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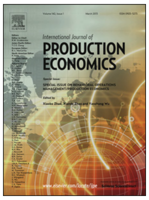

A Stackelberg game theoretic model for optimizing product family architecting with supply chain consideration ☆

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ABSTRACT

Planning of an optimal product family architecture (PFA) plays a critical role in defining an organization's product platforms for product variant configuration while leveraging commonality and variety. The focus of PFA planning has been traditionally limited to the product design stage, yet with limited consideration of the downstream supply chain-related issues. Decisions of supply chain configuration have a profound impact on not only the end cost of product family fulfillment, but also how to design the architecture of module configuration within a product family. It is imperative for product family architecting to be optimized in conjunction with supply chain configuration decisions. This paper formulates joint optimization of PFA planning and supply chain configuration as a Stackelberg game. A nonlinear, mixed integer bilevel programming model is developed to deal with the leader–follower game decisions between product family architecting and supply chain configuration. The PFA decision making is represented as an upper-level optimization problem for optimal selection of the base modules and compound modules. A lower-level optimization problem copes with supply chain decisions in accordance with the upper-level decisions of product variant configuration. Consistent with the bilevel optimization model, a nested genetic algorithm is developed to derive near optimal solutions for PFA and the corresponding supply chain network. A case study of joint PFA and supply chain decisions for power transformers is reported to demonstrate the feasibility and potential of the proposed Stackelberg game theoretic joint optimization of PFA and supply chain decisions.

1. Introduction

Product family architecting aims at optimal planning of an underlying architecture of an organization's product platform based on commonality and planned variability, such that various product variants can be derived through module configuration. The challenge of product family decision making resides with how to reuse product components and structures throughout the product family while differentiating product variety with decreased costs and time (Jiao and Tseng, 1999). From the perspective of product design and development, a product architecture defines how the functional elements of a product are arranged into its physical units and how these units interact with one another. A product family architecture (PFA), on the other hand, deals with configuration of modules according to a given product architecture by distinguishing what are the common modules and structural design to be shared among product variants, and by optimizing product differentiation while leveraging upon the performance of the entire family (Jiao and Tseng, 2000).

The focus of PFA has been traditionally limited to the product design stage, yet with limited consideration of the downstream supply chain-related issues (Jiao et al., 2007). The fulfillment of product families is enacted through assembly-to-order production, which nowadays more and more involves globally distributed operations and manufacturers (Jiao et al., 2009), leading to such supply chain concerns as facility locations and node selection in a manufacturing supply chain network (ElMaraghy and Mahmoudi, 2009). Supply chain decisions affect not only the end cost of product family designed, but also the decision models of module configuration within a PFA (Huang et al., 2005). For example, product family configuration must take into account the implications and consequence of different outsourcing policies of PFA modules in the supply chain (Lamothe et al., 2006). The corresponding supply chain decisions to a PFA constitute a supply chain architecture (SCA) that addresses how to configure a supply chain

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for the product families, involving such configuration decisions as the selection of supply options at each echelon of the supply chain and the placement of inventory at each supply chain echelon (Truong and Azadivar, 2005). Therefore, optimal PFA planning is coupled with supply chain configuration and in turn joint decision making is deemed to be imperative (Shahzad and Hadj-Hamou, 2013).

Existing decision models for joint optimization of product families and supply chain configuration are originated from a basic assumption that the PFA and SCA decisions can be integrated into one single optimization problem by aggregating two different types of objectives into a single-level objective function through certain coordinated protocol, e.g., a weighted sum (Fujita et al., 2013). However, such an “all-in-one” approach neglects the complex tradeoffs underlying two different decision making problems and fails to reveal the inherent coupling of PFA and SCA (Jiao and Tseng, 2013). In practice, PFA decisions are mostly made by a company's designers, whereas SCA decisions are often attributed to many other companies in the supply chain that play their individual roles as suppliers, manufacturers, assembly plants, or distribute centers (DCs). Different priorities of decision making between the PFA and the SCA lead to many conflicting goals and constraints that must arrive at equilibrium solutions among diverse decision makers. Such joint optimization of product families and supply chain issues necessitates a non-cooperative game, which entails a leader–follower decision structure between the PFA and the SCA.

To handle the inherent interactions and hierarchical characteristics of joint decision making between two self-interested roles of PFA and SCA, we propose a Stackelberg game theoretic optimization model for coordinated product family architecting and supply chain configuration. Moreover, the existing literature on product family design mainly focuses on optimization of module configuration based on a given PFA, in which the modular architecture is already established, and thus contains a fixed number of decision variables. To the contrary, PFA planning is about how to design such a PFA by determining an optimal modular architecture. Due to the fact that the modular architecture is unknown before PFA planning concludes, PFA planning must deal with an uncertain number of decision variables.

The paper proceeds as follows. The state-of-the-art research is reviewed in Section 2. Section 3 defines the problem context of supply chain issues in PFA planning. The optimization problems of PFA planning and supply chain configuration are elaborated in Sections 4 and 5, respectively. Section 6 presents a bilevel optimization model that coincides with the game theoretic decision making process between a leader and a follower. The leader problem represents PFA planning for optimal combinations of product variants and the common modular structure. The follower problem deals with SCA decisions by observing the results of PFA planning and meanwhile possesses the autonomy in determining appropriate facility locations and operational variables for the suppliers, manufacturers, assembly plants and DCs. Consistent with the bilevel optimization model, a nested genetic algorithm is developed in Section 7 to derive near optimal solutions of PFA and SCA. Section 8 reports a case study of joint PFA and supply chain decisions for power transformer products, along with performance analysis of the proposed Stackelberg game theoretic joint optimization model.

2. Related work

2.1. Product family architecting

Any product family exhibits a certain form of an architecture that impacts on product performance, product upgrades, product variety, component standardization, manufacturability, and product change (Ulrich, 1995). Jiao and Tseng (2000) review the fundamental issues of PFA planning, including modularity and commonality, functional and technical variety, and multiple views of a PFA. Based on function analysis, Stone et al. (2004) propose a module assembly heuristic for product architecture conceptualization. Rodriguez and Ashaab (2005) develop a knowledge driven collaborative product development system to facilitate knowledge supply in product architecting. Zhu et al. (2010) apply rough sets and neural networks to predict performance of new product family configuration.

Towards the goal of optimal product variant configuration with limited resources, PFA planning calls for extensive applications of optimization techniques. For a balance of versatility and performance among product variants, D'Souza and Simpson (2003) use formal experiment design to identify important factors of product family design and develop a multi-objective genetic algorithm for product variant performance optimization. Fujita (2002) proposes a hybrid method that uses genetic algorithm, mixed integer programming and constrained nonlinear programming. Jiao and Zhang (2005) propose a 0–1 mathematical programming model for portfolio planning of a PFA that emphasizes customer–engineering interaction. Huang et al. (2005) propose to integrate product platform, process and supply chain decisions to minimize total supply costs and improve supply chain efficiency. Li and Huang (2009) consider PFA planning as a multi-objective optimization problem, considering product performance, product family penalty function, and degree of commonality in the objective function, leading to a multilayer evaluation method for product family analyses at different levels, i.e. product, module, component, and parameter. Cao et al. (2011) consider the life cycle costs in the optimization process, through mathematical programming models to reduce performance loss within the product range. Fujita et al. (2013) propose a mathematical model for simultaneous design of product families and the global supply chain configuration, through selecting of manufacturing sites, product assembly and distribution.

2.2. Product family and supply chain coordination

Lee et al. (2009) point out that companies need to integrate the supply chain and share the product information. Cheng (2011) shows that customization drives manufacturers using modular design model for managing their supply chain. Verdouw et al. (2010) observe that changes in product structures can influence the dynamics of supply chains, such as outsourcing and transferring production of more components to suppliers and combination of first-tier suppliers into mega suppliers. Doran (2003) also shows consequences of coupled product architecting and supply chain decisions, including reorganization of value creation activities where some former first-tier-suppliers become value-added second-tier supplier, suppliers becoming more powerful with an increased bargaining power because of the larger role as a full service supplier, and formation of more strategic alliances or partnerships between the OEMs and their suppliers.

More consensuses on focusing on product development and supply chain relationships at the product architecting stage have been reported in recent years. Pero et al. (2010) report case studies indicating that the performance of supply chain depends upon the matching between product development and supply chain