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Modeling and solving the mixed-model sequencing problem to improve productivity

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ABSTRACT

In this paper, it is presented an extension of the mixed-model sequencing problem with work overload minimization (*MMSP-W*) for production lines with serial workstations, parallel homogeneous processors, and variable operation processing times. This extension is intended to consider that the processing times of the operations can be prolonged or shrunk with respect to the established standard processing times depending on the work pace of the workers. To do this, the activity of workers is set by means of functions which take into account the periods of adaptation and fatigue of the beginning and end of the workday, respectively. Thus, two mathematical models and four functions for the work pace factor are presented and their performances are analyzed through a case study of the Nissan powertrain plant in Barcelona, using the Gurobi solver. The results show that the work overload can completely be either eliminated with an increase of the activity of operators of 5% over their normal work pace or reduced by 88% with an increase of 3.33%. Consequently, the losses due to the uncompleted work or the hiring costs of auxiliary operators can be avoided by demanding a greater effort to workers at certain moments of their workday, but always respecting the limits set by collective agreement.

1. Introduction

Flexible manufacturing systems composed of cells and modules or workstations in assembly lines are very common in production environments related to the automotive sector (e.g. engines, stamp forging, body welding, body painting and trim and chassis lines). In this type of production systems, the manufacture of products may require different processing times at each manufacturing stage or different use of resources because not all manufacturing processes involve the same workload, and the manufactured product units may not be completely identical. When this happens, i.e., when the resource usage depends on the type of product, e.g., in the product-oriented production systems, several problems can be found such as the line-balancing problems and batch or product-unit sequencing problems.

Within the sequencing problems, there are different problems depending on the variation of the processing times of the mixed-products. Among them, there are (I) the "flow-shop" or permutation sequencing problems with considerable differences in the processing times of mixed products (Pan and Ruiz, 2013; Bautista et al., 2012c; Lin and Ying, 2013); (II) the Economic Lot Scheduling Problems (*ELSP*) with processing times depending on the number of units that constitute a batch of pieces (e.g. in the line sequencing of parts to stamp car bodies) (Elmaghraby, 1978; Raza and Akgunduz, 2008); and (III) the mixed-product sequencing problems that arise when the processing times of mixed products differ slightly at each stage (homogeneous units).

In problems III, the objective is to establish a manufacturing sequence that must be maintained wherever possible at all manufacturing stages and supply chain of the production systems governed by the Just in Time (*JIT*, Toyota) and Douki–Seisan (*DS*, Nissan) philosophies. This production order depends on the characteristics of the line, the products manufactured therein and the elements of the production system under which the optimization criteria were established. Thus, according to these optimization elements and the work of Boysen et al. (2009), we identified the following mixed-product sequencing problems:

A. Problems solved by establishing a product sequence that minimizes the stock levels of products and components. Among them, we encounter the product rate variation problem (*PRVP*) introduced by Miltenburg (1989), and the output rate variation problem (*ORVP*) proposed by Monden (1983).
B. Problems solved by minimizing the work overloads that can appear when the mixed-product units require different processing times at each stage or workstation. A clear example of these problems is the mixed-model sequencing problem with work

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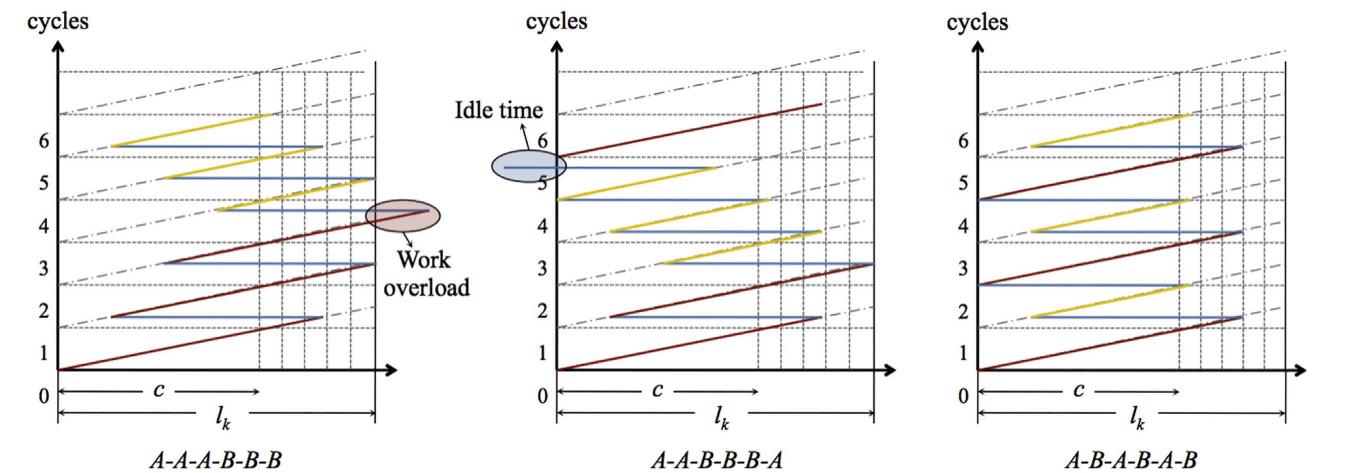

Fig. 1. Work overload, idle time and completed work according to the sequence.

overload minimization (*MMSP-W*) presented by Yano and Rachamadugu (1991) from which several variants have been solved (Bautista et al., 2012d; Bautista and Cano, 2011).

C. Problems solved by minimizing the number of subsequences of products with special options. One of this type of problems is the car sequencing problem (*CSP*) (Parrello et al., 1986; Drexl et al., 2006; Gagné et al., 2006; Bautista et al., 2008a, 2008b), where the bottlenecks generated by special options of some products are the relevant element of the manufacturing system.

Specifically, this work focuses on the problem III-B, i.e. the *MMSP-W*. The original problem is an NP-hard problem (Yano and Rachamadugu, 1991) for which several alternative solutions have been proposed, such as exact procedures based on branch-and-bound (Bolat, 2003), dynamic programming (Yano and Rachamadugu, 1991; Bautista and Cano, 2011; Bautista et al., 2012b), heuristic procedures based on local search (Yano and Bolat, 1989; Bautista and Cano, 2008), greedy algorithms with priority rules (Bolat and Yano, 1992; Bautista and Cano, 2008), meta-heuristics (Scholl et al., 1998) and beam search (Erel et al., 2007). Several studies have also considered the multi-criteria option (Aigbedo and Monden, 1997; Kotani et al., 2004; Ding et al., 2006).

In short, the problem lies in sequencing a production plan of T units of products grouped by product type ($d_i \ \ \forall i \in I$) with the aim of completing the maximum quantity of required work.

Indeed, each homogeneous processor of the workstations has the cycle time, c, (at normal activity) to work on a product unit. However, the fact that the product types require different processing times, $p_{i,k}$ (at normal work pace or activity), forces processors to work on a given product for a longer time than the cycle time and therefore it is given to each processor a time greater than the cycle time and which is called temporal window, l_k ($l_k - c \geq 0$).

Despite this extra time, sometimes, given a production plan, processors cannot complete all the work required for one product unit and the work overload or unfinished work, $w_{k,t}$ ($k = 1, \ldots |K|, \quad t = 1, \ldots T$), appears. This overload is measured in units of time (at normal work speed).

Thus, the aim of the problem is either minimizing the work overload or maximizing the completed work depending on the product sequence. This objective can be achieved by means of two ways. First, by minimizing the work not completed (work overload) by the processors and therefore guaranteeing the fulfillment of most work required; and second, through the minimization of unproductive time (idle time) of the processors.

Fig. 1 shows the effect produced by 3 sequences of 6 product units at one workstation. There are two product types (type *A* with high load and type *B* with low load). The first sequence (*AAABBB*) generates work overload, while the second (*AABBBA*) produces idle time. However, the third sequence (*ABABAB*) does not produce neither of these two effects.

Although there are different variants of the *MMSP-W* in the literature, rarely the human factor has been taken into account when mixed products are sequenced. In fact, when human resources are present in the workstations of a line, some conditions agreed between the company and labor unions through collective agreements should be considered. Among these conditions there are the maximum levels of saturation and performance of workers.

Usually, when human resources participate in the operations in *JIT* and *DS* manufacturing environments, the processing times are initially determined using the Methods and Time Measurement system (*MTM*). These times, known as the predetermined standard times (Aft, 2001), correspond to the time required by an average skilled operator working at normal pace or normal speed to perform a specified task using a prescribed method and allowing time for personal needs, fatigue and delay.

An average skilled operator is someone who knows the job and can consequently perform it throughout the entire workday and the normal pace is a rate of work that can be maintained for all the workday. However, rarely any worker will perform his workload at the normal pace for an entire workday. In fact, sometimes the operators will work faster than the normal pace and others slower. Hence, the normal pace, normal activity or normal work speed represents an ideal that the industrial engineer judges the average worker should be able to maintain long-term.

Thus, taking into account that the work speed of the operators can be different along the workday and, therefore the standard times can be modified, the collective agreements set the maximum levels that can be assumed by the operators regarding the activity and the occupation of workers throughout their workday.

In this respect, Bautista et al. (2015) seek to improve working conditions by limiting the saturation of the processors in the workstations and, simultaneously, they try to reduce the work overload generated by the saturation limitation by means of the work pace factor of workers. In this way, the negative effect of limiting the saturation level of operators on the productivity is reduced.

Thus, noting the increase of work overload when saturation conditions agreed by collective agreement are considered, the motivation for this paper is to increase productivity in a manufacturing line of mixed-engines within the legal framework by reducing the work overload to zero. To do this, we solve an extension of the *MMSP-W* that considers variable work pace over the workday by means of linear programming. Specifically, we focus on eliminating