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A scenario-based stochastic programming approach for the product configuration problem under uncertainties and carbon emission regulations

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ABSTRACT

To handle the product configuration problem with uncertain supply and demand, stochastic programming approach is applied to formulate the problem as a stochastic mixed-integer programming model. Carbon emission is further integrated into the deployed stochastic model under four different carbon emission regulations. Benders decomposition algorithm is utilized to solve the stochastic model. Computational studies show that the Benders decomposition method can solve large-scale stochastic programming problems with faster convergence rate than commercial solver CPLEX does. The results from the numerical experimental analysis demonstrate the impacts of carbon emission regulations on product configuration decisions.

1. Introduction

Confronted with the demand for product diversification and quick responsiveness to customer requirements, modern manufacturing industries are under great pressure to satisfy these requirements and achieve cost reduction simultaneously. To deal with these challenges, more and more manufacturers are transforming from mass production to mass customization (MC) (Yang et al., 2015). With the paradigm of MC, products are designed in modular form and composed of flexible common components and variant components (Mpampa et al., 2010; Simpson, 2004). Product configuration (PC), as one of the key enabling technologies for MC, is defined to select a set of components from the components catalog and connect these components into a valid product such that all the configuration rules and customer individualized requirements are satisfied (Yang et al., 2012; Feng et al., 2009). For obtaining feasible configurations, a number of studies on the solving technology such as CSP (constraint satisfaction problem) (Mittal and Frayman, 1989; Tseng, 1993), rule-based reasoning (Mcdermott, 1982) and CBR (case-based reasoning) (Lee and Lee, 2006; Tseng et al., 2005) have been conducted in product configuration domain. Further, some researchers pay attention to product configuration problem within the context of supply chains (Huang et al., 2007; Khalaf et al., 2011). However, almost all of the studies only dedicate to the deterministic product configuration problem where configuration parameters like component supplies are fixed and predetermined. Few studies consider the impact of uncertainties in supply chains on product configuration decisions. Nevertheless, in reality, customer demands for end-item products are hard to predict and it exhibits uncertainty and randomness. In addition, the capacities of component suppliers also suffer from fluctuation, which is caused by the uncertain factors in the supply chain, such as infrastructure breakdowns, unexpected equipment maintenances, complicated production processes (He and Zhao, 2012). The existing deterministic configuration models are unable to handle the uncertainties well because the optimal configuration solution may

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become invalid when the uncertainties are addressed. Therefore, it is of great importance to incorporate the uncertainty in supply and demand into the product configuration problem.

Furthermore, few researches pay attention to effects of greenhouse gases (GHG) emissions on product configuration decisions. GHG emissions are the main cause for warm surface of the earth and the climate changes (Benjaafar et al., 2012). Governments worldwide are actively taking measures to reduce these GHG emissions, (UNFCCC, 1997; E.TS, 2009). Hence, motivated by the concern of environmental issues and its resulting costs, we further consider the impact of carbon emissions on product configuration decisions.

Our contribution is twofold. Firstly, we incorporate the uncertainties in component supply and product demands into product configuration problem. The uncertainties are modeled using discrete scenario-based stochastic programing where every possible random situation of the problem data is represented by a scenario with the associated probability (Birge and Louveaux, 1997; Soleimani et al., 2016; Klibi and Martel, 2012). Secondly, we consider the effect of carbon emissions on product configuration decisions, especially carbon regulatory policies, such as carbon cap, carbon tax, cap-and-trade, and carbon offset mechanism. Further, owing to decomposable structure of the model and a numerous number of constraints in the model, Benders decomposition algorithm is employed to solve the configuration optimization model. The presented algorithm is compared with the commercial solver CPLEX through a case of ship engine and power generator system (SEPGS) configuration problem. The experimental result indicates that the suggested algorithm can substantially improve the efficiency of obtaining optimal configuration. The analysis of the effect of carbon emissions on product configuration decisions provides comprehensive managerial insights considering the trade-off between total configuration costs and emissions under different regulatory mechanisms.

This paper is organized as follows. Related literatures are reviewed in Section 2. Section 3 focuses on the problem description and the formulation of product configuration models under uncertainty using stochastic programming. In Section 4, the mathematical models are extended with carbon emission related to transportation activity of components. Section 5 addresses BD algorithm for solving the stochastic models. Computational experiments are presented and managerial insights are discussed in Section 6. Section 7 concludes the work and suggests some future research directions.

2. Literature review

2.1. Mass customization (MC) and product configuration (PC)

Mass customization (MC) was firstly put forward by Davis in the early 1990s (Davis, 1987). Owing to its obvious advantage in both high production efficiency and a variety of product variants, MC has become an effective production means to deal with the challenge of increasingly individualized requirements (Niblock, 1993). Within the context of MC, products are designed as a set of common and variant modules or components (Jiao et al., 1998, 2007). Product configuration (PC), as one of the key enabling technology for MC (Salvador and Forza, 2004; Forza and Salvador, 2002), aims to select components and constitute a customized products with configuration rules and customized requirements simultaneously satisfied (Mittal and Frayman, 1989). The first successful commercial application of product configuration is XCON configuration system (Barker et al., 1989). Since then, configuration technology is widely used in various industries to configure a variety of products, such as in the telecommunication industry, computer industry, and automotive industry (Fleischanderi et al., 1998; Fohn et al., 1995; Wang, 2013). As a consequence, a numerous number of researches have been conducted in solving technology for product configuration. The main solving technologies include constraint satisfaction problem (CSP) (Jiao et al., 2007; Fleischanderi et al., 1998), case-based reasoning (CBR) (Tseng et al., 2005; Xuanyuan et al., 2011; Dan et al., 2011; Ahn et al., 2003), rule-based reasoning, and Unified Modeling Language (UML) (Felfernig et al., 2001). For example, IBM-corporation used constraint satisfaction problem to build its configuration system Saturn to check the orders correctness and configure personal computers according to the customer requirements (Fohn et al., 1995). Chao and Chen (2001) employed ruled-based reasoning to establish the product's assembly rules and then integrate the rules into a configuration model. Felfernig et al. (2001) adopted a knowledge-based approach by utilizing the unified modeling language to configure customized products. However, almost all those studies focused on the configuration problems which occur within a single enterprise, where the components to be configured have been purchased in advance and kept in the enterprise's warehouse. The related supply-chain issues are ignored in the studies.

2.2. Joint research on product configuration and supply chains

Nowadays, an increasing number of enterprises are involved in global supply chains, and purchase necessary components from the suppliers in the chains instead of internal production due to cost advantage and other factors. The global purchase has prompted a number of researchers to integrate the supply chains into product configuration studies. The work conducted by (Yang et al., 2015) is one of the first studies that consider the product configuration problem and supply chains jointly by formulating the optimization model as a leader-follower Stackelberg game. Cao et al. (2012) utilized consumer choice theory to express the probability of the final product determination, and combine the product configuration problems with the supplier selection decisions. Jafarian and Bashir, 2014 introduced a new model that optimizes product configuration decisions and dynamic configuration of supply chains. Rezapour et al. (2015) studied the problem of concurrent design of a product family and its supply chain network. Other related papers (Khalaf et al., 2010, 2011; Gupta and Krishnan, 1999) proposed the simultaneous optimization of product modules and supply chains. Lamothe et al. (2006) proposed a mixed integer linear programming model for selecting a product family and design its supply chain. Yadav et al. (2008) employed a multi-objective approach to developing a product family and its supply chain. An Interactive Particle