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Efficient assignment algorithms to minimize operation cost for supply chain networks in agile manufacturing

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ABSTRACT

While the production process evolves toward modularization and decentralization, the design of supply chain networks, in particular considering the agile manufacturing scenario, becomes challenging due to the following reasons: (1) supply chains that produce a network of components become large-scale; (2) the number of possible assignments is growing exponentially as the increasing choices of plants for components. In this paper, the assignment problem considers the strategic and tactical decisions together, which involves the mapping of components to geographically distributed plants, the selection of logistics services between the mapped plants, and the allocation of inventories in each plant. The goal of this paper is to find the optimal assignment with the minimum total cost under the constraint of production rate. We first mathematically formulate the problem as a mixed integer linear program. Then, by deriving the properties of pipelined production in supply chain networks, we develop dynamic programming algorithms to efficiently obtain the optimal assignments. By the consideration of high degree of pipelining, our techniques can make a good tradeoff between high production rate and low operation cost. Extensive computational experiments show that the proposed algorithms can find high quality solutions, which achieve significant improvement compared with the initiative approaches.

1. Introduction

As the development of industry engineering, such as ‘‘Industry 4.0” in German, ‘‘Industrial Internet” in North America and ‘‘Made in Chain 2025”, the production and manufacturing process evolves toward modularity, customization, flexibility, decentralization and real-time capability. Companies in the changing competitive environment face a lot of challenges; in particular, it is hard to individually produce one component which typically involves a network of productions to produce sub-components. In the meanwhile, companies have to consider the improvement of production efficiency and the reduction of total operational cost. The agile manufacturing was proposed as a novel manufacturing paradigm to respond to these challenges. It employs the concept of virtual organizations (Goldman, 1995) that share competencies, resources and costs. Virtual organizations make it possible to respond to the changing market, but require an efficient way to construct the supply chain network when the market opportunity emerges.

In the design of supply chain networks, it commonly includes two planning stages: strategic and tactical (Cortinhal, Lopes, & Melo, 2015; El-Sayed, Afia, & El-Kharbotly, 2010; Pan & Nagi, 2013). The strategic planning involves the decisions of plants and logistics service. While the tactical planning involves the decisions of production, inventory and the consideration of operation cost. In the agile manufacturing scenario, strategic and tactical planning should be considered together, due to the ‘‘short-lived” durations of virtual organization. For example, new technologies, new markets, and even new competitors are appearing and disappearing within short periods of time in today‘s changing environment (Chinnaiah & Kamarthi, 2000). Therefore, it requires optimal algorithms to efficiently construct supply chain networks, in which the strategic and tactical decisions are simultaneously considered.

As to the strategic planning, this paper introduces Component Flow Graph (CFG), a directed acyclic graph, to describe the dependencies of components to produce a product. The CFG reflects the flow of components in the whole supply chain network, based on which decision makers can comprehensively address the ‘‘assignment” problem to obtain the global optimal solution. In this paper, we consider two realistic decision functions in the assignment problem. First, the same component in CFG can be produced by many choices of plants in different locations with different production costs. Hence, we need to decide which plant a component should be mapped to. Second, between geographically distributed plants, various logistics services have different costs and delays.

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Hence, we need to select a logistics service to ship produced components between two plants.

As to the tactical planning, the tradeoff between high production rate and low operation cost need to be addressed. In particular, we need to accelerate the production rate of the end product to meet the customer demand; in the meanwhile, the total operation cost should be minimized. In this paper, we employs pipelines in supply chain to keep plants as busy as possible, and further to make the production and transportation proceeded in parallel. The critical factor of realizing the pipelined production-transportation network is to add storage (or called inventory); however, this incurs unexpected cost.

In the design of supply chain networks, an important problem arises: how to find the optimal assignment that satisfies the customer demand and meanwhile has the minimum total operation cost, including purchasing cost, production cost, logistics cost and storage cost. To solve the optimal assignment problem, this paper presents a mixed integer linear programming (MILP) formulation; however, with the increasing size of problems, MILP approach cannot generate feasible solutions in reasonable time (e.g., it cannot obtain a solution within 24 h, even when only 20 sub-components need to be mapped to 10 optional plants and 2 optional logistics services can be selected). In reality, the design of supply chain are much more complicated. For instance, the automotive supply chain may contain over 50 plants to produce more than 100 components of automobiles (Alford, Sackett, & Nelder, 2000; Brettel, Friederichsen, Keller, & Rosenberg, 2014). Therefore, MILP is not practical to solve such problems, and we need a technique to obtain the optimal solution efficiently.

In order to develop a more efficient technique that can better explore the tradeoffs between high production rate and low total operation cost, we study the properties of supply chain networks, such as how to efficiently calculate its production rate and how to add the minimum number of storages to maximize its production rate. Based on the presented properties, we find that the global optimal solution of the assignment problem is composed of the optimal solutions of subproblems. In consequence, we develop efficient dynamic programming algorithms to compute the optimal solution in a bottom-up fashion, which can generate the optimal results in polynomial time. Note that the properties of supply chain networks and algorithms presented in this paper can apply to agile manufacturing paradigm as well as the traditional manufacturing paradigms.

The main contributions of this paper are listed as follows.

- We formally define and study the optimal assignment problem in the design of supply chain networks in agile manufacturing scenarios, which integrally consider the strategic and tactical planning to minimize the total operation cost under the constraint of production rate.
- We study the fundamental properties of supply chain networks and establish theorems to accurately measure its production rate.
- We develop efficient algorithms to obtain the optimal assignment in polynomial time.
- We conduct comprehensive computational experiments that show the efficiency and effectiveness of the proposed algorithms.

The rest of this paper is organized as follows. In Section 2, we review the related literature. In Section 3, we introduce the system model and define the optimal assignment problem. In Section 4, we show motivational examples. MILP formulation is given in Section 5. Then, we present the fundamental properties of supply chain networks in Section 6. Dynamic programming algorithms are proposed in Section 7. In Section 8, we show the computational results and Section 9 concludes this paper.

2. Literature review

Existing research efforts (Altiparmak, Gen, Lin, & Paksoy, 2006; Masoud & Mason, 2016; Sadjady & Davoudpour, 2012; Silva, Sousa, Runkler, & da Costa, 2009; Srivathsan & Kamath, 2012; Yu, Normasari, & Luong, 2015) on the cost optimization commonly focus on echelon-based or stage-based supply chain network. Masoud and Mason (2016) defined the cost optimization problem in two-stage supply chain networks. Sadjady and Davoudpour (2012) designed a two-echelon supply chain network and aim to minimize the total cost of network and production cost. Yu et al. (2015) developed an integrated model to minimize the production cost and distribution cost in a four-echelon network. However, the optimization approaches targeting on the small scale system can hardly be applied to the large-scale supply chain networks considered in this paper.

In the fiercely competitive environment, a company cannot independently produce complicated products. The company gradually integrates individual production capacity in cooperation that forms a complicated supply chain network (Alford et al., 2000; Beran, Fiedler, & Zezulka, 2010; Brettel et al., 2014; Che, Che, & Hsu, 2009; Garcia & You, 2015; Goldman, 1995; Pan & Nagi, 2013; Wang, Yu, & Xue, 2007; Wang, 2008; Yan, Chen, Huang, & Mi, 2008). Wang (2008), Wang et al. (2007), and Yan et al. (2008) demonstrated the importance of plant selection in the design of supply chain networks. Garcia and You (2015) depicted a globalized supply chain in which facilities are connected by varieties of transportation and delivery methods. The above research efforts emphasize the importance of mapping component to plants, selecting logistics services as well as allocating storage space.

Sequentially optimizing operation cost by mapping components to plants, selecting logistics servers and allocating storages, however, cannot obtain the optimal assignment. Integrated assignment (Javid & Azad, 2010; Jung, Chen, & Jeong, 2005; Kim, Yun, Park, Park, & Fan, 2008; Pan & Nagi, 2013; Russell, Chiang, & Zepeda, 2008; Sarmiento & Nagi, 1999) that integrally optimizes different functions simultaneously is able to obtain the optimal solution. Kim et al. (2008) presented an integrated model of the supply network and production planning. In the presented model, distribution costs can be reduced by relocating distribution centers. Javid and Azad (2010) presented a model to simultaneously optimize location, capacity, inventory, etc. in a supply chain network. In this work, authors proposed heuristics to obtain a near-optimal solution. Pan and Nagi (2013) integrated the formation of supply chain networks, involving production, inventory, and transportation. The Lagrangian relaxation was developed to obtain a near-optimal solution. All above research efforts addressed the importance of integral optimization in the design of supply chain networks.

In order to obtain the global optimal solution, the mathematic programming models, such as Mixed-Integer Linear Programming (MILP), are widely used, Jung et al. (2005), Kim et al. (2008), Pan and Nagi (2013), Sadjady and Davoudpour (2012), Relvas, Matos, Barbosa-Povoa, Fialho, and Pinheiro (2006), and Yu et al. (2015). In particular, Pan and Nagi (2013) considered the production cost, logistics cost and storage cost in their MILP formulation. The selection of logistics services was not considered in their model. Even we can add service selection constraints in the MILP model, it takes a huge time to generate the results. Therefore, it requires efficient algorithms to find optimal solutions for the large-scale problems.

The simulation-based optimizations have also been employed in many existing research efforts. Hishamuddin, Sarker, and Essam (2015) described a simulation approach for the three-