Journal of Cleaner Production 184 (2018) 754–773

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Coordinated optimization of low-carbon product family and its manufacturing process design by a bilevel game-theoretic model☆

Wenxing Xiao [a], Gang Du [a], Yingying Zhang [b,*], Xiaojie Liu [c,d]

[a] College of Management and Economics, Tianjin University, Tianjin, 300072, China
[b] School of Economics and Management, Shijiazhuang Tiedao University, Shijiazhuang, 050043, China
[c] Center for Management Innovation and Evaluation, Tianjin University of Commerce, Tianjin, 300134, China
[d] School of Management, Tianjin University of Commerce, Tianjin, 300134, China

ARTICLE INFO

Article history:

Keywords:
Bilevel game-theoretic model
Coordinated optimization
Low-carbon product family
Manufacturing process configuration
Nested bilevel genetic algorithm

ABSTRACT

While increasing environmental issues arising from product development and manufacturing activities have attracted much attention from both academia and industry alike, few researches have addressed joint optimization of product family architecting (PFA) and its manufacturing process configuration (MPC) considering environmental concerns. Moreover, the hierarchical characteristics underlying these two optimization problems and complex interactions among PFA, MPC, and environmental concerns are failed to be revealed and addressed in the previous research. In this paper, a bilevel game-theoretic model for coordinating low-carbon PFA (L-CPFA) and low-carbon MPC (L-CMPC) is proposed. The L-CPFA decision by a designer (game-leader) is represented as an upper-level optimization problem for optimal configuration of module instances and architecture of compound modules and product variants from the perspectives of economic and environmental performances. The L-CMPC decision by a manufacturer (game-follower) is modeled as a lower-level optimization problem in order to determine the optimal low-carbon realization process planning of each primitive module, each compound module, and the assembly and transportation mode of each product variant according to the upper-level decision. A nonlinear, 0–1 integer bilevel programming model is developed, and then solved by a nested bilevel genetic algorithm (NBGA). A case study of a microwave oven product family is presented to demonstrate the feasibility and potential of the proposed model and algorithm. The results indicate that the carbon emissions have apparently impact on the optimal PFA and MPC decisions, and integrating low-carbon awareness into product family development activities is beneficial and advisable for enterprises to increase customer-perceived utilities and competitive advantages. Our proposed model can handle well the conflict and coordination between L-CPFA and L-CMPC, and balance well enterprise's benefits with environmental impacts triggered by development activities.

1. Introduction

Global warming has already become one of the most intractable problems facing humanity. The fourth assessment report of Intergovernmental Panel on Climate Change (IPCC) said that carbon emissions from human activities mainly give rise to global warming (Change, 2007). Product development activities are considered to be one of the primary sources of carbon emissions (Wang et al., 2016b). The product development phase influences not only more than 80% of the economic cost of a product, but also 80% of the social and environmental impacts of a product (Mascle and Zhao, 2008; Charter et al., 2017). Additionally, the International Energy Agency (IEA) indicated that 36% of carbon emissions stem from product manufacturing processes (IEA, 2007). Devanathan et al. (2010) presented that it is necessary for designers and manufacturers to make a shift from concerning on performance and cost to striving for a balanced performance among environment, economy and society. Therefore, both academia and industry increasingly focus on researches about reducing carbon emissions from product development and manufacturing activities (Baud-Lavigne et al., 2014).

☆ This research is sponsored by National Natural Science Foundation of China under Project Number 71371132.

* Corresponding author.
E-mail address: zhangy0909@tju.edu.cn (Y. Zhang).

https://doi.org/10.1016/j.jclepro.2018.02.240

Abbreviations

AIO	All-in-one
BOM	Bill of Material
CA	Conjoint Analysis
DPS	Decision Propagation Structure
GBOP	Generic Bill-of-product
GSCS	Generic Supply Chain Structure
GA	Genetic Algorithm
GHG	Greenhouse Gas
IPCC	Intergovernmental Panel on Climate Change
IEA	International Energy Agency
KKT	Karush-Kuhn-Tucker
LFJO	Leader-follower Joint Optimization
L-CMPC	Low-carbon MPC
L-CPFA	Low-carbon PFA
LLC	Lower-level Chromosome
MPC	Manufacturing Process Configuration
MNL	Multinomial Logit
NBGA	Nested Bilevel Genetic Algorithm
NG-LFJO	Non-green Leader-follower Joint Optimization
PFA	Product Family Architecting
QRF	Quality Requirements of a software Family
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution
ULC	Upper-level Chromosome
VSM	Value Stream Mapping

While the measurable environmental influence causing by product development and manufacturing activities has been recognized, considerable researches on low-carbon product development and manufacturing process configuration (MPC) problems are conducted separately (Luh et al., 2010; Yue et al., 2013; Tseng et al., 2008; Jeswiet and Kara, 2008; Fang et al., 2011; Su et al., 2012; Ji et al., 2013; Chang et al., 2013). Fewer researchers recognized the inherent joint relationship between those two problems (Huang et al., 2016; Wang et al., 2016a). In fact, the product manufacturing process is closely coupled with product design especially in mass customization contexts such as platform-based product family design. On the one hand, with the emergence of globally distributed operations and assembly-to-order production models (Jiao et al., 2009), product family realization process decisions affect not only the cost of product family design, but also the decisions of module configuration with product family architecting (PFA) (Huang et al., 2007). On the other hand, PFA must consider the implications and consequence of different production strategies of certain modules (module instances and compound modules) in manufacturing process. In addition, since each product variant of a product family prefers to be designed and produced based on a product platform by various design and process plans, the decisions of platform design and process configuration not only affect the costs of a product family, but also influence the greenhouse gas (GHG) emissions of life cycle for all product variants in the product family (Wang et al., 2016b). For example, if process policies and product platforms (as a part of PFA) with high GHG emissions have been applied to product family development, some product variants with high GHG emissions will be designed and produced. Therefore, PFA and MPC with simultaneous considerations of costs and GHG emissions are tightly correlated to each other, and it is imperative to explore the inherent joint decision mechanism for solving this coordinated optimization problem (Koren and Shpitalni, 2010; Raz et al., 2013; Jiao et al., 2007c; Wu, 2012).

Existing researches related to coordinated design of PFA and MPC considering carbon emission concerns are very limited (Xu et al., 2015; Wang et al., 2016a, b; Huang et al., 2016). The weakness of these studies, on the one hand, is that the problem of PFA and its interaction with MPC and environmental concerns have not been studied. On the other hand, the hierarchical structure and conflicting goals underlying those two different decision-making problems are ignored, and the inherent coupling between them is failed to be revealed (Jiao and Tseng, 2013). In practice, many companies as designers prefer to work on the front-end design of products and then outsource back-end manufacturing activities to other manufacturing companies. PFA decisions are mostly made by a designer, while MPC decisions are often carried out by a manufacturer after receiving the product family design planning from the designer. Thus, many underlying conflicting goals and restrictions are attributed to different priorities of decision-makings between PFA and MPC, and those goals and restrictions must arrive at equilibrium solutions between the designer and the manufacturer, instead of global optima.

Toward this end, the coordinated optimization of the low-carbon product family architecting (L-CPFA) and low-carbon manufacturing process configuration (L-CMPC) is studied in this paper. In this research, L-CPFA is defined as incorporating low-carbon thinking into the planning of platform-based products. Similarly, L-CMPC refers to the decision-making on the product realizing processes with consideration of carbon emission impacts. The research emphasis of this paper lies in solving three key technical challenges as follows:

(1) *Integrating low-carbon considerations into PFA and MPC.* Compared with a single low-carbon product design problem, L-CPFA itself is a more complex cross-space design problem which involves multiple spaces from the customer space, to the product space, to the module space, and to the attribute space (Yang et al., 2015). Moreover, L-CMPC entails a cross-echelon configuration decision, including process allocation, assembly planning, and transportation assignment. Thus, it is challenging to incorporate the low-carbon consciousness into PFA and MPC in line with multiple dimensions.
(2) *Complex trade-offs and conflicting goals between L-CPFA and L-CMPC.* The joint PFA and MPC optimization problem involves multiple decision-makers and conflicting goals (Jiao and Tseng, 2013). For instance, PFA (determined by the designer) aims at maximizing the customer-perceived utility per cost (Jiao et al., 2007b; Zhang et al., 2007; Wang et al., 2016a), whereas MPC (determined by the manufacturer) is geared toward minimizing the total manufacturing cost (Yıldız, 2009; Song and Lee, 2010). In addition, the hierarchical relationships underlying these two different decision-making problems should be fully considered in the optimization process (Yang et al., 2015).
(3) *Handling the interactions among PFA, MPC, and environmental factors.* The previous researches failed to reveal the interaction between PFA and MPC, as well as the impacts of carbon emissions on the PFA planning at the early design phase (Xu et al., 2015; Wang et al., 2016a, b; Huang et al., 2016). However, owing to the implication of environmental factors on the utilities of the product family and the modes of its