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Ying Mei
1Department of Mechanical and Manufacturing Engineering, University of Calgary, Calgary,T2N 1N4, Canada

Zhigang Zeng
Department of Mechanical and Manufacturing Engineering, University of Calgary, Calgary,T2N 1N4, Canada

Yiliu Tu
Department of Mechanical and Manufacturing Engineering, University of Calgary, Calgary, Canada, paultu@ucalgary.ca

Study and Prospects: Adaptive Planning and Control of Supply Chain in One-of-a-kind Production

Ying Mei[1],*Zhigang Zeng*[1],*Yiliu (Paul) Tu*[1*]
[1]Department of Mechanical and Manufacturing Engineering, University of Calgary, Calgary,T2N 1N4, Canada

Abstract: Based on the research project titled "AdaptivePlanningandControlofSupplyChaininOne-of-a-kind Production", the research group performed a systematicreview ofsupply chain integration, riskprediction and control and traceability. Studies of a computer-aided and integrated production system for cost-effective OKP systemare included. Our efforts relevant to integration of supply chain in OKP, modeling &control of ripple effects in OKP supply chain and the traceability of the OKP supply chain are introduced in this paper.

Keywords: Supply chain integration, One-of-a-Kind Production, Systematic review

1. INTRODUCTION

Manufacturing is Canada's largest business sector, accounting for 17% of Canada's economic activity and providing employment for 2.1 million people [1]. However, manufacturing in Canada has been on a downward trend since 2002 [1]. Most of Canadian manufacturing companies are small- and medium-sized enterprises (SMEs) which produce customized products often in one batch size, i.e. one-of-a-kind production (OKP). One-of-a-kind production (OKP) has the advantages of high customization, short lead times and high flexibility in addressing customer requirements. The main drawbacks of OKP are high costs and low efficiency. A novel and efficient production system theory and technology is needed to improve the production efficiency and reduce costs. Wortmann et al. [2] described OKP methodology as a manufacturing paradigm that produces customized products within a product domain at nearly mass production efficiency.

To achieve a cost-effective OKP system, our research has mainly focused on the development of a computer-aided and integrated production system, which is able to produce highly customized products at near the efficiency of mass production. This research program approaches the problem by optimizing the entire integrated supply chain from the point of view of a customer order driving the integrated supply chain business model. This requires the review and redevelopment of conventional production planning and control theory. Therefore, we expect to make a significant contribution to the theory of production planning and control in general and to OKP methodology in particular.

A common finding in the literature has been that great benefits can be achieved if an integrated supply chain can be planned and controlled. Holl and Potts [7] demonstrated that integration and cooperation between suppliers and manufacturers could reduce costs by 20-100%. Therefore, the outcomes from this research will impact the economy in developed countries by helping the manufacturing companies in these countries, particularly SMEs, enhance the integration between enterprises in the supply chain and reduce their production costs, thereby improving their overall competitiveness.

2. LITERATURE REVIEW

In general, supply chain management (SCM) has become one of the most popular topics in manufacturing

*Corresponding author.Email: paultu@ucalgary.ca

research, and the literature on this topic is very extensive [3, 4]. Thomas and Griffin [3] did a review of SCM literature and indicated that over 11% of the gross national product of the U.S. is devoted to non-military logistics, and that the expenditure for logistics for many products accounts for over 30% of the cost of the product. Burgess et al. [4] in their literature review point out that the SCM is a relatively "new" multidisciplinary research area. Within traditional SCM research, the literature most relevant to our research is related to integrated production and distribution models, supply chain disruptions, and traceability.

Sarmiento and Nagi[5] and Chen [6] provided literature reviews on integrated production and distribution models and discussed research problems in supply chain scheduling on the integration of echelons (two adjacent tiers) in a supply chain, e.g. manufacturer and its suppliers, distributors or third party logistics (3PLs) [6, 7]. Supply chain integration is widely understood as the need for production schedule synchronization among the echelons in a supply chain; hence it becomes an extended production planning, scheduling and control problem. However, the literature on supply chain integration is only between two adjacent tier echelons, i.e. only a partially integrated supply chain.

In the integration of suppliers and manufacturer scheduling, Lee et al. [8] proved that minimizing makespan (total shop floor time for completing a batch of jobs) in an assembly system with two suppliers and one manufacturer is intractable. They provided an enumerative algorithm and analyzed special cases and heuristics. A number of models improving upon Lee et al.'s [8] work can be found in the literature [7, 9, 10]. A relatively recent study on the integration and scheduling of raw material or parts supply and production focused on the modeling and optimization of the cooperation between suppliers and manufacturers [11].

For the integration of production and distribution, Potts [12] proposed an economically inefficient model to integrate a production schedule with the distribution plan. Potts' model was limited to the production schedule, as the delivery vehicles were considered as unlimited, and each job was delivered by a separate shipment to its customer immediately after it was processed. Lee and Chen [13] studied machine scheduling problems with explicit transportation considerations. They offered models that were considered for two types of transportation situations. When transportation capacity and transportation times are explicitly taken into account in the models, they showed that many problems are computationally difficult. Hall et al. [14] developed a model to integrate the production schedule with a delivery plan that had fixed delivery dates. Li et al. [15] suggested a model that considered the delivery vehicle routing decision. However, both Hall and Li did not consider transportation cost as an objective. Chen and Vairaktarakis[16] developed a more general integrated scheduling model of production and distribution operations. Both customer service level and total distribution cost were optimized. They claimed that all the existing models on the integration of production and distribution in a supply chain were either special cases of their model or structures that could not be generally applied in practice. Chen [6] offered a comprehensive review of the models for this integration. However, the integration for echelons on three adjacent tiers, i.e. suppliers – manufacturer – 3PLs, is widely considered as extremely difficult [6, 16].

To integrate echelons on three adjacent tiers, we researched two approaches: adaptive production scheduling and dynamic pricing. In adaptive production scheduling, we have developed two fast production scheduling heuristics, i.e. APT-LVR (average processing time with lever) [46]and SS (state space) [45] heuristics by which we can quickly adjust (or schedule and re-schedule) the production and distribution to cope with the changes of supply. However, the drawback of adaptive production scheduling is that some schedule adjustments are not practical due to the operational constraints, e.g. the time to set-up a production line. The other approach is through dynamic pricing models [43], which will be further discussed in Section 4.

Since the attacks on the World Trade Centers in 2001, supply chain vulnerability has attracted a lot of attention. The risks to supply chains include disruptions, delays, information and networking, forecasting, intellectual property, procurement, customers, inventory, and capacity [17]. And the paper [17] suggested that managers must not only create a shared, organizationwide understanding of supply-chain risk but also determine how to adapt general risk-mitigation approaches to the circumstances of their particular company through stress testing and tailoring. Kleindorfer and Saad[18] grouped the supply chain risks into two categories: risks from coordinating supply and demand, and risks resulting from disruptions to normal activities. The paper is concerned with the second category of risks and provided a conceptual framework that reflects the joint activities of risk assessment and risk mitigation that are fundamental to disruption risk management in supply chains. The first category of supply chain risk can be mitigated through supply chain integration. Therefore, our research will be focused on the second category of supply chain risks, i.e. supply chain disruptions. The paper [19] investigates the effect of a transportation disruption on supply chain performance using system dynamics simulation, comparing a traditional supply chain and a vendor managed inventory system (VMI) when a transportation disruption occurs between 2 echelons in a 5-echelon supply chain. Wilson [19] defined a supply chain disruption as an event that interrupts the material flow in the supply chain, resulting in an abrupt cessation of the movement of goods.

There are not many papers that directly address the second category of risks [19]. Studies that are indirectly relevant to this area include inventory and capacity planning [20, 55, 58], demand uncertainty and forecast accuracy [21, 50], information distortion [22, 23, 24], purchasing and procurement strategies [25], and price variation [26]. However, these research papers do not clearly answer questions on prediction and control of the effects of supply chain disruptions, which can "quickly cripple the entire supply chain" [27], but only provide the techniques and methods to mitigate the risks, such as information sharing, electronic data interchange, collaborative planning forecasting and replenishment, lead-time reductions, consistent low prices, and vendor-managed inventory. It has been found that these techniques and methods have a limited effect for prediction and control of the disruptions [19], which can cause ripple effects in the supply chain. Ripple effects are very costly [27] and a case study showed that an unexpected fire in a Philips chip manufacture plant in Mexico caused Ericsson (US) to lose $400 million with their market share falling from 12% to 9% [28]. The OKP supply chain is particularly vulnerable to this type of risk, e.g. a late delivery from a customized windows and doors manufacturer can cause a house builder to completely lose control of their production, resulting in reduced market share.

The ISO 9001:2000 standard defines supply chain traceability as the ability to trace the history, application or location of an entity by means of recorded identifications throughout the entire supply chain [29]. With this definition, supply chain traceability actually means both tracing and tracking. Tracing means the history of a lot (i.e. a component, product or batch) and the activities (manufacturing processes) upstream of a supply chain, whereas tracking means the applications and locations of a lot and activities downstream in the chain. Research on the traceability of supply chains is mainly found in the food and agriculture sectors, due to the safety and legal requirements in these industries [29, 30]. Due to complicated data exchange and lack of alignment of the different systems in various segments of a supply chain, research has focused on the applications of various data modeling techniques (e.g. extensible Markup Language or ebXML) for establishing an efficient and standard electronic data exchange framework [30], automatic data recording and exchange technologies (e.g. barcodes and radio frequency identification for developing traceability systems [31]), and the integrated environment for supporting supply chain traceability [32, 33]. However, this research is not directly applicable to OKP supply chain traceability. First, current data modeling tools are insufficient for modeling the customized product design and production in an OKP system [60]; therefore, we have proposed an integrated product production structure (PPS) and constraint tree (CT) data modeling tools [51, 60]. Second, due to high customization, OKP needs alternative suppliers to fulfill specific customer orders. This implies that a traceability data model should include alternative tracing and tracking paths associated with alternative product designs, manufacturing process plans and operation schedules, which has not been properly addressed by current traceability research. Third, the alternative tracking/tracing paths form different supply chains for meeting a specific customer order, and the economical evaluation of these supply chains is needed in OKP supply chain traceability research. For solving these problems, we have developed models and heuristics for computer-aided supplier selection in OKP [42, 49, 53]. Zhang and Huang [34] also reviewed and proposed models and methods on product family planning considering suppler selection and supply chain configuration. For economical evaluation of supply chains, Zhang [35] introduced the concept of supply chain economy, reviewed and developed different models for economical and competitive supply chain evaluations. However, none of these papers have meaningfully addressed the OKP supply chain traceability problems.

3. OUR RESEARCH PROGRESS

There have been many studies, including those by our research group, on developing OKP methodology through improvement of production efficiency and reduction of costs for SMEs：these have been reviewed in references[36, 51, 60]. Over the last six years, ourresearch activities mainly focused on computer-integrated OKP. We have developed a dynamic pricing algorithm called price menu for OKP supply chain integration[43]: we model a dynamic pricing strategy (DPS) in the setting that an OKP firm offers two types of orders (due-date guaranteed and due-date unguaranteed) at different prices to the sequentially arriving customers, who are also OKP production firms and then compared our DPS with a constant pricing strategy (CPS). In paper [45, 46, 47, 48, 54], adaptive OKP scheduling and control models and heuristicshave been presented: our state space (SS) heuristic, integrated with a closed-loop feedback control structure, demonstrates significant potential to improve production efficiency because of its simplicity and computational efficiency.We have proposed computer-aided supplier evaluation and selection heuristics and algorithms[42, 49, 53], an information system framework for mass producing OKP products in a local window and door manufacturing company[51, 60], generic algorithms and heuristics for planning capacitated production with outsourcing in OKP[55, 58, 59], computer-aided cost estimates for rapid OKP product development[61], computer-aided and Internet-based customer interface in OKP[56, 63], generic modeling and optimal design of OKP products[42, 52, 57, 62, 64], state space modeling and simulation of OKP systems[44].

The following problems have been identified in our past research: 1) lack of an efficient technology to integrate an entire OKP supply chain; and 2) the great uncertainties (i.e. uncertain delivery dates and disruptions) and traceability in an OKP supply chain can dramatically impact the integration of the OKP supply chain and hence the production efficiency, quality and customer satisfaction. Furthermore, the current research on supply chain risk management and traceability does not address the special requirements in OKP, such as supplier selection for different product designs and manufacturing processes, supply uncertainty versus lead-time and after-sale customer service, and economic evaluation of different supply chains in fulfilling a specific customer order. These problems have limited the development of OKP methodology to further improve OKP efficiency and customer satisfaction and reduce costs.

4. RESEARCH PROSPECTS

4.1. Research Goal, Objectives and Deliverables

The long-term goal of this research is to help manufacturing companies, particularly SMEs, improve their production efficiency and customer satisfaction and reduce their costs and lead-time by advancing OKP planning and control theory and training HQP. The short-term objectives of this research are: (1OKP supply chain integration; (2) risk prediction and management of the OKP supply chain; and (3) models and methods for OKP supply chain traceability.

In line with the goal and objectives, the deliverables from theresearch will be novel concepts, definitions, models, algorithms, heuristics and system frameworks, which are further specified in Section 4, for the integration, risk prediction and control, and traceability of the OKP supply chain. An additional outcome will be the training of HQP in the multidisciplinary area of manufacturing systems, engineering optimization, computer simulation and modeling, and management science.

4.2. Research Plan and Methodology

4.2.1 Objective 1: Integration of Supply Chain in OKP

A supply chain can be generally considered as a network that consists of branch trees with a basic topology of echelons on three adjacent tiers, i.e. suppliers – manufacturer – 3PLs (3PLs can be inserted between suppliers and manufacturer), called a basic branch tree (BBT).The supply chain begins with the original raw material production companies and ends with customers. With this definition, an OKP supply chain can be viewed as a virtual manufacturing/distribution consortium that consists of companies under different ownerships. If a customer order is placed with this consortium, it is fulfilled by a branch tree with alternative echelons from this network or supply chain. This branch tree may be composed of one or more BBTs, where a customer order drives the integrated supply chain business model, an idea not found in the literature. With this concept, the integration of the OKP supply chain can be defined as a collaborative production schedule among all echelons in a branch tree to meet a customer order with global economical optimization (maximum profit or minimum cost) of the branch tree.

It is extremely difficult to integrate a supply chain that consists of more than one BBT with the existing mathematic models and heuristics for supply chain scheduling. To solve this problem, we will modify our dynamic pricing method (price menu), which can be understood as a cost function of the production lead-time, i.e. $F(L_j)$, where L_j is the lead-time of customer order j. $F(L_j)$ is, in fact, an algorithm for the calculation of minimum prices for various lead-time options considering the production schedule and constraints of a manufacturing company or a 3PL. There are various models for $F(L_j)$ in the literature on dynamic pricing has reported, but these models cannot be used in this research since they have a limited number of discrete lead-times e.g. one week, two weeks or four weeks [37]. We need an $F(L_j)$ that is nearly a continuous function of lead-time, at least at an hourly basis. Using the price menu, a supply chain production planning and scheduling problem becomes a problem for searching a global economical optimization among lead-time options and relevant inventory costs of all the echelons in the supply chain. This supply chain integration method requires an answer to the following question: Does this method give a long-term (e.g. a half year or longer) economic optimization for an echelon?

Our research group will work on this price menu technology by modifying our current price models [43] to further take the different pricing policies in OKP companies and 3PLs into consideration, as well as develop efficient computation methods to solve the non-linear price menu model. Meanwhile, we will develop a simulation model using MATLAB and Arena (production simulation package) to simulate a supply chain under three scenarios – just-in-time deliveries, flexible-time (or no lead-time requirement but expecting the cheapest order), and rush orders – assuming every echelon in the chain employs the price menu technology.With this simulation model and empirical studies in local OKP companies and their supply chains, we can investigate the above question which will lead to an effective technology and strategies for integrating an entire OKP supply chain. Gienow Windows and Doors Ltd. and Startec, which are two OKP companies in Calgary, have agreed to provide their supply chain data for us to carry out the research.

4.2.2 Objective 2: Modeling and Control of Ripple Effects in OKP Supply Chain

Wilson [19] employed a computer simulation package, Inthink®, to simulate the ripple effects resulting from disruptions or delays in a supply chain with five echelons. A computer simulation package, like Inthink®, provides an easy means to build a simulation model for predicting ripple effects. However, the simulation models based on the simulation packages are not sufficient for analyzing the predictability and controllability of the ripple effects. Furthermore, these approaches also lack a systematic evaluation and optimization of supply chain performance from a risk or reliability point of view. In our previous research, we employed SS (state space) technology to model an OKP system [38, 44]. By applying observability and controllability concepts in control theory, the stochastic variables in an OKP system can be systematically predicted and controlled.

For our research, we will first extend the current SS model to cover a whole OKP supply chain. We will then model supply chain disruptions caused by stockouts (supply < demand) and delays (i.e. variations in lead-time), with a disruption considered as a special stockout case with a very large or infinitive lead-time. Consequently, an OKP supply chain becomes a multi-state k-out-of-n system [39] that can be evaluated and optimized by existing reliability models [40]. Our research group will work on the SS modeling and simulation to develop the concepts and methods for observability and controllability of ripple effects in the OKP supply chain. To evaluate and optimize the performance of an integrated OKP supply chain, we propose two approaches: (1) application of a novel process control technology [41]which has been developed in our current research to monitor the OKP supply chain; and (2) application of multi-state k-out-of-n reliability optimization models [40] to evaluate and optimize the OKP supply chain performance.

4.2.3 Objective 3: The Traceability of the OKP Supply Chain

To address the problems of traceability research in an integrated OKP supply chain, two approaches are proposed. First an integrated data structure for OKP supply chain traceability will be developed by applying PPS (product production structure) and CT (constraint tree) [51, 60]. This data structure can record all the possible alternative suppliers/3PLs (or echelons)since the OKP supply chain as defined in Section 4.2.1 is a network consisting of possible branch trees for fulfilling a customer order. We will use the OKP Management and Control Software (OKPMCS) system© system, which has a PPS graphical interface, to develop this data structure and test it in local OKP companies (Gienow and Startec) and their supply chains. Consequently, the tracking and tracing methods will be developed in terms of this data structure.

Second, due to high customization and great uncertainties in OKP, scheduling and control must be carried out in an adaptive manner [45]. High customization requires a large number of alternative echelons in an OKP supply chain [42, 49, 53], which results in numerous combinations of branch trees to fulfill a customer order. This provides a challenge for OKP supply chain traceability, i.e. supplier selection and supply chain evaluation with consideration of economical optimization (Objective 1) and reliability optimization (Objective 2) requires methods and models for supplier selection and supply chain evaluation as parts of the traceability system. Without these methods and models, a traceability system has to trace (for production planning phase) and track (for both production planning and control phases) all possible data in the branch trees for fulfilling a customer order, which may be too large to be manageable. We have developed a computer-aided supplier selection model in terms of data envelopment analysis (DEA), fuzzy set theory and analytical hierarchy process (AHP) [53]. By addressing the trade-off between the two optimizations into our current model, we can further develop methods and models for supplier selection and supply chain evaluation in an OKP supply chain traceability system.

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