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Coordination of inbound and outbound transportation schedules with the production schedule

Utku Koç [a], Ayşegül Toptal [b,*], Ihsan Sabuncuoglu [c]

[a] Industrial Engineering Department, MEF University, İstanbul 34396, Turkey
[b] Industrial Engineering Department, Bilkent University, Ankara 06800, Turkey
[c] Rector Abdullah Gul University, Kayseri 38039, Turkey

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A B S T R A C T

This paper studies the coordination of production and shipment schedules for a single stage in the supply chain. The production scheduling problem at the facility is modeled as belonging to a single process. Jobs that are located at a distant origin are carried to this facility making use of a finite number of capacitated vehicles. These vehicles, which are initially stationed close to the origin, are also used for the return of the jobs upon completion of their processing. In the paper, a model is developed to find the schedules of the facility and the vehicles jointly, allowing for effective utilization of the vehicles both in the inbound and the outbound. The objective of the proposed model is to minimize the sum of transportation costs and inventory holding costs. Issues related to transportation such as travel times, vehicle capacities, and waiting limits are explicitly accounted for. Inventories of the unprocessed and processed jobs at the facility are penalized.

The paper contributes to the literature on supply chain scheduling under transportation considerations by modeling a practically motivated problem, proving that it is strongly NP-Hard, and developing an analytical and a numerical investigation for its solution. In particular, properties of the solution space are explored, lower bounds are developed on the optimal costs of the general and the special cases, and a computationally-efficient heuristic is proposed for solving large-size instances. The qualities of the heuristic and the lower bounds are demonstrated over an extensive numerical analysis.

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1. Introduction and related literature

Supply, production and delivery are among the key functions for manufacturing companies. Although these functions are managed independently in many traditional systems, recent studies in supply chain management show that there is significant opportunity for savings if the related decisions are coordinated (Dawande, Geismar, Hall, & Sriskandarajah, 2006; Hall & Potts, 2003; Thomas & Griffin, 1996). Coordination of decisions among the various stages and functions of the supply chain is an issue that prevails at different phases of planning. Examples include coordination of decisions in the following areas: innovation, pricing at the strategic level; inventory control, lot sizing at the tactical level; scheduling at the operational level. Our focus in this study is on coordination of scheduling decisions involving production as well as inbound and outbound transportation.

We consider a setting consisting of two close warehouses–one for unprocessed jobs and the other for processed jobs, and a production facility far away from the warehouses. Shipment schedules of incoming materials and outbound delivery schedules in any system are linked to the production schedule through the inventories of unprocessed and processed jobs, respectively. In the specific setting of interest, the inventory holding costs for both types of jobs at the production facility, transportation costs and times between the facility and the warehouses are significant. Therefore, planning for effective interaction of the schedules for the production facility and the vehicles, serves as an important tool for lowering total inventory holding and transportation costs.

Our study is motivated by the practice of a worldwide home appliance manufacturer in Turkey, which imports a significant amount of its raw materials and exports a major portion of its end products. The company uses maritime transportation for import and export. The manufacturing facility is located inland whereas the two warehouses–one for holding the imported raw materials and one for holding the end products to be exported, are located at the harbor. Transportation of materials between

* Corresponding author.
E-mail address: toptal@bilkent.edu.tr (A. Toptal).

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the manufacturing facility and the harbor is done via containers. Traditionally, the company arranges for transportation after the production schedule is made. This hierarchical decision making results in many containers being used only one way and traveling empty the other way. The company thinks that transportation costs can be reduced significantly if the inbound and outbound shipment schedules are coordinated so that the containers are utilized both ways. This kind of planning offers an opportunity but at the same time it turns out to be a challenge, because there is a limit on the time that a vehicle can be held at the facility, and the cost of holding the materials at the facility is high.

Motivated by the above practice, we study the problem of jointly finding the production schedule of the facility and the schedules of a finite number of capacitated vehicles subject to a waiting limit constraint at the facility. This waiting limit may originate in practice due to the length of the vehicle hire period. The objective is to minimize the total inventory holding and transportation costs for a certain number of unprocessed jobs to travel from an origin to a distant facility, get processed and return back to the origin. All vehicles are assumed to be identical, but jobs are allowed to occupy different amounts of space in the vehicles.

It is important to note that, the problem solved in this paper relates to a simplified version of the problem faced by the appliance manufacturer in question. As opposed to the real practice where multiple components form a final product, our model assumes that one inbound job is converted into one finished job after processing. This aspect of the proposed model makes it more applicable in a setting where jobs travel to and from a subcontractor for some of their operations to be performed. We refer to the subcontracting operations in the appliance manufacturer mentioned above and in the textile industry in U.S., as examples. The manufacturer in question outsources a portion of injection molding processes from subcontractors. Plastic fibers are sent to a subcontractor and the molded parts are then shipped back to the factory. As another example, some US textile manufacturers cut fabrics in the country and ship the cut fabrics to a low wage country, such as Mexico, for assembly. The assembled products are then returned back to US for finishing. Sen (2008) reports that, there are international agreements between US and Mexico on reducing the duty for outsourcing activities in the textile industry. In a setting where subcontracting is in place, our model may be of use if the objective is to minimize the sum of transportation costs and the inventory holding costs at the subcontractor.

Supply chain scheduling with transportation considerations has received significant attention over the past decade (e.g., Chang & Lee, 2004; Chen & Vairaktarakis, 2005; Li & Ou, 2005; Tang & Gong, 2008, 2009; Tang, Gong, Liu, & Li, 2014; Wang & Cheng, 2009). A common property of the studies in this area is that they model the factory as a single machine or parallel machines, and consider the scheduling of a group of jobs taking into account transportation times, capacities and/or costs in the inbound and/or the outbound. For the purpose of this paper, we classify the literature in terms of part of the supply chain where the transportation issues are modeled (i.e., inbound and/or outbound of the factory), and the objective function considered. As reviewed by the latest survey by Chen (2010), most papers focus on the delivery side (e.g., Agnetis, Aloulou, & Fu, 2014; Chang & Lee, 2004; Chen & Pundoor, 2006; Chen & Vairaktarakis, 2005; Gao, Qi, & Lei, 2015; Koc, Toptal, & Sabuncuoglu, 2013; Li, Vairaktarakis, & Lee, 2005; Toptal, Koc, & Sabuncuoglu, 2014; Wang & Cheng, 2006; Wang & Lee, 2005; Zhong, Dósa, & Tan, 2007). A few take into account inbound transportation (e.g., Tang & Gong, 2009; Tang et al., 2014), or both the inbound and the outbound transportation (e.g., Li & Ou, 2005; Tang & Gong, 2008; Wang & Cheng, 2009). Another feature that differentiates these studies from one another, is the objective function they consider. Many of the papers reviewed, optimize a scheduling related objective such as functions of makespan, completion time of jobs, or total tardiness (e.g., Chang & Lee, 2004; Gao et al., 2015; Li & Ou, 2005; Li et al., 2005; Tang & Gong, 2009; Tang et al., 2014; Wang & Cheng, 2006, 2009; Zhong et al., 2007) whereas others take account of a combined measure of transportation costs and scheduling objectives (e.g., Chen & Pundoor, 2006; Chen & Vairaktarakis, 2005; Wang & Lee, 2005).

An important feature of our study is that we model transportation issues both in the inbound and the outbound of the production facility. To our best knowledge, Li and Ou (2005), Tang and Gong (2008), and Wang and Cheng (2009) are the only few papers with this consideration. Tang and Gong (2008) study a coordinated scheduling problem that involves a single batching machine with the objective of minimizing the sum of makespan and an increasing function of total number of batches. Li and Ou (2005) and Wang and Cheng (2009) consider minimization of makespan as an objective whereas our study aims to minimize total inventory holding and transportation costs. Moreover, our study differs from Li and Ou (2005), Tang and Gong (2008) and Wang and Cheng (2009) in the characteristics of the settings, concerning the number of vehicles used and the locations they operate in-between. Both Tang and Gong (2008) and Wang and Cheng (2009) assume that there are two vehicles–one for carrying items in the inbound from the warehouse to the factory, and one for carrying items in the outbound from the factory to a single customer location. It is important to emphasize that in both of these settings, different vehicles are utilized for the inbound and the outbound transportation, whereas, we consider a more restrictive case in which same vehicles handle the transportation in both directions. In this regard, Li and Ou (2005) is the only paper that exhibits some similarities to ours. They model the availability of one vehicle traveling between a factory and a warehouse where both the unprocessed and processed jobs are held.

Our paper builds on the idea of planning the schedules of a limited number of vehicles between two locations so that as many vehicles as possible are utilized both ways. Decreasing the number of trips made by the vehicles not only helps the total costs to be reduced, but it also brings down transport-related air pollution and the need for energy consumption. Although our primary focus is to solve the underlying production and transportation scheduling problems jointly in the specific setting of interest, we would like to note that some recent papers also study the different solution approaches resulting from sequentially solving the subproblems in varying settings (e.g., Agnetis et al., 2014; Toptal et al., 2014). In the paper, we show that the problem under consideration is NP-Hard in the strong sense. Therefore, analyzing this problem is both practically important and theoretically challenging.

In the next section, we begin with a detailed description of the problem and present a mixed integer linear programming formulation. In Section 3, we establish the computational complexity of the problem and present lower bounds on the optimal value of the objective function. We also present some properties of a class of solutions for the general case and a special case of the problem. This is followed by a description of the proposed heuristic in Section 4. In Section 5, we report the results of a computational study. Finally, in Section 6 we conclude the paper.

2. Problem definition and formulation

The system under consideration consists of two warehouses and a production facility. The warehouses, the first for unprocessed jobs and the second for end products, are close to each other. Therefore, they can be considered as in the same location, that is the origin. The production facility is far away from the warehouses.

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