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Integrated cost optimization in a two-stage, automotive supply chain

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ABSTRACT

The efficiency of the automotive supply chain is crucial for ensuring the competitiveness of the automotive industry, which represents one of the most significant manufacturing sectors. We model the integrated production and transportation planning problem of a Tier-1 automotive supplier while taking into account realistic conditions such as sequence-dependent setups on multiple injection molding machines operating in parallel, auxiliary resource assignments of overhead cranes, and multiple types of costs. Finished parts go to the integrated supply chain's second stage, transportation, for subsequent delivery by capacitated vehicles to multiple distribution centers for meeting predefined due date requirements. We develop a mixed-integer, linear programming model of the problem, and then present a hybrid simulated annealing algorithm (HSAA), including a constructive heuristic. Our proposed HSAA employs an effective encoding-decoding strategy to solve the NP-hard problem to near optimality in a timely manner. Computational results demonstrate the promising performance of the proposed solution approach.

1. Introduction

The automotive industry is the largest manufacturing sector in the United States (U.S.) in terms of the number of people employed and it also has one of the largest employment multiplier effects in the U.S. economy. Growth or contraction of this sector has a significant impact on the U.S. Gross Domestic Product [15]. Consequently, the competitiveness of the automotive industry is indispensable for achieving prosperity. As automotive companies face intense competition, ever-increasing customer expectations, unpredictable customer loyalty, and little tolerance for poor quality, the industry has developed rigid production systems and excess capacity where possible. Furthermore, due to the nature of this industry, companies operate under tremendous pressure to carry low inventory levels while still meeting acceptable customer service levels [7]. The automotive industry has been focusing on its supply chains to increase customer satisfaction with the ultimate aim of generating greater levels of productivity, profitability, and competitiveness [18,20].

A supply chain typically consists of suppliers, manufacturing centers, warehouses, distribution centers, and retail outlets, as well as raw materials, work-in-process inventory, and finished products that flow between the facilities. In practice, it is desirable to be efficient and cost-effective across the entire supply chain rather than simply minimizing transportation costs or minimizing inventories in isolation [19]. In addition to being economically important, the automotive industry is one of the most technologically complex industries. More information about relatively recent developments in the automotive supply chain is presented by [1] and [24].

The motivation for this research comes from interactions with a Tier-1 automotive supplier to several major automobile manufacturers. The primary application of this research is the production and transportation of bulk interior parts for automotive OEM plants. An injection molding process is used by the supplier to produce dashboards, door panels, and other automotive parts. The finished parts are then transported to several distribution centers for supplying OEM plants. We focus on the integrated production and transportation planning problem while taking into account realistic conditions such as sequence-dependent setups on multiple injection molding machines operating in parallel, auxiliary resource assignments of overhead cranes, and multiple types of incurred costs.

The research problem deals with multi-period planning for production, inventory, and transportation in a two-stage, integrated supply chain system. In the first stage, production, different parts must be scheduled on multiple parallel machines according to part-machine compatibility restrictions—we seek to determine appropriate part production lot sizes. Setups pertaining to tool change vs. color change must be performed to allow an injection molding machine to changeover to different tools or colors. Another limited resource in the production stage is cranes that are

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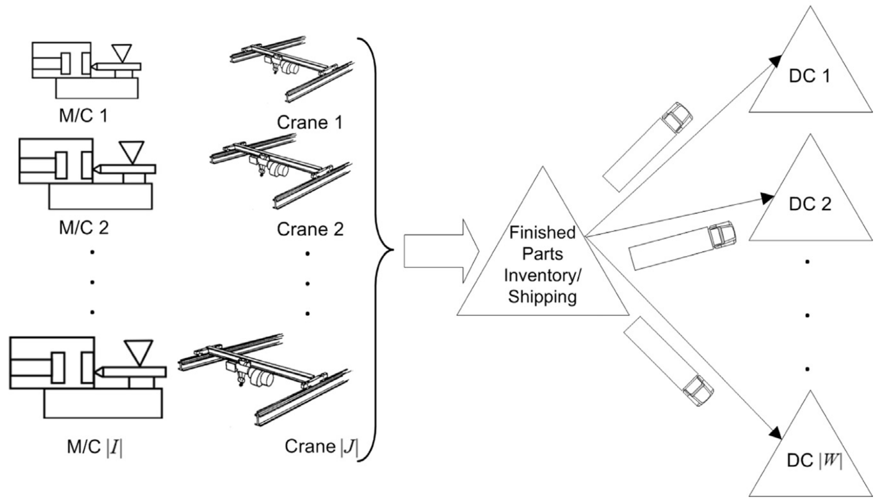

Fig. 1. Schematic of the automotive supply chain under investigation.

required for machine changeovers to a different tool. However, each crane can only serve certain machines due to crane-machine compatibility constraints.

The manufacturing plant's finished parts warehouse has a limited capacity. Finished parts go to the integrated supply chain's second stage, transportation, for subsequent delivery by capacitated vehicles to multiple distribution centers (DCs) to meet predefined due date requirements. Transportation occurs via full truck load (TL) and transportation cost is fixed from the plant to each DC. As the manufacturer typically outsources transportation, we assume that there exists an infinite number of delivery vehicles. Each manufactured part is associated with a customer (i.e., DC) and has its own required cycle time, size (i.e., storage space requirement), and demand schedule (i.e., quantities and due times at a DC). The supply chain only allows direct deliveries without any intermediate stops (i.e., only one customer per trip). Fig. 1 shows the supply chain system under study. Our motivating research objective is to minimize total cost, which is comprised of setup costs, inventory (holding) costs, transportation costs, and outsourcing costs.

One approach in supply chain planning is to integrate different supply chain functions (e.g. purchasing, production, distribution and storage) into a single, monolithic model [14]. [22] noted that there is scarcity in the literature addressing supply chain coordination at an operational level. [3] confirmed that there is a gap of integrated models at the detailed scheduling level and that there is a need for fast solution algorithms. [2] reviewed existing models that integrate production and outbound distribution scheduling in make-to-order supply chains with little or no finished product inventory in the supply chain, such as the production and distribution of fashion apparel and the assembly and delivery of personal computers.

[12] indicated that proposed integrated production and transportation planning models in the literature often are validated by numerical examples more than by actual case studies applied to real-world supply chains. Mixed-integer linear programming is applied to the integrated production and transportation planning problem in different contexts, such as continuous manufacturing [23] and process industries [16,17]. We could not identify any paper that models the current integrated production and transportation planning problem in the automotive or other industry at a detailed, operational level, reflecting its technological complexity, discrete manufacturing aspects, sequence-dependent setup times, and compatibility constraints.

[10] used Monte Carlo simulation to analyze critical issues in container demand planning for the product development phase of a new car model before the start of production. [11] introduced a mathematical cost model for evaluating the assignment of automotive parts to one of two possible material supply systems: kitting or line stocking. [25] studied the trade-offs between inventories, production costs and customer service level in an automobile manufacturing supply chain network, but do not model the details that are included in our proposed research problem. Although a somewhat relevant model to the current research is the one presented by [5], our proposed research problem is different as we incorporate transportation and auxiliary resource (i.e., crane) decisions. Furthermore, we analyze a more extensive experimental problem instance set to reflect realistic conditions in the automotive industry. The current research aims to start filling the literature gap of integrated automotive supply chain planning at a detailed, operational level.

The rest of this paper is organized as follows. Section 2 formulates a mixed-integer linear programming (MILP) model that captures various pertinent aspects of the problem under study. Due to the problem's complexity and the associated inability to solve large problem instances optimally, a hybrid simulated annealing algorithm is developed for industry application in Section 3. Then Section 4 describes the experimental study used to evaluate the proposed solution methodologies. Section 5 overviews the computational results, and Section 6 presents the conclusions and future research directions.

2. Mixed-integer linear programming model

We now present a mathematical programming model for minimizing total cost in an integrated, two-stage automotive supply chain. Before presenting the model and its associated notation, we first detail the necessary assumptions made in our research study:

- The number of part types produced by a machine is restricted to one per time period.
- Every machine has a production capacity that cannot be exceeded.
- Parts are shipped directly to customers or held in inventory for shipping in later periods.
- Finished part warehouse at the plant has a holding capacity that cannot be exceeded.
- Every transport vehicle has a capacity bound that cannot be exceeded.
- A maximum of one machine setup per time period can be performed by a crane.