](#); [Borchardt et al., 2011](#)). Basically, the greenness level of a product depends on two categories of decisions: the first category regroups decisions that directly impact the characteristics of the product while the second category includes decisions that do not change the product characteristics but rather impact its environmental image. For instance, the product design decisions fall into the first category. According to [Chen \(2001\)](#), the greenness is closely related to the design decisions since they affect the product recyclability, the energy and resource consumption during the use of the product, etc. The second category involves mainly production and supply chain decisions. For instance, the selection of manufacturing processes (clean or dirty technologies) impacts on the level of carbon emission and energy consumption during production which affects the environmental image of products. According to [Ottman et al. \(2006\)](#), the greenness of a product highly depends on the characteristics of its manufacturing process. Furthermore, the selection of components used to manufacture a product has a direct impact on the product greenness. For instance, for a given component, the company may have the choice between ordinary suppliers and green suppliers. According to [Sarkis \(2003\)](#), a supplier may be considered as green if he offers green components and/or has environmental certifications such as ISO 14000 certification. Here, we only focus on the supply chain decisions that impact product greenness and, in particular, on manufacturing processes and components selection.
- Once the greenness level is quantified, the next step is to model the demand and/or price as a function of the greenness level. This is difficult to obtain since customers' awareness to environment depends on many factors (ethical, geographical, psychological, type of product, etc.). The literature is relatively scarce regarding this issue. In particular, the optimization of logistics and production activities with environmental considerations and the study of the greenness of products are disconnected subjects in the literature.
- Furthermore the consideration of the relation between supply chain decisions, product greenness its demand and its selling price, we have also to integrate environmental legislations given their important impact on supply chain activities and in particular on manufacturing systems. In this work, we consider the most common forms of environmental legislations: emission thresholds that cannot be exceeded on some emissions, taxes (penalties) based on the amount of output for some emissions, and trading of output allowances for some emissions. Here, the modeled legislations concern the emissions of production process.

The objective of this paper is to develop optimization models for the selection of manufacturing processes and input components

of a product for which the demand and/or price depend on the greenness level. Hence, on the one hand, we model the demand and/or price of the product as a function of its greenness level. On the other hand, we express the greenness level as a function of problem decisions, namely manufacturing processes and components selection. This relationship (illustrated in [Fig. 1](#)) is our underlying tenet in the present paper and distinguishes our work from the classical optimization models where the demand and price of products are considered as input parameters that are determined exogenously. It is important to highlight that we do not address the component selection decision from a product design perspective but rather from a logistics perspective. We consider that the product design process is already achieved and that the product designer has already defined the different components. However, for each component we can choose between an ordinary variety and a green variety. For instance, the selection of a component may refer to the selection of its supplier (green or ordinary) as explained earlier. The product design decisions are beyond the scope of this paper.

With this scope in mind, we propose two optimization models to address our problem. In the first model, the firm offers a single product to all customers. The demand of the product is assumed to be increasing with the increase of its greenness level and the price is assumed to be constant and determined exogenously. In the second model, the market is assumed to be segmented between two types of customers (ordinary customers and green customers as in [Chen, 2001](#)) and the firm decides to offer a different variety of the product to each segment. The ordinary customers are not sensitive to environment. Therefore, the demand and price of this segment do not depend on greenness and are consequently assumed to be constant for different greenness levels. The green customers are sensitive to environment. The demand and price of the product offered to this segment are assumed to be increasing with the increase of greenness. The objective of both models is to maximize the firm's profit while considering environmental legislations.

Our research makes two main contributions. First, we address innovative complexities in the optimization of production systems since we capture the correlation between model decisions and product greenness, on the one hand, and between product greenness and market demand/price, on the other hand. Second, we perform computational experiments on the proposed models using realistic data from the textile industry and derive insights regarding the impacts of integrating a greenness-dependent demand.

The remainder of this paper is organized as follows. [Section 2](#) is dedicated to a literature review. The different features of the studied problem are detailed in [Section 3](#). In [Section 4](#), we present the first model (single product) and its corresponding computational experiments. In [Section 5](#), we study the second model (two varieties of the product). We finally conclude and discuss future work directions.

2. Literature review

The environmental issues have been considered in production and supply chain management literature from different

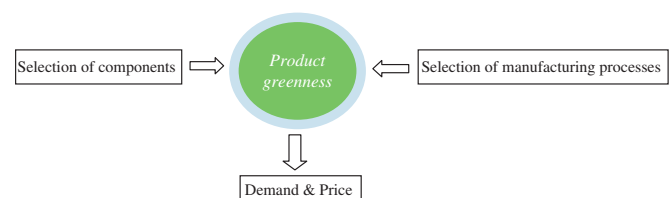


Fig. 1. Relation between product greenness and demand/price.

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