Computers & Industrial Engineering 84 (2015) 43–55

Contents lists available at ScienceDirect

Computers & Industrial Engineering

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

Optimal configuration of cluster supply chains with augmented Lagrange coordination

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ARTICLE INFO

Article history:
Received 4 September 2014
Received in revised form 29 November 2014
Accepted 22 December 2014
Available online 3 January 2015

Keywords:
Cluster supply chain
Supply chain configuration
Supplier selection
Multidisciplinary design optimization
Augmented Lagrangian coordination

ABSTRACT

Enterprises in an industrial cluster could dynamically alliance in the form of cluster supply chains to share inner-cluster resources and services, and respond to the ever-fluctuating customer demands in a cost-effective way. However, an effective and feasible method enabling such dynamic cluster supply chain configuration (CSCC) lags behind practice due to the conflict of interests. Researchers are designing All-in-One theoretic models to optimize CSCC with the assumed decision details of all enterprises, while in fact clustered enterprises are seeking effective decentralized decision mechanisms which protect their decision autonomy in the frequently re-configured CSC. A newly emerged multi-disciplinary optimization method, Augmented Lagrangian Coordination (ALC), which supports the open-structure collaboration with strict optimization convergence, is thoroughly investigated in this paper and applied to solve the conflict. Through a complete analysis of CSC's configuration policies in typical stages, a generic CSCC model is proposed and then partitioned into an ALC-based decentralized decision model by the typical decision autonomy distribution in clusters. Clustered enterprises collaborate vertically and laterally along the ALC model through multi-dimensional couplings to achieve the overall consistency and optimality. Results have proved the effectiveness of ALC for CSCC problem. A set of sensitivity analysis is also conducted to find out the condition in which an order has to be fulfilled in a CSC and the most appropriate configuration.

1. Introduction

Industrial cluster is a group of all-sized enterprises of a specialization division located in a certain area. They collaborate to gain both cost and time advantages through convenient and effective resource and service sharing, and cultivate higher industrial prestige to achieve better regional competitiveness and market opportunity (Beaudry & Breshi, 2003; Pandilt, Cook, & Peter Swann, 2002). Cluster-based production is normally initiated by a leading enterprise which owns an independent product brand, and is operated in the form of cluster supply chain (CSC) which comprises several coupled single supply chains and a set of independent suppliers (Li, Xiong, & Park, 2012). Literature concerning with industrial clusters normally refers to the CSC as an alliance and the leading enterprise as alliance leader (Huang, Qu, Zhang, & Yang, 2012; Li, Huang, Fang, & Qu, 2013), and this terms will be followed in this paper. Large and urgent orders will adopt outsourcing approaches in the CSC, either horizontally subcontracting the order to other single supply chains or vertically sourcing components from independent suppliers or in a combined way, to guarantee the service time and quality requirement of the order with cluster advantages (Kawtummachai & Hop, 2005). Industrial cluster is becoming an important cost-effective industry development mode for enterprises to respond to the frequently changed market demand and thus being promoted by more and more countries.

Cluster supply chain is essentially an order-based production alliance system, which is subject to the naturally existed short lifecycle, especially in the trend of ever-flourished product varieties and frequently changed customer demands. Therefore, to effectively and efficiently configure and reconfigure a CSC has become a key stage for the CSC operation. Supply chain configuration (SCC) is a 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 (Huang & Qu, 2008). Following this definition, cluster supply chain

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http://dx.doi.org/10.1016/j.cie.2014.12.026
0360-8352/

configuration (CSCC) is responsible for selecting suitable single supply chains and independent suppliers to collaborate a given customer order in an appropriate way so that certain cluster production measures could be optimized. Due to the higher configuration frequency brought by the shorter supply chain lifecycle and the multiplied number of supply chain participants, the CSCC decision process becomes largely complicated.

Since MIT researchers proposed the SCC problem (Graves & Willems, 2001), abundant works have been conducted in this area, including the SCC modeling toward different product structures (Huang, Zhang, & Liang, 2005), sourcing policies (Amini & Li, 2011; Li & Amini, 2012), supplier constraints (Li & Womer, 2008), etc. Various All-in-One (AIO) optimization methods are also proposed for SCC solution, including DP (*Dynamic Programming*) (Graves & Willems, 2005), GA (*Genetic Algorithm*) (Huang et al., 2005), etc. During the increase of supply chain scale which contains dynamically changed supplier base, maintaining the decision autonomy of suppliers while enhancing the overall SCC optimization efficiency have become a major concern of SCC (Fan, Stallaert, & Whinston, 2003; Lee & Whang, 1999). Therefore, decentralized SCC with MDO (*Multidisciplinary Optimization*) application has attracted the interests from researchers (Walsh & Wellman, 2003). The authors of this paper have attempted to use ATC (analytical target cascading) to solve the configuration problem of assembly supply chains and obtained satisfactory results (Huang & Qu, 2008; Qu, Huang, Chen, & Chen, 2009; Qu, Huang, Cung, & Mangione, 2010).

The current research outputs concerning with CSCC are scarce, with limited research width and depth. Most of researchers mainly focus on investigating coordination of inventory and lateral transshipments (Lorenzo & Stefano, 2011; Yang & Qin, 2007). A few researchers use simplified models to deal with the configuration, which discuss either horizontal subcontracting to sibling supply chains (Bikram, Bahinipati, & Deshmukh, 2009; Xiang, Faishuai, & Feifan, 2014) or vertical sourcing from independent suppliers (Camarinha-Matos, Afsarmanesh, & Galeano, 2009). A few CSCC works consider both yet only take a two-stage approach (Li et al., 2012), i.e. deal with the two-way collaborations in different stages, and restrict the number of configurable cross-chains. Such simplifications largely hinder the obtaining of the global optimal CSCC in the cluster. While for the optimization methods, most literatures assume the supreme decision right of the alliance leader for the CSCC and apply AIO optimization models. In fact, these two limitations of CSCC models and solution methods are twined together, i.e. it is difficult to establish the optimization models for AIO methods such as DP and GA if the CSC structure and the number of single supply chains cannot be fixed. So far, we have not found any literature talking about MDO approach applied for CSCC. This situation prevents the application of research output from solving practical problems, especially with the ever-demanding CSCC requirements of supporting larger scale, shorter lifecycle, and higher-level privacy protection. Without an effective and adaptable MDO method supporting decentralized and collaborative CSCC decision making, the integration of the actual decisions and operations of cluster enterprises in a practical CSCC system is difficult.

ALC (*Augmented Lagrange Coordination*) is a newly emerged decomposition-based MDO method with strict convergence proof and supports collaborative optimization (Tosserams, Etman, & Rooda, 2008, 2010). ALC is put forward by Tosserams (2008) and 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 (Zhang, Huang, Sun, & Yang, 2014; Zhang, Zhang, et al., 2014), and then to coordinate the elements' local decision process by ALC to obtain the global optimal solution. As compared to other MDO methods, ALC offers higher flexibility to the system's coordination. First, ALC supports open collaboration structure allowing for both horizontal and vertical interaction among decision elements. Second, ALC supports not only quasi-separable coupling (Tosserams, Etman, & Rooda, 2007) among elements, but also coupling function including objective coupling function and coupling constraint function. Such flexible features make ALC applicable for CSCC problem with complex and dynamic collaboration relationships among cluster enterprises.

In order to maintain simplicity without losing generality, this research designates the supply chain of a given product with one key/bottleneck component as a research problem. As the supply chain sourcing process of different components is usually independent for an enterprise, this research is extensible to the model considering multiple components. In case of the coming of a large order with urgent service time, the order owner wishes to configure a CSC to collaborate with other homogeneous manufacturers (single supply chains) and independent suppliers to solve the capacity limitation problem. The major research questions of this paper are as follows. First, the mechanism of cluster supply chain formation will be investigated, including the general policies of order subcontracting and component sourcing in the case of limited production capacity. Second, a general modeling and solution strategy of a decentralized ALC process will be established for CSCC in specific and for all supply chain related problems in general. Third, the optimization effectiveness and efficiency of ALC and other optimization methods will be compared to provide a useful reference for researchers. Fourth, the condition that an enterprise should resort to cluster supply chain instead of normal supply chain will be investigated, and the corresponding CSCC is compared.

The remainder of this paper is structured as follows. Section 2 will investigate the formation mechanism of cluster supply chain and analyze the current solution challenges. Section 3 presents the ALC principles with a reference problem modeling procedure, which is then applied to the CSCC modelling in Section 4. The detailed ALC solution procedure is given in Section 5, and results are analyzed with sensitivity analysis. Finally, the paper concludes in Section 6, where managerial implications and future research directions are outlined.

2. Problem description

2.1. Supply chains clustering modes

There are three types of enterprises normally existed in an industrial cluster, namely product manufacturers (M), manufacturers' private suppliers which have long-term stable relationships (S), and other independent suppliers dispersed in the cluster (O), as shown by the three grey dotted blocks in Fig. 1(a). Literature has reported various collaboration modes among these enterprises, mainly falling into the two categorizes of horizontal order-subcontracting among sibling supply chains and vertical component sourcing among independent suppliers. The former means, a manufacturer – normally a brand owner – will take orders from market and split and subcontract a portion of the order to other manufacturers, i.e. sibling supply chains (also referred to as single supply chains in literature) (Li et al., 2012). Some highly specialized industrial clusters also have a special kind of so-called brand operators who dedicate to the marketing and a fixed group of OEM (*Original Equipment Manufacturers*) for order fulfilling, i.e. subcontract all the orders. The latter means, after a manufacturer takes an order, it could source components from both its private suppliers and multiple independent suppliers in the consideration of cost optimization, safe supply, price control and workload control, etc.