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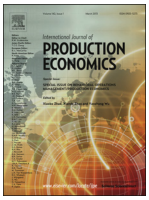

Workforce minimization for a mixed-model assembly line in the automotive industry

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ABSTRACT

A paced assembly line consisting of several workstations is considered. This line is intended to assemble products of different types. The sequence of products is given. The sequence of technological tasks is common for all types of products. The assignment of tasks to the stations and task sequence on each station are known and cannot be modified, and they do not depend on the product type. Tasks assigned to the same station are performed sequentially. The processing time of a task depends on the number of workers performing this task. Workers are identical and versatile. If a worker is assigned to a task, he/she works on this task from its start till completion. Workers can switch between the stations at the end of each task and the time needed by any worker to move from one station to another one can be neglected. At the line design stage, it is necessary to know how many workers are necessary for the line. To know the response to this question we will consider each possible takt and assign workers to tasks so that the total number of workers is minimized, provided that a given takt time is satisfied. The maximum of minimal numbers of workers for all takts will be considered as the necessary number of workers for the line. Thus, the problem is to assign workers to tasks for a takt. We prove that this problem is NP-hard in the strong sense, we develop an integer linear programming formulation to solve it, and propose conventional and randomized heuristics.

1. Introduction

The current highly competitive market forces manufacturing based industries to optimize their production costs. Workforce minimization in manual assembly lines is one of the challenging issues. This paper proposes models and methods to help the practitioners to dimension and schedule workforce resources on mass production manual mixed-model assembly lines.

On manual mixed-model lines, not only one but a set of similar products (variants or models) are assembled. Usually, for mixed-model assembly line balancing, a set of tasks for each variant is assigned to each workstation on the line and is performed by the worker(s) available at this workstation. Depending on the presence of the different product variants on the line and the processing time required to treat each task of a particular variant at each particular workstation, the distribution of workload among workstations can present considerable inequalities over time. The problem of how to balance the workload among workstations has been intensively studied in the literature (Venkatesh, 2008). However, because of the inequalities of task processing times for different variants, the perfect balance can rarely be attained if at all. This results in idle times and an inefficient use of workforce resources.

Our paper suggests approaching this problem differently. We assume that the assignment of tasks to workstations is known and it is the same for all product variants. It cannot be modified. In contrast, the assignment of workers to workstations can be dynamic depending on the state of the line.

We study the case where a line is designed for a mass production of different variants of a product. The total volume and the ratios of demands for product variants are known. To smooth the production of different variants, a sequence of product variants is defined such that the numbers of product variants in the sequence respect given ratios, and this sequence is repeated cyclically. Considering a given number of product variants and known variant ratios, we can enumerate all possible cyclic sequences of product variants. This number is not so large. In this

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paper, we will consider a given sequence of product variants. The approach and model are the same for all other possible sequences.

The assembly line is paced, i.e. at the end of each takt, all items are simultaneously moved to the next stations. The takt time is the time available to execute the tasks assigned to stations.

A state of the line is defined by variants of the product at stations, i.e. if we know which variant is at each station for a takt, we know the state of the line for this takt (and consequently task processing times). For a given cyclic sequence of product variants, all possible states of the line are known and their number (thus the number of takts to consider) is equal to the sequence length. They are repeated cyclically. We will develop a model for only one takt; obviously this model is valid for all other takts, because the takt state structural information is the same for all takts (workers and workstations with their tasks); the differences among takt states concern only processing times which is the input data of our model.

We consider that all workers are polyvalent (identical) and each of them can execute any task at any workstation. The time needed by any worker to move from one station to another one can be neglected. A task is executed by one or several workers. The processing time of a task is inversely proportional to the number of workers performing it. When a task is finished at one workstation, a worker can move to another workstation in order to speed a task completion there and to balance the workloads of both workstations. The assignment of tasks to the stations and the task sequence on each station are known and cannot be modified, and they do not depend on the product variant. Tasks assigned to the same station are performed sequentially. Therefore, for a given takt, the considered optimization problem is to find the optimal assignments of workers to sequences of tasks, so as to find a schedule of their moves along workstations, taking into account the state of the line in the considered takt. The objective is to minimize the total number of workers required for the given takt.

As aforementioned, this problem is the same for any takt; only the states of the line are different, i.e. the product variants are situated differently at stations for diverse takts. Thus, if we have a model to optimize assignment of workers for a takt, this model can be applied to all other takts. The worker moving times are neglected, thus the working positions for different takts can be considered independently. The number of workers assigned to the line cannot be modified from one takt to another one. By applying the model to each possible takt separately, we can obtain a minimum number of workers necessary for this line and a work schedule for each of them. This approach is used to dimension the workforce at the line design stage.

To summarize, we consider one takt scheduling problem for workers for a given sequence of product variants. The objective is to find a schedule of moves of workers along workstations minimizing the number of necessary workers under a takt time constraint and taking into account workloads of stations (the state of the line for the considered takt). This problem is also related to line balancing problems, because it can be considered as an assignment of tasks to workers to minimize the number of workers.

Section 2 presents an industrial case which motivated our research. *We call this problem P*. Production environment and numerical characteristics of the problem are described. Related literature is analyzed in Section 3. A Mixed-Integer Program (MIP) is presented in Section 4. Problem *P* is proved to be NP-hard in the strong sense in Section 5. Five heuristics developed for problem *P* are described in Section 6. Section 7 reports computer implementation and experiments. Finally, the paper concludes with a summary of the results.

2. Industrial case

Problem *P* was stated by one of our industrial partners. This enterprise from the automotive industry has to design a new assembly line for three variants of an engine: V12, V16 and V20. While doing the line design, it is necessary to dimension the workforce: to know how many workers should be employed on this line. This number should be as small as possible in order to decrease the labor costs. Thus, a workforce planning for this assembly line, minimizing the number of workers, is necessary.

The assembly stations are connected by a unidirectional conveyor. The sequence of the assembly stations to be visited by the semi-finished engines, and the sequences of tasks to be performed at the assembly stations are the same for all engine variants. However, the task processing times depend on the variant of engine. For the same number of workers assigned to a task, some tasks for V20 engines take a longer time than those for V16 engines, and some tasks for V16 engines take more time than those for V12 engines, while some other tasks have the same processing times for all engine variants.

The assembly line is paced, therefore, the sum of task times at any assembly station in each takt must not exceed a given takt time.

To calculate the takt time, the following information given in Table 1 is used.

The annual production volume and shares (ratios) of demand for each engine variant are known, they are given in Table 2.

Taking into account the information that the line is designed to produce 1450 engines per year, the takt time in hours needed to produce one engine is calculated as follows:

$$\text{Takt time} = \frac{230\left[\frac{\text{days}}{\text{year}}\right] * 2\left[\frac{\text{shifts}}{\text{day}}\right] * 8\left[\frac{\text{hours}}{\text{shift}}\right]}{1450\left[\frac{\text{engines}}{\text{year}}\right]} = 2.5\ [\text{hours/engine}]$$

The manufacturer prefers to have evenly distributed engine variants on the line. Due to this requirement, a cyclic sequence of variants to enter the line was designed taking into account the ratios of engine models in the total annual production. These ratios are as follows:

$$\text{Ratio V12} = 75\% = \frac{3}{4} = \frac{15}{20}$$

$$\text{Ratio V16} = 20\% = \frac{1}{5} = \frac{4}{20}$$

$$\text{Ratio V20} = 5\% = \frac{1}{20}$$

Therefore, the following cyclic sequence respecting the criteria of smoothness and ratios was selected: see Fig. 1.

Mass production with push principle, the smoothness criterion for variant releases and given variant ratios can explain this choice made by our industrial partner. The total annual sequence of

Table 1
Available production time.

Days per year	230
Shifts per day	2
Shift duration (h)	8

Table 2
Annual production volume and variant ratios.

Annual volume for all variants (engines/year)	1450
V12 share	75%
V16 share	20%
V20 share	5%

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