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Innovative Applications of O.R.

Multiple-source learning precedence graph concept for the automotive industry

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ABSTRACT

In modern production systems, customized mass production of complex products, such as automotive or white goods, is often realized at assembly lines with a high degree of manual labor. For firms that apply assembly systems, the assembly line balancing problem (ALBP) arises, which is to assign optimally tasks to stations or workers with respect to some constraints and objectives. Although the literature provides a number of relevant models and efficient solution methods for ALBP, firms, in most cases, do not use this knowledge to balance their lines. Instead, the planning is mostly performed manually by numerous planners responsible for small sub-problems. This is because of the lack of data, like the precedence relations between the tasks to be performed. Such data is hard to collect and to maintain updated.

Klindworth, Otto, and Scholl (2012) proposed an approach to collect and to maintain the data on precedence relations between tasks at a low cost, as well as to produce new high-quality *feasible* assembly balances based on this data. They utilize the knowledge on former production plans *available* in the firm. However, due to reliance on the single source of information, their concept needs long warming-up periods. Therefore, we enhance the concept by incorporating *multiple* sources of information available at firms, as the modular structure, and present guidelines on how to conduct valuable interviews. The proposed interview enhancements improve the achieved results significantly. As a result, our approach generates more efficient new feasible assembly line balances without requiring such long warming-up periods.

1. Introduction

The assembly line balancing problem (ALBP) was formulated by Salveson (1955) over 60 years ago and was proven to be NP-hard (Wee & Magazine, 1982). Since that time a huge amount of real-world problems and restrictions found their way into mathematical models and the scientific literature (for an overview see, e.g., Boysen, Fliedner, & Scholl, 2008). Because of customization of the products and, consequently, a high variety of product variants with volatile demands that have to be produced on the same assembly line, assembly lines have to be re-balanced intermittently (Boysen, Fliedner, & Scholl, 2009b).

Balancing assembly lines manually is a time expensive and challenging job, especially for assembly lines with a large number of work operations (tasks) to be performed. Thus, balancing an average assembly line in the automotive industry requires assignment of about 1000–3000 tasks to workstations. Overall, by automation of assembly line balancing about one third of the planner's time can be saved (Hirschbach, 1978, chap. 2). Furthermore, the solution quality of the manual assembly line balancing is, at best, only suboptimal, because, in order to be handled manually, this very large optimization problem is divided into manageable sub-problems assigned to different planners in the firm.

Although there exist fast exact solution methods as well as highly effective heuristic approaches (see Becker & Scholl, 2006), the implementation of such methods can be found in the relevant industries only seldom. This is because of several reasons. First of all, in the past computers were less powerful and the implementation and computation would have caused a lot of additional costs without direct noticeable improvements. This argument does not count so much nowadays, because the computation capacity grew rapidly in the last 20 years and the development of very effective heuristics allows us to get optimal or nearly optimal solutions with low computational times.

Secondly, and what is in our perception the *fundamental reason*, firms do not collect and store all the necessary data for solving the ALBP automatically, because such data collection is too expensive. In the first line, information about *precedence relations* between the tasks has to be specified. Precedence relations show that certain tasks have to be completed before other tasks can be started. E.g., every tire has to be mounted before it can be fixed

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with the screws. All the precedence relations must be met to guarantee feasible line balances. At firms, the knowledge about the precedence relations exists implicitly in the heads of the planners, who generate feasible plans for their segments of the assembly line. Hence, methods for effective and cost-efficient collecting of this implicit knowledge are of the highest importance, in order to be able to balance assembly lines (semi-) automatically.

Klindworth, Otto, and Scholl (2012) analyzed the literature for the existing manual and (semi-)automated methods for gathering information to identify ALBPs. All the methods are time- and cost-intensive, fault prone or they miss important information and, thus, do not guarantee feasible solutions of the ALBP. Generalizing the ideas of Minzu, Bratcu, and Henrioud (1999) and Altemeier (2009, chap. 5.2), Klindworth et al. (2012) developed a new approach, which we call *basic learning graph concept* (BLGC), that leads to applicable for practice solutions. This concept uses former (feasible) production plans that are available and documented in firms. From those available plans, the concept allows generating *new feasible* production plans even if precedence relations or independencies between pairs of tasks are evaluated only *partially*, i.e., no high initial investment is required to implement the approach. Moreover, the concept is *expandable* and new information can be easily integrated to produce feasible production plans of even better quality.

However, as we will show in this paper, the performance of BLGC worsens significantly at certain conditions which are widespread on real-world assembly lines. To overcome this disadvantage, we propose the new *extended learning graph concept* (ELGC). ELGC integrates further valuable information available in practice and the results of an effective interview technique. We will show that easy but structured, focused questions suffice to efficiently collect enough information for formulating a meaningful ALBP *very close* to the underlying but unknown problem. Elaborated computational experiments (Section 6) show that ELGC outperforms BLGC dramatically, especially in the initial time, where only few production plans are available. Although the difference between two approaches gets smaller with each additional production sequence, after 20 input production sequences (or about 20 months) BLGC still cannot catch up with ELGC approach. Even then, ELGC brings by 2.5 percentage point more improvement than BLGC compared to the best historical production plan.

Our findings further contribute to close the gap between theory and practice. Since assembly line planners will be able to implement the balancing methods proposed in the literature in real-world planning situations, a feedback to the research community about the requirements on models and methods will lead to adjustments and refinements in this field. The concepts and findings in this paper can be applied to all the generalizations of assembly line balancing problems as well as to other problems for which precedence relations between operations must be considered, such as project scheduling problems. Thus, we contribute to a wide range of well investigated problems in the literature that currently cannot be solved automatically in the real world because of the lacking input data.

We will proceed as follows. In Section 2, we shortly present BLGC. Section 3 describes two important constituent parts of the new approach ELGC. These are the incorporation of the known hierarchical and modular structure of products and assembly tasks as well as the implementation of interviews. In Section 4, we introduce interview enhancements that improve the effectiveness of interviews by several times. The overall logics of ELGC and implementation advice is presented in Section 5. Our conclusions are confirmed by extensive tests provided in Section 6. We give a conclusion and an outlook in Section 7.

2. Problem description and literature overview

In this section, we give a brief introduction into assembly line balancing (Section 2.1) and the learning precedence graph approach BLGC (Section 2.2).

2.1. Assembly line balancing in the literature and in manufacturing

The basic, or simple, version of the assembly line balancing problem (SALBP) is to assign a set of n non-dividable tasks to stations, which are ordered sequentially along a paced line, according to some objective. Each workpiece is available at each station for a given time, called the *cycle time* c. In this time span, a worker or a machine at each station fulfills the tasks at the workpiece. For each task $j \in V$, $|V| = n$, a deterministic time t_j is determined, e.g., by MTM-technique (see Hu et al., 2011). The sum of the tasks' times, which are assigned to one station, must not exceed the cycle time c. Further, the tasks underlie precedence relations because of technical or organizational restrictions. All information about tasks, inclusive their times and precedence relations, is stored in the directed and acyclic precedence graph $G = (V, E)$. In this graph each node $j \in V$ stands for a task with the weight t_j, and the set of arcs E marks the precedence relations, i.e., $(i, j) \in E$ if and only if task i is a direct predecessor of j. From E we can easily derive the transitive closure E^I, the set of direct and indirect (*transitive*) precedence relations. The *order strength* of graph G, $OS(G) = \frac{2\cdot|E^I|}{|V|\cdot(|V|-1)}$ refers to the degrees of freedom for planning. If $OS = 1$, a graph is highly restricted and only one task sequence can be generated, while it is possible to derive $|V|!$ different task sequences from graphs with $OS = 0$ (see, e.g., Scholl, 1999, chap. 2).

Fig. 1 shows a precedence graph where solid lines mark the direct precedence relations and the dotted lines the indirect ones. The order strength of the presented graph G is $OS(G) = \frac{2\cdot8}{6\cdot5} = 0.5$. If we set cycle time c at 5, then an optimal solution will require three stations: $\{1, 3\}, \{4, 5\}, \{2, 6\}$. The *idle time* of a station is the time during the cycle, where no tasks are performed. For example, the idle time of the first station with tasks 1 and 3 in the station load is $c - t_1 - t_3 = 5 - 4 - 1 = 0$.

Different objective functions in the formulation of SALBP exist. Since it is prevalent in most real-world problems, we refer to the objective "minimizing the number of stations m for a given cycle time c" throughout the article. Nevertheless, our approaches and findings can be transferred to models with other objectives as well as to most other versions of generalized ALBP.

Although task times are assumed to be deterministic for SALBP and most versions of ALBP, they may vary over time in practice. Due to this, for the current task assignment, the cycle time may be violated at some stations. Therefore re-balancing is regularly performed at firms. On the one hand, process planners provide updates in their MTM-analyses, e.g., whenever new handling tools or new ideas of process development are implemented. On the other hand, task times vary because of changes in the model mix assembled at the assembly line due to fluctuations in demand. For example, the option "air conditioner" may be chosen for half of all the ordered cars in the first period and for a fifth of the orders in the second period. A common practice in planning and modeling

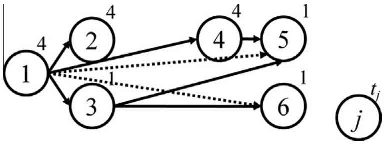

Fig. 1. Precedence graph G.