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Cyclic scheduling of flexible mixed model assembly lines with parallel stations

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ABSTRACT

In this paper, the problem of balancing and cyclic scheduling of flexible mixed model assembly lines with parallel stations is studied. To exploit the connection between balancing and cyclic scheduling problems for an efficient line management, they are considered simultaneously. A novel constraint programming model including problem specific symmetry breaking constraints is proposed to solve this problem. Experiments on extensive number of test instances with various sizes are also presented.

1. Introduction and background

Assembly lines are widely used flow-line mass production facilities for manufacturing single or mixed models and consist of serially connected stages with one or more identical or non-identical parallel stations in each stage.

The design and operation of mixed assembly lines give rise to two problems; assignment of tasks to stations (i.e., balancing, [1]) and sequencing of models on the stations. The model sequencing problem is usually dealt with in a sequential manner in published literature [2–4]. However, in recent years there is an increasing interest to simultaneously consider both problems in the same time frame in order to exploit the advantages of flexible production systems such as considering alternative stations to perform assembly tasks [5,6]. This problem is known as simultaneous balancing and scheduling of flexible mixed model assembly lines, (SBSFMMAL). Öztürk et al. [7] provides a detailed survey on SBSFMMAL problem. In the same study, the authors propose a constraint programming (CP) model to solve the SBSFMMAL problem and they show that CP model, which guarantees optimality [8], outperforms the MIP and MIP based decomposition methods in all instance sizes within a reasonable solution time. An important extension to this problem is to consider parallel stations which increase adaptability of an assembly system to changes in market requirements and unexpected situations like machine failures [9]. Öztürk et al. [10] develop a mixed integer programming (MIP) model and MIP based decomposition algorithm to solve SBSFMMAL problem with parallel stations and they show that the cycle time can be decreased by more than 70 percent in some instances.

In mixed model assembly lines, the problem of producing different products with different demand levels within the same planning horizon is reduced to producing the minimum part set (MPS) in repeating cycles to meet the total demand. Considering only one cycle of the MPS while solving the mixed-model balancing and scheduling problem yields suboptimal solutions since blocking and idle times of stations between repeated cycles are ignored. Cyclic schedules have many managerial advantages such as easier implementation due to the simplicity, better station utilization, improved material handling and material flow, shorter production lead times, reduced planning and control costs, decreased inventory levels, and increased labor efficiency due to standardization [11]. As a result of surveying the current relevant literature, it has been noted that the great number of published studies focus on only one cyle while solving this problem. There are a few studies [12,13] dealing with this problem in cyclic manner. In a recent survey on complexity of cyclic scheduling problems, Levner et al. [12] show that cyclic flow shop problem – which is a restricted version of our problem-is NP-hard. Sawik [13] also considers cyclic scheduling of assembly lines with

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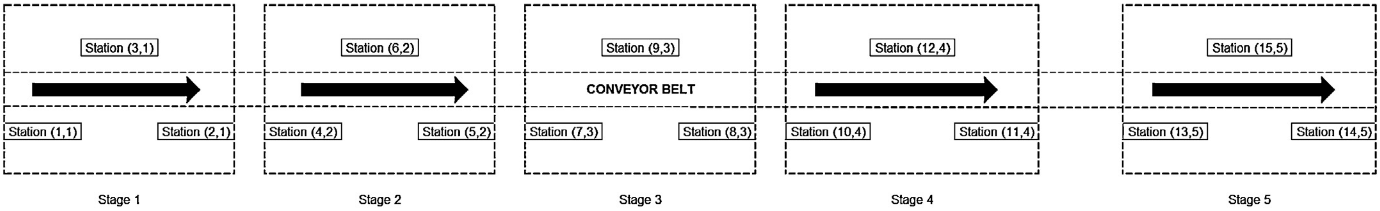

Fig. 1. An illustrative example.

parallel stations but assumes that task assignment and scheduling decisions are previously made. In other words, assignment, scheduling and balancing problems are not solved simultaneously. As stated in Karabati and Sayin [27], considering these problems simultaneously brings difficulties both in modeling and solving perspectives. Furthermore, McCormick et al. [14] and [15], Karabatı and Kouvelis [30], Kouvelis and Karabati [31] show that the steady state cycle times can be reached in very early replications of the MPS.

Considering the perceived gap and due to its success in representation, modeling and solving combinatorial problems in general and scheduling problems in particular [16–18] in this study we develop a new constraint programming model formulation for simultaneous balancing and cyclic scheduling of flexible mixed model assembly lines with parallel stations to minimize cycle time of models. This study is a continuation and extension of authors' earlier works [7] and [10]. The MIP model proposed in the previous work of the author's to solve the non-cyclic version of this problem has a great advantage on proving optimality due to its ability to use LP relaxation in search tree [19]. However, its success is limited to solving small size instances. Whereas, the CP model proposed in the earlier study of authors for the same non-cyclic problem without parallel stations finds a solution in one hour for all instance sizes. Moreover, that CP model finds optimal solutions to larger number of instances as compared to the MIP model. Hence, we could state that the CP models for the similar problems outperform the MIP and MIP based decomposition heuristics and CP seems to be the best method for modeling and solving the flexible mixed model assembly line problems. Furthermore, Flener et al. [20] show efficiency of the *lex* global constraint for breaking assignment based symmetries on the model formulation of a set of combinatorial problems. Considering the success of earlier model to deal with non-cyclic version of balancing and scheduling of flexible mixed model assembly lines with parallel stations, this study proposes a CP model to solve cyclic version of the same problem along with employing assignment based symmetry breaking constraints and customized search strategy. Note that to the best of our knowledge there is no study in the literature dealing with this problem using constraint programming.

The rest of the paper is structured as follows. In Section 2, the problem definition for balancing and cyclic scheduling of flexible mixed model assembly lines with parallel stations is presented with an illustrative example. Survey of the literature on cyclic scheduling of assembly lines is also provided in Section 2. The proposed CP model to solve the balancing and cyclic scheduling of flexible mixed model assembly lines is given in Section 3. Computational studies testing the performance of the proposed model are presented in Section 4. Finally, the concluding remarks and future research directions are provided in Section 5.

2. Problem definition

In this section, we provide a numerical example to explain the main features of the problem considered in this paper. The features of the problem can be represented with a 7 dimensional tuple as <*Stages, Stations, Tasks, Products, Jobs, Precedence, Constraints*> where *Jobs* stands for the set of <*task, product*> pairs and *Constraints* refers to the restrictions to consider while assigning and scheduling tasks and products. As seen in Fig. 1, the example involves a five-stage assembly line with three parallel stations in each stage. The stages are connected via a conveyor belt. Note that station (q,s) in Fig. 1 shows the station "q" in stage "s" and parallel stations in each stage have the same capability. We assume that stations in the same stage are at equal distances from each other, hence transfer times between the stations are not considered while making product/job assignment and scheduling decisions.

Each station on the assembly line is capable of performing certain assembly tasks and has a limited working space area (as shown in Table 1) where each of 10 tasks uses a portion of this available working space, see Table 2. Note that "-" entries in Table 2 show that the station is not capable for that task.

Each assembly task must be assigned to at least one of the eligible stations. In other words, assembly tasks are flexible operations and there is more than one station which can perform the same task. This feature makes the assembly line flexible and may result reduction in the cycle time by increasing the number of alternative stations which can process the assembly task. In addition, enabling flexible operations empowers reliability of the assembly line by making them less sensitive to machine failures and helps to distribute the workload through stations smoothly. Flexible operations can be observed in high technology manufacturing systems such as automated computer numerical control (CNC) machines and assembly of printed circuit boards (PCB) [5]. If required tools are loaded in the tool magazine, CNC machines can perform various operations. Similarly, machines in PCB lines are capable of performing different operations if they are equipped with necessary tools. Surface mount technology lines that are used in producing printed wiring boards are also examples of systems with flexible operations (Sawik, 2011a).

The illustrated example involves producing 7 products (i.e., mixed models) in this serial assembly line in repeating cycles which require subset of 10 assembly tasks. These products could be considered 7 different models of the same product such as different models of an air conditioner with some common and distinct tasks (see Table 3).

In this paper, we refer the combination of each task t of any product p as a job <t,p> or simply job j. As shown in Table 3, while product 2 involves 3 jobs, product 3 involves 4 jobs which are actually "operations" in assembly line literature. Based on

Table 1
Total available working space of each station m (in m^2) (b_m).

Stations (m)	1,1	2,1	3,1	4,2	5,2	6,2	7,3	8,3	9,3	10,4	11,4	12,4	13,5	14,5	15,5
b_m	9	9	9	8	8	8	7	7	7	8	8	8	5	5	5