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Optimal configuration of assembly supply chains based on Hybrid augmented Lagrangian coordination in an industrial cluster

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ABSTRACT

Industrial cluster is becoming an ever more important cost-effective industry development mode especially when enterprises are required to give more rapid responses to the frequently changed customized demands. The explosive number of homogeneous enterprises/suppliers with geographic proximity provides multiple options for each supply chain stage, which thus leads to higher potential to form a more satisfactorily performed assembly supply chain (assembly system) in industrial clusters. However, the increased candidate options also incur inevitably higher decision complexity to the decision model of configuring such cluster supply chains. The situation may be more challenging if the autonomous decision requirement of individual suppliers is accommodated. A general assembly cluster supply chain configuration (ACSCC) model is established which considers both horizontally and vertically collaborations in a cluster, meaning it accommodates the typical cluster relationships including subcontracting and outsourcing. In order to achieve the complexity reduction and autonomy protection, a newly emerged decomposition-based solution method named augmented Lagrangian coordination (ALC) will be adopted. Especially, two classical ALC formulation variants named the centralized coordination formulation and the distributed coordination formulation are innovatively integrated to form a hybrid ALC solution strategy, which deals with different assembly branches with different alliancing structures. Experimental results have proved the effectiveness of the proposed hybrid ALC method for the ACSCC problem. From the perspective of supply chain management, a set of sensitivity analysis for profit of each collaborative enterprise is conducted to obtain some important managerial insights.

1. Introduction

A supply chain is composed of a complex sequence of processing stages, ranging from the raw materials supplies, parts manufacturing, components and end-products assembling, to the delivery of finished products (Bilgen & Ozkarahan, 2004; Chen, 2010; Huang & Qu, 2008; Qu, Huang, Chen, & Chen, 2009; Qu, Huang, Cung, & Mangione, 2010). Along with the continuously decreasing of both machines costs and manufacturing entrance thresholds, a great deal of SMEs (both small-and-medium and even small-and-micro enterprises) have been rapidly emerging, especially in the three assembly-related supply chain levels including parts manufacturing, component subassembly and end-products assembling (Amini & Li, 2011; Graves & Willems, 2001, 2005; Hu, Zhu, Wang, & Koren, 2008; Huang, Zhang, & Liang, 2005). Stages in these levels undertake the assembly-related tasks of a product which are also executed in a comparatively concentrated operational series by enterprises with closer business relationships. Therefore, they are normally studied and managed as a whole system and collectively referred to as an assembly supply chain (Huang & Qu, 2008).

Further development of industrial and specialization division entails a healthy environment to be built for the rapidly emerged enterprises, and therefore many counties begin to promote *Industrial Cluster* (Doeringer & Terkla, 1995; Porter, 1998, 2000) as a new industry development mode. Enterprises of various sizes around a specialization division are clustered in the geographically proximate area of an industrial cluster. They collaborate with each other to gain both cost and time advantages through convenient and effective resource and service sharing on the one hand (Beaudry & Breshi, 2003; Pandit, Cook, & Peter Swann, 2002), and cultivate higher industrial prestige to achieve better regional

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competitiveness (Belso-Martinez, Molina-Morales, & Mas-Verdu, 2011; Liu, Li, Li, et al., 2011) and market opportunity on the other (Punj & Stewart, 1983). Industrial cluster is becoming a more and more important cost-effective industry development mode especially when enterprises are required to give more rapid and customized responses to the frequently changed market demands.

In many countries such as Germany, Italy, India, China, and the USA etc., the development of industrial clusters has played and still plays a very important role in fueling their productivity growth and honing their ability to compete effectively in the global area (DeWitt, Giunipero, & Melton, 2006; Huang & Xue, 2012). Currently, both the number of clusters and the number of enterprises/suppliers in the cluster are quickly increasing. The gradual maturation of the cluster-oriented operation and management mode has not only given birth to more and more single supply chains which competes while enjoying cooperation, mutual trusts and stable partnerships, but also cultivated a great deal of independent suppliers for capability and capacity supplement. The explosive number of such homogeneous supply chains and suppliers with geographic proximity provides manifold options for each supply chain stage, which thus leads to higher potential to form a more satisfactorily performed assembly supply chain (assembly system) in industrial clusters. However, the inevitably incurred higher decision complexity has hereby made supply chain configuration (SCC) a vital topic (Qu, Nie, Chen, et al., 2015). SCC is formally defined as the complex decision process aiming to optimize certain performance indicators of the supply chain through making decisions such as selecting suitable suppliers for each stage, assigning values to characteristics parameters of each stage and setting operation policies for governing the interrelationships among these stages (Graves & Willems, 2005; Huang & Qu, 2008). Following this definition, supply chains operating in the industrial cluster and their corresponding configuration process are therefore referred to as cluster supply chain (CSC) and cluster supply chain configuration (CSCC) respectively. Considering the ever-flourished product varieties and frequently changed customer demands on the one hand, and the abundant choices of the cluster resources on the other, a CSC is subject to the naturally existed short lifecycle. Therefore, to effectively and efficiently configure and reconfigure a CSC has become a key issue for the CSC operation.

Clustering effect mainly brings two kinds of opportunities for the configuration of assembly supply chains. First, multiple homogeneous single supply chains could collaborate for the same assembling order (Bikram, Bahinipati, & Deshmukh, 2009), enabling multiple alternative branches to be configured upstream an assembly stage. Second, both the suppliers pertaining to a single supply chain and the independent suppliers could collaborate for the same supply order (Camarinha-Matos, Afsarmanesh, Galeano, et al., 2009; Kawtummachai & Hop, 2005), enabling multiple suppliers to be configured in a networked way at a sourcing stage. A few literatures have conducted preliminarily research on these two effects, yet they are subject to the following two major limitations. (1) Most of them separately investigate the first effect in the form of inter-manufacturer order subcontracting among multiple single supply chains (Li, Xiong, Park, et al., 2012) or the second effect in the form of two-echelon sourcing among multiple clustered suppliers (Xiang, Song, & Ye, 2014). Yet very few of them consider the integral effect of combining both the horizontal cluster collaboration and the vertical cluster collaboration simultaneously in an integrated model. (2) Most works investigate the CSCC with limited scopes, e.g. only two single supply chains (Li et al., 2012), two echelons (Xiang et al., 2014), and one stage in each echelon (Casanueva, Castro, & Galán, 2013). Those considering the complete CSCC process of a general assembly supply chain with systematic and feasible optimal solution framework are rare.

This paper will discuss the optimal problem of assembly cluster supply chain configuration (ACSCC) in an industrial cluster. For the solution approach, we found that most literatures assume the supreme decision right of the alliance leader for the CSCC and apply AIO (All-in-one) optimization models (Li et al., 2012; Xiang et al., 2014). However, it is difficult to establish a centralized optimization model for a CSCC problem with those normally adopted AIO methods such as DP (dynamic programming) (Graves & Willems, 2005) or GA (genetic algorithm) (Afrouzy, Nasseri, & Mahdavi, 2016; Li et al., 2012). This is not only because the AIO optimization model is subject to frequent changes if the CSC structure and the number of single supply chains cannot be fixed, but also because the short-term collaborative relationship prevents the suppliers from sharing the details of their decision models. The authors have endeavored to explore the feasibility and effectiveness of applying MDO (multidisciplinary design optimization) methods which enables distributed solution to address the above challenges, and obtained satisfactory results (Huang & Qu, 2008; Qu et al., 2009; Qu et al., 2010). In literature (Qu et al., 2015), supply chains was firstly considered in a cluster and a single-period CSCC problem which considered a single component order subcontracting among single supply chains and multiple sourcing from independent suppliers was solved by a newly emerged MDO method named ALC (augmented Lagrange coordination) (Tosserams, Etman, & Rooda, 2008).

ALC is a decomposition-based MDO method with strict convergence proof and supports collaborative optimization (Tosserams, Etman, & Rooda, 2007, 2010; Tosserams et al., 2008). ALC put forward by Tosserams is used to deal with the optimal design problem of large complex system (Allison & Papalambros, 2010). The basic principle of ALC is to partition the system into a decentralized decision structure composed of a set of independent decision elements based on certain partition rules, e.g. decision autonomy, and then coordinate the elements' local decision process by ALC to obtain the global optimal solution. ALC has two coordination variants, i.e. centralized and distributed coordination. As compared to other MDO methods, it has offers higher flexibility to the system's coordination, for example, supporting open collaboration structures, highly privacy protections, distributed self-making decisions and multi-dimension couplings, allowing for both horizontal and vertical interaction among decision elements. What's more, it is verified that ALC was successfully applied for CSCC problem with complex and dynamic collaboration relationships among cluster enterprises (Qu et al., 2015).

Actually, the assembly supply chain configuration (ASCC) problem is very common in practice especially when enterprises satisfy the individuating demands of customers and keep pace with the dynamical market environment. However, the traditional assembly supply chain has characteristics of the geographical location dispersion of enterprise facilities, the product composed of a wide variety of components, the assembly processing with diversity technology, which leads to coordinate enterprises difficultly, and could result in the disruption of the entire supply chain because of lack of some component. While the assembly supply chain in an industrial cluster has characteristics of geographical proximity and mutual cooperation, etc., which coordinate enterprises easily and conveniently, and enhance their competitiveness. Therefore, there is very important significance to study the operation of assembly supply chains, especially, the ASCC of the brand product composed of core components and non-core components in the industrial cluster. But, at present, except that a single-period CSCC problem, which considered a single component order subcontracting among single supply chains and multiple sourcing from independent suppliers, was studied using ALC (Qu et al., 2015), there is little research on the optimal configuration problem of the typical product assembly cluster supply chain in the industrial cluster.