Int. J. Production Economics 151 (2014) 186–194

Contents lists available at ScienceDirect

Int. J. Production Economics

journal homepage: www.elsevier.com/locate/ijpe

Minimizing setup costs in a transfer line design problem with sequential operation processing

Alexandre Dolgui [a], Sergey Kovalev [b], Mikhail Y. Kovalyov [c], Jenny Nossack [d], Erwin Pesch [d,*]

[a] LIMOS UMR CNRS 6158, Ecole des Mines de Saint-Etienne, 158, cours Fauriel, 42023 Saint-Etienne Cedex 2, France
[b] Transport and Traffic Engineering Laboratory, The French Institute of Science and Technology for Transport, Development and Networks, 25 avenue François Mitterrand, Cité des Mobilités, 69500 Bron, France
[c] United Institute of Informatics Problems, National Academy of Sciences of Belarus, 220012 Minsk, Belarus
[d] Institute of Information Systems, Faculty III, University of Siegen, 57068 Siegen, Germany

ARTICLE INFO

Article history:
Received 7 April 2012
Accepted 17 October 2013
Available online 24 October 2013

Keywords:
Reconfigurable transfer line
Line design
Line balancing
Setups
Integer linear programming
Complexity

ABSTRACT

Design problems constitute the first stage in developing a machining transfer line. This paper is concerned with a problem in which a transfer line has to be designed in an optimal way to produce parts of different types. Each part of a specific type requires a unique set of operations to be executed on the stations. Parts move along the stations in the same direction one after another in a given sequence, and a station is set up if at least one operation is executed on this station. Setup costs and times are part-type dependent. Each operation has its size, which is the number of standard tools required to perform this operation, and its processing time. Operations on the same part assigned to the same station are performed sequentially. Re-design, i.e., re-assignment of operations when switching from one type part to another is not allowed. Precedence relations are given on the superset of all operations. There is an upper bound on the total size of operations assigned to the same station, and an upper bound on the time that a part of a given type stays on the same station for all types. The primary objective is to minimize the number of stations. The secondary objective is to minimize the total setup cost. We establish computational complexity of various special cases of this problem, present constructive heuristic algorithms, integer linear programs as well as computational results. These results are applicable in designing transfer lines for mechanical parts manufacturing by multi-spindle turret heads in situations where the station costs are the primary concern and the station setup costs are the secondary concern of the designer.

1. Introduction

Manufacturing of mechanical parts constitutes a major cost of the final product in automotive and machine building industries. Modern technologies suggest that the parts are processed on transfer lines consisting of reconfigurable stations equipped with a range of processing tools. This paper studies a problem encountered in a company that produces machining lines for mass production of mechanical parts of several given types. Major operations are making holes of different depth, diameter, shape and type of carving in blank parts (billets). They are performed by rotating tools mounted on multi-spindle turret heads of limited capacity. The heads are stations of the transfer line and their cost, depending on their number, is the overwhelming part of the overall line cost, and it has to be minimized at the line design stage. As there can be many line configurations with the same number of stations, a secondary criterion can be addressed, which is minimizing the total station setup cost in our practical application. Problem details are given below.

A paced transfer line consisting of several stations has to be designed to produce parts of f types, $f \geq 2$. Parts move along the stations in the same direction one after another in a given sequence. Let $F = \{1, \ldots, f\}$. Each part of type $v \in F$ requires each operation of a given set N_v to be executed exactly once on the line. Operations of the set N_v are called *type v operations*. Different sets N_v can contain common operations, thus, the same operation can be of different types. Let $N = \cup_{v=1}^{f} N_v = \{1, \ldots, n\}$ denote the superset of all the required operations, and let T_i denote the set of types of the operation $i \in N$, i.e., $T_i = \{v | i \in N_v,\ v \in F\}$.

Operations of the same type assigned to the same station are performed sequentially. A setup time t_v and cost a_v are associated with all operations of type v assigned to the same station, $v = 1, \ldots, f$. Each operation $i \in N$ is associated with its *size* s_i, which is the number of standard tools required to perform this operation, and processing time p_i. The total size of all operations (total

* Corresponding author. Tel.: +49 271 7402420.
E-mail addresses: dolgui@emse.fr (A. Dolgui), sergey.kovalev@ifsttar.fr (S. Kovalev), kovalyov_my@newman.bas-net.by (M.Y. Kovalyov), jenny.nossack@uni-siegen.de (J. Nossack), erwin.pesch@uni-siegen.de (E. Pesch).

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http://dx.doi.org/10.1016/j.ijpe.2013.10.013

number of tools) assigned to the same station should not exceed the *station capacity* r. The total processing time of all operations of the same type v assigned to the same station plus corresponding setup time should not exceed U_v, $v=1,\dots,f$. This is equivalent to saying that the total processing time of type v operations assigned to the same station should not exceed $U_v - t_v$ for all stations and types. Therefore, we simplify the problem formulation by re-setting $U_v := U_v - t_v$, $v \in F$, and assume that there are no setup times.

Note that U_v can be viewed as an *upper bound on the line cycle time* for parts of type v if they are processed contiguously. Therefore, the corresponding constraints are cycle time constraints if parts of all types are sequenced according to the *Group Technology* principle. This principle implies that all products of a certain type enter the line one by one and there are no products of another type in between them. It is widely used in manufacturing, see Mitrofanov (1966), Opitz (1970), Tatikonda and Wemmerlöv (1992), Ham et al. (1985), Wemmerlöv and Hyer (1989), Hadjinicola and Ravi Kumar (1993), and Gunasekaran et al. (2001). It is also assumed in the practical application which motivates our studies.

The objective of the line design is to determine the number of stations, assign operations of the set N to the stations and sequence the stations. Re-design, i.e., re-assignment of operations when switching from production of one type part to another, is not allowed.

Binary *precedence relations* are given on the superset N. If operation $i \in N$ precedes operation $j \in N$, then i and j are of at least one same type, j cannot be assigned to a station preceding the station of i, and if j is assigned to the station of i, it cannot be executed earlier than i. Precedence relations are represented by a directed acyclic graph $G = G(N, A)$, in which there is an arc $(i,j) \in A$ if and only if i precedes j. Precedence relations characterize the technological process. They can be defined separately for each part-type, but since re-design is not allowed, type dependent precedence relations must be consistent. Hence, they can be defined on the superset N.

Note that operations assigned to the same station can always be feasibly ordered with respect to precedence constraints, for example, by the *topological ordering* procedure of Kahn (1962).

Let x_v denote the number of setups for any single part of type v, $v = 1,\dots,f$. A decision has to be made with respect to the number of stations, k, an assignment of the operations to the stations $1,\dots,k$ such that the capacity bound r and the line cycle time bounds $U_1,\dots,U_f$ are satisfied and the following two objectives are addressed. The primary objective is to minimize the total number of stations, which is standard for the line balancing problems. The secondary objective is to minimize the total setup cost, $a_1x_1 + \dots + a_fx_f$. We denote the problem with only the primary objective as $P_{seq}(prec|k)$ and with the two ordered objectives as $P_{seq}(prec|k, cost)$. The latter minimizes the total setup cost on the set of optimal solutions for the former. Let (k^*, c^*) denote optimal solution values for the problem $P_{seq}(prec|k, cost)$, where k^* is the minimal number of stations and c^* is the minimal total setup cost for solutions with k^* stations.

To eliminate infeasible instances, we assume without loss of generality that $s_i \le r$ and $p_i \le U_v$ for operation i of type v over all operations and types. With these assumptions, a feasible solution to the problem $P_{seq}(prec|k, cost)$ always exists.

Any solution for this problem can be represented as a table, in which columns represent stations and a rectangle in the column represents an operation, say i, followed by its types (set T_i) in brackets. An operation of an upper rectangle is assumed to be performed earlier than an operation of a lower rectangle. The size of the operation is the number of rows the rectangle spans. For example, consider a problem with 16 operations of 3 types, capacity $r=6$, and no precedence constraints. Table 1 presents a solution for this problem with the minimum number of stations $k^* = 4$ and the total setup cost $3a_1 + 3a_2 + 3a_3$ because each type is present on 3 stations.

Note that minimizing the total setup cost is not sufficient to minimize the number of stations and vice versa. For the previous example, the total setup cost can be diminished by increasing the number of stations, see Table 2.

As we already mentioned, problem $P_{seq}(prec|k, cost)$ was observed in a company producing machining lines. Such a line is designed for the mass production of several types of a part according to the Group Technology principle. The proportion between the quantities of parts of different types is known. For example, for a_1 parts of type 1 it is required to produce a_2 parts of type 2 and a_3 parts of type 3. In our model, these ratios can be considered as relative setup costs.

Each station of the line is equipped with a single multi-spindle turret head, see Battaïa et al. (2012), where several tools such as borers, milling cutters, grinding heads and chamfering mills are mounted to execute a *composite operation* of boring, milling, grinding or chamfering on a blank part. A composite operation is a collection of single *sequential* operations whose precision can be lost if the part is moved between them. The result of the composite operation is one or several flat, threaded or chamfered holes of certain depths and diameters.

The cutting tools of a multi-spindle turret head are activated sequentially. Kovalev et al. (2012, 2013) studied a problem with the spindle heads which are activated simultaneously. This difference implies that the station processing time is equal to the maximum of operation processing times in the former studies and it is their sum in the studies of this paper. It further implies a different effect of precedence constraints and easier handling of the line cycle time constraints in the former studies.

A magazine for the required tools is associated with each multi-spindle turret head. All magazines have the same capacity, r. When a part of a specific type comes to a station, there is a setup. The unnecessary tools are dismounted from the multi-spindle head and returned to the magazine. Then, required tools are sequentially taken from the magazine, mounted on the multi-spindle head, perform their composite operations, dismounted and are returned to the magazine. The processing time of any composite operation spans the time from dismounting the unnecessary tools till finishing the operation. Practical observations show that dismounting of a tool takes about a second and it is tool independent, while its mounting ranges between several seconds and several minutes and it is tool dependent. Therefore, we reasonably assume that tool dismounting times are negligibly

Table 1
Four stations, $cost = 3a_1 + 3a_2 + 3a_3$.

<table>
<tr><th>Capacity units</th><th>St. 1</th><th>St. 2</th><th>St. 3</th><th>St. 4</th></tr>
<tr><td>1</td><td rowspan="3">2(1,2,3)</td><td>1(1,2)</td><td rowspan="2">3(1)</td><td>12(2)</td></tr>
<tr><td>2</td><td rowspan="3">4(1,2)</td><td>13(2)</td></tr>
<tr><td>3</td><td>5(1)</td><td>14(2)</td></tr>
<tr><td>4</td><td rowspan="2">7(1,2,3)</td><td>6(1)</td><td>15(2)</td></tr>
<tr><td>5</td><td rowspan="2">10(1,2)</td><td>8(3)</td><td rowspan="2">16(3)</td></tr>
<tr><td>6</td><td>9(2,3)</td><td>11(3)</td></tr>
</table>

Table 2
Five stations, $cost = 3a_1 + 3a_2 + 2a_3$.

<table>
<tr><th>Capacity units</th><th>St. 1</th><th>St. 2</th><th>St. 3</th><th>St. 4</th><th>St. 5</th></tr>
<tr><td>1</td><td rowspan="3">2(1,2,3)</td><td>1(1,2)</td><td rowspan="2">3(1)</td><td>12(2)</td><td>8(3)</td></tr>
<tr><td>2</td><td rowspan="3">4(1,2)</td><td>13(2)</td><td>11(3)</td></tr>
<tr><td>3</td><td>5(1)</td><td>14(2)</td><td rowspan="2">16(3)</td></tr>
<tr><td>4</td><td rowspan="2">7(1,2,3)</td><td>6(1)</td><td>15(2)</td></tr>
<tr><td>5</td><td rowspan="2">10(1,2)</td><td rowspan="2">-</td><td rowspan="2">-</td><td rowspan="2">-</td></tr>
<tr><td>6</td><td>9(2,3)</td></tr>
</table>