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Applications

Optimizing real-time vehicle sequencing of a paint shop conveyor system[☆,☆☆]

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ABSTRACT

A discrete event simulation model and a decision optimizer that were developed for a General Motors paint shop conveyor system are presented. The simulation model interacts with the decision optimizer at four critical points in the system, trying to regroup batches of different colored vehicles. The decision optimizer employs dynamic programming and integer programming to optimize vehicle routing policies. Simulation results of the current decision making policies are compared with those of the proposed optimized policies showing that the number of paint head changes can be significantly reduced resulting in substantial savings on paint head cleaners and paint.

1. Introduction

The General Motors (GM) Corporation plant in Arlington, Texas, paints approximately 1000 vehicles in two work shifts per day. In such paint shops, vehicle bodies will have to undergo several manufacturing steps before they are actually painted to a predetermined color. The conveyor system in the paint shop thus moves vehicles between and through these manufacturing steps, but also includes buffers where vehicle bodies can be temporarily stored, as some of the steps cannot be stopped, while others require periodic shutdowns. Painting the body to the final color is one of the last steps in this process, which is usually done in several paint booths in parallel. If consecutive vehicles on the conveyor system do not have the same paint color, then the paint in the gun needs to be flushed, and the paint head cleaned with solvent. This process not only wastes time and money but is also a burden on the environment.

Batches of vehicles, grouped to be painted to the same color, enter the paint shop on a conveyor from the body shop. Optimally, for a shift, vehicles to be painted with the same color would be batched together and thus would follow each other on the conveyor system without being intermixed. However in reality, the vehicles coming from the body shop are not arriving in homogenous batches due to a seemingly random injection of vehicles that require some more bodywork before painting; i.e., there is already some interleaving of different colors of vehicles coming in from the body shop. Shuffling vehicles inside the paint shop due to buffering creates more mixing between consecutive batches. At the paint booth, which is completely automated, these color-batch shuffles can result in a significant number of *changes in the paint heads*. Based on conversations with the GM management, such paint head changes cost USD15 on average and occur roughly after every 3 vehicles; the annual cumulative cost due to paint head changes in the Arlington, Texas paint shop is over USD1,2M. This has a significant impact on GM's production cost and contributes to environmental pollution. Realizing this, plant management was looking for methods to increase batch sizes and thus reduce the number of paint head changes. Experimenting with the facility's conveyor layout was not an option that could be pursued, as it would have incurred huge setup costs and would have caused significant down times for production. However, a simulation study of the current facility and conveyor routing decisions was offered as an effective method to study the response to changes in the system. Such approach provides a significant amount of savings on cost and time.

In order to understand how the conveyor system could re-sort vehicles and thus change batch sizes, we identified buffer conveyors that consist of several parallel sections. At the beginning and end of these buffer conveyors, there are critical points where decisions have to be made on how to split or merge to/from the parallel conveyors. Originally splitting and merging was done

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either in round-robin fashion or with a preference for a shorter conveyor. Although this did not introduce any more shuffling, it was not used to re-sort vehicles back to their original batches.

In this paper, we describe the research and development of a discrete event simulation model of the GM paint shop conveyor system in Arlington, Texas, which interacts with a decision optimizer. Although our simulator was developed specifically for this paint shop, the program objects and modules we have developed could be reused to create simulations of other conveyor systems. Dynamic programming and multi-commodity flow integer programming modules are integrated with the simulation model of the paint shop. The optimization modules are periodically called by the simulator to make assessments at critical decision points. We show simulation results for two scenarios—one without the decision optimizer, which reflects the current paint shop's conveyor system and another one using the decision optimizer. By analyzing output traces of the simulator, we can compare the performance (in terms of paint head changes) of the original system and the proposed optimized decision maker.

The rest of this paper is organized as follows. Section 2 overviews related literature while relating our contribution to existing research. Section 3 describes the current physical model of GM's paint shop and details the simulation model we developed; it also describes the decision optimizer that we used in our simulations. In Section 4, we explain the experimental set up for our simulations. Discussions on results can be found in Section 5. Section 6 concludes the paper, providing a summary of key research points. Finally, small illustrative examples are described in the Appendixes.

2. Related literature and contribution

A survey of simulation modeling using discrete event simulation in manufacturing plants can be found in Semini, Fauske, and Strandhagen [1]. Simulation of industrial systems has been prevalent since the early 1960s and has been used to study numerous problems in automotive manufacturing. Discrete event simulation software has been constantly in use for evaluation of production policies [2], lot sizes [3], work-in-process inventory levels [4], and production plans/schedules [1]. Simulation studies of automobile assembly plants can be found in the literature, including those for GM [5], PSA Peugeot/Citroën [6], Visteon's Sterling plant [7], and general automobile assembly [8,9]. In addition to simulation studies, Blackhurst et al. [10] develop a hierarchical Petri Net for conflict detection in the supply chain of a radio chassis manufacturer, which includes a painting process. However, these studies do not integrate a decision optimizer as they focus on timing and how disruptions propagate through a system, while we consider how a conveyor system can regroup vehicles using existing parallel conveyors.

Numerous research papers focus on optimization techniques to sequence vehicles on conveyor and manufacturing systems. A recent survey by Boysen et al. [11] references more than 200 articles. These articles are on sequencing vehicles prior to assembly, and they generally assume that the sequence is not disrupted. Consequently, they attempt to solve a very large integer programming assignment problem with side constraints. Because these problems are NP-hard, they are usually solved with heuristic techniques, such as local search (e.g., [12–15]), tabu search (e.g., [16]), simulated annealing (e.g., [17,18]), and ant colony optimization (e.g., [19,20]). In certain instances, they are solved with exact branch-and-bound algorithms (e.g., [21,22]).

The research in this paper though is on resequencing a disrupted vehicle sequence. Recently, resequencing vehicles has become popular topic in the literature, and a discussion survey on this research is given in Boysen et al. [23]. Within this body of literature, the most relevant related research to this paper is the diverging sequential ordering problem (DSOP) in Han and Zhou [24–26]. They develop a constrained assignment algorithm and several rule-based heuristics for DSOP and evaluate it using simulation. DSOP is equivalent to the splitting problem in this paper, and their constrained assignment model is a similar formulation to our multi-commodity flow model. However, they do not consider merging the vehicles, nor do they describe the interaction between the DSOP and the simulation. Ding and Sun [27] study sorting areas to order vehicles with the same paint colors. They provide an integer program to optimize the ordering in the sorting areas as well as several rule-based heuristics. Their research is closely related because their *sorting areas* have a similar theoretical background to the re-sorting buffers in this research. However, an implicit assumption in their integer program is that the duration of time that vehicles are in each line are similar, which is not the case in this research due to the inherent conveyor design at the GM plant. Consequently, the research in this paper considers the action of splitting a single conveyor into multiple conveyors and merging multiple conveyors into a single conveyor separately. Furthermore, [27] acknowledges that the integer program presented is impractical to solve for real-time decision making. Consequently, they consider several heuristic rules for sorting. In fact, most of the articles discussed in [23] use heuristics. In our research however we use a multi-commodity flow model for splitting, and we did not face any run-time restrictions where the algorithms did not perform well within real-time constraints.

In addition to the vehicle resequencing articles, Banerjee et al. [28] develop a multi-commodity flow problem for reducing material flow congestion for a conveyor. The multi-commodity flow model in [28] is similar to the one for splitting in this paper but is designed for general planning of batches of materials, whereas the one here is for on-line decision making of flows of single items, specifically automobiles, to minimize color changes. Lin et al. [29] study heuristics for a three-machine assembly-type flowshop problem in which jobs are sequenced on two parallel machines and then merged to a single second-stage machine using a dynamic program. The dynamic program in [29] is similar to the one for merging in this research but only models two incoming flows and minimizes makespan, while the one in this paper includes multiple source conveyors and minimizes color changes.

The contribution of this paper includes the following components:

- We develop a simulation model using paint shop data collected from the GM plant in Arlington, Texas, which is the first to include the details of the paint shop of the plant.
- We formulate a new dynamic programming model for re-sorting batches of different colors when merging vehicles from multiple conveyors to a single conveyor.
- We formulate a new integer multi-commodity flow model for re-sorting batches of different colors when splitting vehicles from a single conveyor to multiple conveyors, which can be solved exactly in real time.
- We integrate these merging and splitting algorithms as well as those currently used at the GM plant within the simulation.
- We conduct simulation experiments comparing the use of these merging and splitting algorithms with the current practice at the GM plant.
- We conduct simulation experiments that help determine an optimal size of batches of the same-colored vehicles.

3. Models

In this section we outline the models used in our study.

3.1. Conveyor simulation model

The paint shop at GM can be divided into different logical blocks. Fig. 1 depicts the flow of vehicles between work processes