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Robust dynamic schedule coordination control in the supply chain

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ABSTRACT

Coordination plays crucial role in supply chain management. In this paper, we extend the existing body of literature on supply chain coordination by representing a robust schedule coordination approach. A hybrid discrete/continuous flow shop supply chain with job shop processes at each supplier stage is studied. For this purpose, the developed scheduling model comprises operations control (for customer order fulfillment dynamics), channel control (production machine and transportation dynamics), resource control (material supply dynamics), and flow control (processing and shipment dynamics) with multiple objectives. Based on the scheduling model, we introduce a robust analysis of schedule coordination in the presence of disruptions in capacities and supply. The application of attainable sets opens a possibility to analyse schedule coordination dynamics under disruptions. The results provide insights of how to integrate the coordination issues into schedule robustness analysis. We exemplify the developed approach for the case of two-stage supply chain coordination, and derive managerial insights for both considered scheduling problem and application of dynamic control methods to supply chain coordination in general.

1. Introduction

Coordinated decision-making distinguish supply chain (SC) scheduling problem as a specific research topic. The studies on SC scheduling by Hall and Potts (2003), Agnetis, Hall, and Pacciarelli (2006), Chen (2010) and Choi, Yeung, and Cheng (2013) developed major frameworks, classifications and solution techniques in this research domain. Details of mathematical models across the publications on SC scheduling differ, but most share a basic set of attributes: a finite sets of jobs, customers, and suppliers, fixed time span over which a schedule should be generated, and multi-stage schedule coordination.

In recent years, disruptions in SC capacities occurred in greater frequency and intensity. These events rippled quickly through global SCs and caused significant losses in revenues (Ivanov, Sokolov, & Dolgui, 2014). In this setting, the issues of the SC robustness become more and more important. When handing these issues, new challenges for SC scheduling exist that concern uncertainty and disruptions along with coordination activities (Sawik, 2013). Most recently, Sawik (2015) points out that although the impacts of schedule coordination on SC performance may be substantial, the research on coordinated scheduling optimization is fairly recent and there is still a research gap in regard to the magnitude of these impacts.

In this study, we focus on robust coordinated SC scheduling for the production systems with continuous material flows. SC in continuous production systems comprise multi-stage network of suppliers. Continuous flow scheduling problems have their place in many industries such as gas, oil, chemicals, glass and fluids production as well as production of granular goods and steel details (Bożek & Wysocki, 2015; Ivanov, Sokolov, Dolgui, Werner, & Ivanova, 2015; Puigjaner & Lainez, 2008; Shah, 2004; Subramanian, Rawlings, Maravelias, Flores-Cerrillo, & Megan, 2013). Since the SC process typically has a multi-stage structure, the issue of capacity and supply disruptions is crucial for the overall SC schedule performance. The disruptions in processing and transportation capacities may result in increase in flow times, makespan, tardiness, and decrease in throughput, on-time delivery, and SC service level. In this setting, the dynamic schedule representation and schedule robustness analysis become important issues. Moreover, the coordination needs to be included in the scheduling and robustness analysis.

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List of abbreviations

AS	attainable set	OPC	optimal program control
CT	control theory	SC	supply chain

The main points of this study can be stated as follows:

- We consider a hybrid discrete/continuous flow shop SC with job shop processes at each supplier stage and study it with the help of dynamic optimal control models.
- We develop operations, channel, resource and flow control models with multiple objectives.
- Based on the developed scheduling model, we introduce a robust analysis of schedule coordination in the presence of disruptions in capacities and supply with the help of attainable sets (AS).
- We exemplify the developed approach for the case of two-stage SC coordination, and derive managerial insights for both considered scheduling problem and application of dynamic control methods to SC coordination in general.

To the best of our knowledge, there is no published research on robust coordinated SC scheduling for the production systems with *both* continuous flows and disruptions *and* schedule coordination considerations. The objectives of this study are twofold:

- to extend the existing body of knowledge on SC scheduling by representing the robust schedule coordination in a hybrid continuous flow shop SC with job shop processes at each supplier in the dynamic optimal control model and
- to develop a method for synthesis and analysis of dynamic robust coordination schedule control policies in the SC with the help of AS and in regard to multi-criteria problem statements.

2. State-of-the-art

In SCs, after the processing at the production plants (i.e., the suppliers), finished products can be delivered to the next production stage in the SC or to the customers. In terms of scheduling theory, we have a flow shop process (Johnson, 1954). At the same time, at each stage in this *multistage* environment, alternative executors (e.g., production plants and transportation modes) exist which are unequal regarding different processing intensities. Once a job is assigned to a supplier, the processing of operations of this job can be done either in job- or flow-shop mode. Thus, the SC is a *hybrid flow shop* (Ribas, Leisten, & Framiñan, 2010). This requires both machine assignment and sequencing tasks.

In considering mathematical models on SC scheduling, Chen (2010) recommends considering such a problem as an integrated production and outbound distribution scheduling problem. A peculiarity of such a simultaneous consideration is that both machine structures and flow parameters may be uncertain and change in dynamics and are, therefore, non-stationary. In the context of SCs and taking into account standard scheduling methods, uncertainty in SC schedule parameters is accepted by research community as important and timely research topic (Agnetis et al., 2006; Hall & Potts, 2003).

The study by Hall and Potts (2003) considered benefits and challenges of *coordinated* decision-making within SC scheduling. Chen and Hall (2007) studied the conflicts and coordination in assembly systems where there are several suppliers providing components. Sarker and Diponegoro (2009) considered optimal production plans and shipment schedules in an SC with multiple suppliers, one manufacturer and multiple buyers subject to known demands of buyers. The overview by Chen (2010) identified that in integrated scheduling and logistics problems, it is necessary to define completion, departure, and delivery times for each job subject to time-based, cost-based or revenue-based indicators. Hall and Liu (2011) investigated the capacity allocation by a manufacturer subject to orders from distribution centers. Ullrich (2013) integrates production and outbound distribution scheduling in order to minimize total tardiness. Choi et al. (2013) study a SC scheduling and co-ordination problem where the manufacturer is a decision maker that selects the orders and aims to maximise its own profit.

The studies on schedule robustness aim at closing the gap between theory and practice regarding the uncertain nature of real environments for the schedule execution. A schedule that is able to achieve the planned performance in spite of disruptions is called *robust* (Sotskov, Lai, & Werner, 2013). Robustness analysis or robust optimization approaches for related problems in assembly line design and scheduling have been considered, for example, in the studies by (Dolgui & Kovalev, 2012a, 2012b; Gurevsky, Battaïa, & Dolgui, 2012; Gurevsky, Hazir, Battaïa, & Dolgui, 2013; Hazir & Dolgui, 2013; Hazir & Dolgui, 2015; Sotskov, Dolgui, & Portmann, 2006). The method developed in this paper is complementary to the robust discrete optimization.

Coordination issues with the help of control theory (CT) have been mostly considered in light of SC contracting (Gan, Sethi, & Yan, 2005; Yang, Choi, Xiao, & Cheng, 2011) or manufacturing system dynamics (Sagawa & Nagano, 2015). Kogan and Khmelnitsky (1995) developed an optimal control method for aggregate production planning in large-scale manufacturing systems with capacity expansion and deterioration and proved necessary optimality conditions for a generalized problem of production scheduling. Wang, Cheng, and Lin (2013) proposed a distributed scheduling algorithm called a closed-loop feedback simulation approach that includes adaptive control of the auction-based bidding sequence to prevent the first bid first serve rule and may dynamically allocate production resources to operations. Ivanov et al. (2015) apply optimal program control (OPC) to distributed SC scheduling in the context of smart factory Industry 4.0.

It can be observed in literature that dynamic aspects of schedule execution and coordination in the SC have been frequently neglected. Robustness in continuous time domain has not been explored in the scheduling settings so far although it has been extensively investigated in system dynamics and CT (Ivanov & Sokolov, 2013; Ivanov, Sokolov, & Dolgui, 2012; Mayne, Rawlings, Rao, & Scokaert, 2000). Recent applications of control theory CT and optimal program control (OPC) to SC coordination and scheduling have been multi-facet but did not