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Selecting new product designs and processing technologies under uncertainty: Two-stage stochastic model and application to a food supply chain

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ABSTRACT

New product introduction frequently requires new processing technologies, and the development of new processing technologies also allows for the introduction of new products. An assessment of these new products and technologies must account for changes in the whole supply chain. This paper presents a two-stage stochastic mixed integer linear programming model that integrates the selection of new product designs and processing technologies in a supply chain context. Special attention is given to the demand uncertainties with regard to product specifications and volumes. The first stage of the model selects the processing technologies that determine the set of feasible product designs, leaving the detailed product designs and the production volumes as recourse actions to the second stage. We apply the developed approach to product designs and processing technologies in the dairy sector. Here, the substitution of milk powders through milk concentrates is currently being considered, which may lead to extensive energy savings in production. In an interdisciplinary effort, we first derive the design space encompassing the feasible dairy technologies and product designs for concentrates. Through numerical investigation we then show that flexible technologies are selected that can be used to produce different product designs. We also show that the selection of technologies is highly dependent on the uncertain demand characteristics of the new concentrate products.

1. Introduction

New products may require the introduction of new processing technologies. For example, in the automotive industry the rising demand for electric mobility has led to the development of not only new traction batteries but also of body parts made of light-weight composite materials. The new product designs require the introduction of new manufacturing technologies for the batteries and parts made from composite materials as well as innovative assembly processes. The required investments are massive, but the adoption of the new products is highly uncertain. It depends inter alia on a range of product design specifications such as the speed and the driving range of the electric vehicles.

Similarly, progress in processing technologies can drive product innovations. For instance, new packaging technologies have enabled innovative packaging designs for food products. Reduced packaging thickness decreases raw material costs and environmental impacts. In the food sector, investments in novel packaging technologies are subject to large uncertainties, because consumers strongly react to changes in packaging. Ease-of-handling, visual and haptic appeal, environmental friendliness, and numerous other product design specifications must be considered. Overall, decisions on product designs and processing technologies are highly interdependent. Managers selecting the processing technologies must consider which product design specifications can be manufactured by the processing technologies.

Product designs and processing technologies also need to be embedded in suitable supply chain structures. The supply chain structure will vary, for example, due to different requirements for transportation or storage, production in new locations, or different sourcing. For instance, the usage of composites in the automotive industry requires new supply chains and results in different requirements for transportation. Furthermore, new suppliers become part of the supply chain. Similarly, new packaging technologies and product designs in the food industry result in changes to the whole supply chain. For example, packaging thickness reductions decrease weights in distribution and possibly also in reverse

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logistics.

Managing the nexus between new product designs, technologies, and supply chains is the key challenge in today's economies with decreasing product and processing technology life cycles. It is further complicated by the above mentioned demand uncertainties. Long before demand characteristics are known, decisions on significant investments must be made by top-level management. Particularly, the adoption of new products is hard to predict. Besides total demand volume, especially the exact product specifications demanded by the customers are often uncertain.

There is substantial literature on integrating processing technology selection with supply chain decisions. This previous work assumes decisions on product design to be given. However, product designs and processing technologies are highly interdependent and must be systematically represented with holistic approaches. An interdisciplinary approach involving product designers, process engineers, and supply chain experts is required to address the nexus. Each of these disciplines needs to contribute to the development of the design space, which encompasses information on the potential product specifications as well as the associated processing technologies and supply chains.

Advances in fractionation technologies are examples of processing technology developments that offer opportunities for the introduction of new products. With the help of these new technologies, raw material can be separated more efficiently into different fractions of its constituents. One industry that strongly profits from these technological developments is the food sector. Milk, for instance, can be concentrated to different levels of dry-matter content. Different technologies may be employed and combined for concentration and heat treatment (for shelf live extension), leading to different product designs. Depending on the customer application, the concentrates can potentially substitute the traditionally used powders. A substantial reduction in energy consumption during processing results. However, this advantage may be offset by the necessity to ship larger volumes (which depends on the degree of concentration) and the necessity to cool certain types of concentrates (which depends on the previous heat treatment). Hence, the extent at which the new concentrates will substitute the powders and the most suitable product specifications for the concentrates are uncertain. The case therefore exemplifies the nexus between product designs, processing technologies, and supply chain, including the characteristic uncertainties.

The main contributions of the paper are (i) the development of a novel modeling approach that integrates the selection of new product designs into the decision making on processing technologies in a supply chain context; (ii) the comprehensive inclusion of product-specification and volume uncertainties related to new product introduction; (iii) the derivation of the design space for a case from the food industry based on extensive interdisciplinary collaboration; (iv) numerical results demonstrating the suitability of our approach and showing that under uncertainties typical for new product introduction, technologies are selected that have the flexibility to produce different products; and (v) the demonstration that technology selection in the case is highly dependent on the uncertain demand characteristics of the products, showing that managers should strive to obtain information on customer demand characteristics, especially on shelf life.

The remainder of this paper is organized as follows. In Section 2, the main related literature is outlined. Section 3 presents the proposed modeling approach. Initially, the design space is derived, in which the interdependence between products and processing technologies is mapped for the product specifications. Then, a two-stage stochastic mixed integer linear programming (MILP) model is presented. In the first stage, the processing technologies that determine the set of feasible product designs are selected. In the second stage, the product designs and their share in production volumes are considered, as well as the decisions on the supply chain operations. Section 4 describes the industry case on new energy efficient dairy processes and products. In Section 5, numerical analyses for an industry case at a German dairy company are carried out. Finally, Section 6 concludes the paper and presents future research opportunities.

2. Related literature

In the following, we first give a brief overview of deterministic and stochastic approaches that deal with selection of technologies (or process design) together with supply chain decisions. These approaches are summarized in Table 1. Because our approach is applied to a case from the food industry, we secondly review some interdisciplinary approaches in which quantitative operations management methods are integrated with food-specific characteristics.

Five of the publications in Table 1 are based on deterministic approaches. Corsano and Montagna (2011) develop an approach for the simultaneous design of plants and supply chain for the batch process industry. Decisions on process design, such as allocation of storage tanks and determination of unit sizes, and planning decisions for the supply chain are integrated in a mixed integer linear programming (MILP) model. Similarly, Corsano et al. (2011) formulate a mixed integer nonlinear programming (MINLP) model in which the sustainable design of plant and supply chain is simultaneously achieved for a bioethanol supply chain. You et al. (2012) present a multi-objective mixed integer linear programming (Mo-MILP) model for the design of cellulosic ethanol supply chains. Decisions are taken on network design, technology selection, production planning, and logistics management. In addition, the model is integrated with a life cycle assessment and input-output analyses. Hugo and Pistikopoulos (2005) also develop a Mo-MILP model for the selection of processing technologies for a chemical supply chain. In their model, the net present value of capital investments is maximized while minimizing environmental impact. The only study from the food industry is presented in Quaglia et al. (2012). They develop an MINLP model for the synthesis and design of processing networks for a case study from the vegetable oil industry, considering both business aspects (such as financial criteria and supply chain) and engineering aspects (such as processing conditions and design of processing technology).

None of the reviewed deterministic studies captures the nexus between new product designs, processing technology selection, and supply chain operations. Integrated decisions on processing technologies and supply chain are addressed in all studies, but assuming that the product is given.

Supply chain planning problems under uncertainty have been widely studied. Six stochastic approaches related to the model developed in our paper are summarized in Table 1. You and Grossmann (2008) develop a Mo-MINLP model for the design and planning of responsive supply chains under demand uncertainty. Uncertainty is addressed by using a probabilistic model in which uncertain parameters are treated as variables with known probability distribution. The model is applied to a polystyrene supply chain. In Guillén-Gosálbez and Grossmann (2009), a stochastic Mo-MINLP model is also developed. The model deals with the design of a sustainable chemical supply chain including technology selection, with uncertainty in the life cycle inventory. This study is extended in Guillén-Gosálbez and Grossmann (2010) for uncertainty in the parameters of the environmental damage model. Also, Ruiz-Femenia et al. (2013) extend the study by Guillén-Gosálbez and Grossmann (2009) by considering demand uncertainties. Gebreslassie et al. (2012) develop a two-stage stochastic model for hydrocarbon biorefinery supply chain under supply and demand uncertainties, accounting also for risk management. Different conversion technologies are analyzed together with supply network design. In Kostin et al. (2012), bioethanol supply chain design with capacity expansion of production and storage facilities under demand uncertainty is addressed.

Like for the deterministic approaches, none of the stochastic approaches captures the nexus between product designs, processing technologies, and supply chain. In all studies, technology selection in a supply chain context is analyzed assuming a given product. All of the reviewed stochastic approaches are from the chemical industry because of the strong link between processing technologies and supply chains in this industry.

The integrated selection of product designs and processing