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Balancing modular transfer lines with serial–parallel activation of spindle heads at stations

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ABSTRACT

The paper deals with an as yet unexplored combinatorial optimization problem concerning balancing complex transfer lines in the machining/process environment. In contrast to similar problems for assembly lines, in transfer line balancing, tasks are grouped into blocks. All tasks of each block are executed simultaneously (in parallel) by one piece of equipment (spindle head). For the transfer lines considered in this paper, spindle heads at each station are activated in serial–parallel order. The set of all available spindle heads is known beforehand. Precedence, cycle time, compatibility, and parallelism constraints for the blocks and tasks are given. The line investment cost is estimated by the sum of block and station costs. The problem is to assign all tasks (using the available blocks) such that all constraints are respected and line investment cost is at a minimum. This paper focuses on solving the problem via a branch-and-bound algorithm. An approach for obtaining an efficient lower bound is offered, based on a reduction of the initial problem to a set partitioning problem. Computational experiments reveal that the proposed approach is efficient mathematically and can be used to solve practical transfer line design problems of a medium size.

1. Introduction

A great number of production systems are organized as an automated flow line. This increases production rate and minimizes production cost. In these lines, an item passes sequentially through all stations at a constant cadence. The maximum available work time per station (maximum time which a product can spend at each station) is limited by a given *cycle time*. The *line cycle time* is defined by the slowest station on a line.

An important problem of flow line design is line balancing. Historically, the line balancing problem has been studied in the assembly environment. This paper deals with line balancing in the machining/process environment which is called a Transfer Line Balancing Problem (TLBP).

Transfer machines or lines are designed for mass production of a single product (or a family of similar products) over a long exploitation time. Transfer lines represent "high automation" and they have large investment costs (sometimes hundreds of millions of euros).

A transfer line has a common transfer system (a conveyor belt). The movements of product items are synchronized. There are no buffers in between stations. When a part is loaded on a station, it is positioned and then, station spindle heads are activated in a fixed order.

The main feature of transfer lines is that the tasks (operations) are grouped into blocks. The tasks of each block are executed simultaneously (in parallel) by one piece of equipment (spindle head). The number of executed tasks is not as great as for assembly lines. As a rule, this number is from 40 to 200 tasks. Often, it is less than 100.

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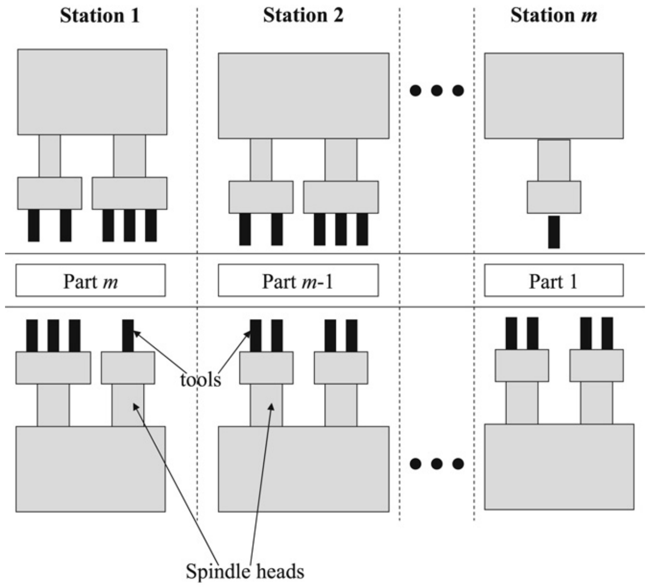

Fig. 1. A transfer line schema.

The advantage of transfer lines is they essentially reduce the amount of equipment and line cycle time, see [9,19]. The typical layout of a transfer line is presented in Fig. 1.

In Fig. 1 a station is defined by the corresponding part position and all the subsequent spindle heads. Several spindle heads can be installed at each station. Each spindle head is equipped with several tools. Each tool executes one or several tasks (if a combined tool is used). All tasks of a spindle head (a block) are executed simultaneously (in parallel). In contrast, the blocks are executed either sequentially, simultaneously or in a mixed order, this order is fixed (it defines a line configuration) and cannot been modified during the functioning of the line.

The activation mode (sequential, parallel or mixed) is fixed at the preliminary line design steps (before line balancing). Usually, a transfer line where blocks at each station are carried out simultaneously has more stations than the transfer line with sequentially activated spindle heads. However, the production rate of the former is appreciably faster than for the latter. Transfer lines having a mixed order of spindle head activation are a compromise between sequential or parallel modes.

Note that the choice of activation mode at stations is provided by mechanical engineers. This depends on many aspects (mechanical feasibility, required productivity, costs of equipment, …). The activation mode is an important parameter of this line balancing problem. For each type of activation mode, a specific line balancing model should be developed.

For the case of modular transfer lines which are composed of "standard" spindle heads, the set of all available spindle heads is given beforehand. This provides greater flexibility when a line is redesigned (as far as possible for transfer lines). The line investment cost can be estimated by the sum of station and block costs. The goal at the line balancing stage is to minimize investment cost.

This paper deals with an unexplored TLBP for modular lines where the set of all available spindle heads is given and spindle heads at each station are activated in a mixed (serial–parallel) order: certain blocks assigned to a workstation are executed in series, others in parallel. For each block, cost and execution time are known. The objective is to minimize the line investment composed of block and workstation costs. More precisely, it is necessary to choose a subset from the given set of available blocks and to find a partition of this subset to workstations so that the line investment cost is minimal. The obtained subset of blocks must cover all the tasks to be executed and must respect all constraints.

This paper is organized as follows. Section 2 presents an analysis of the literature. In Section 3 the notation and the formal problem statement are given. Section 4 deals with the relaxation of the TLBP at hand to a set partitioning problem. Also, an efficient algorithm to obtain a lower bound is suggested. A preprocessing procedure is discussed in Section 5. The branch-and-bound algorithm is presented in Section 6. An illustration of the key procedures of this algorithm via an example and numerical experiments are reported in Section 7. Conclusion remarks are given in Section 8.

2. Related works

Usually, the line balancing problem is studied for the assembly systems. A better known simple assembly line balancing problem of type 1 (SALBP-1) is a single-model deterministic problem. There is a single type of product and all tasks (operations) and precedence constraints are known. The tasks must be assigned to stations in such a way that cycle time and *precedence constraints* are respected and idle time is minimal. For SALBP-1, the idle time is minimal iff (if and only if) the number of stations is minimal as well, see [25].