Assembly line balancing with equipment requirement and parallel workers:
an heuristic algorithm

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Abstract: Production plant design is a key-aspect to compete in the manufacturing industry. Traditional approach aim is to define a certain system configuration that maximizes a specific performance parameter. Furthermore the literature traditionally focuses on the modeling of the aforementioned plant, rather than proposing techniques easy to be exploited in real industry applications. Aim of this paper is to propose an assembly line balancing algorithm that considers simultaneously several performance indices and able to design a complex industry system.

Purpose
Balancing assembly line means to assign assembly tasks to several stations, respecting precedence constraints so as to complete the final product with the minimum expense of resources. Aim of this paper is to suggest an heuristic algorithm to solve the balancing problem considering three important real aspects. First, each task, or elementary assembly operation, requires specific equipment that differ from task to task. Second, large products (e.g. cars, automatic machines or white goods), can be handled by more than one worker contemporarily processing different tasks in the same station (parallel workers). And third, parallel workers operating in the same station, can generate space or handling conflicts, considering task mounting position.

Design/methodology/approach
An heuristic algorithm is presented to design assembly lines considering a set of algorithm configuration parameters: task ordering priority rule, maximum number of parallel workers per station, maximum worker idle time allowed and maximum number of equipment per worker: varying the value of each parameter is possible to determine different assembly line configurations. A Visual Basic application is developed to evaluate such configurations with respect to four significant key performance indices: equipment requirements, employed workers, workers saturation, number of assembly stations. The best solution can be chosen considering plant priorities.

Originality/value
The literature proposes several models that deal with the assembly line balancing problem, nevertheless few of them investigate real world systems. This paper proposes a balancing heuristic algorithm considering the distinctive features of real assembly lines, e.g. equipment requirement. This significant characteristic is usually ignored by the literature, neglecting the equipment duplication. Practitioners and plant managers can benefit from this algorithm exploiting its distinctive feature: the generation of several assembly line configurations. The different solutions can be compared using the key performance indices assessed by the algorithm. The analyst can select the final configuration considering the most relevant assembly line features with respect to the specific plant conditions.

Keywords: Assembly Line Balancing, Parallel workers, Equipment requirement, Assignment restriction, Heuristic algorithm.

1. Introduction and literature review
Assembly lines are the traditional flow-oriented production systems. Aim of the Assembly Line Balancing Problem (ALBP) is to assign a set assembly operations (tasks) to the work stations (Baybars, 1986). Traditional purpose of the ALBP is to minimize the stations number, with respect to the cycle time, that is the time available for each station to complete all tasks assigned (Rekiewicz et al., 2002, Shubin and Dar-el, 1990). The order to perform the tasks along the stations must be in accordance with the precedence diagram. It represents the assembly precedence constraints, due to technological
or organizational restrictions and defines the sets of direct predecessors and successors for each task (Scholl, 1999). Most of the literature over the years has modelled and solved the Simple Assembly Line Balancing Problem. This problem is characterized by several assumptions: paced line with fixed cycle time, deterministic task times, no assignment restriction besides the precedence constraints, serial line layout, all stations are equally equipped of resources (Scholl and Becker, 2006). Nevertheless real world ALBPs present particular characteristics that need a further effort in the modeling phase (Boysen et al., 2007).

**Assignment restriction.** In addition to the precedence diagram, several other restrictions can force or forbid certain tasks to be assigned to a specific station or particular tasks combinations (Scholl et al., 2010):
- Station restriction forces or forbid particular tasks to be assigned or not to certain stations. This constraint usually depends on the impossibility to install the needed equipment in different stations. Some resources have to be necessary installed in particular stations, on the contrary other resources can not be duplicated (Johnson, 1983).
- Incompatible tasks are elementary operations that can not be contemporary assigned to the same station, e.g. a drilling operation is incompatible with dimensional control (Agneti et al., 1995, Bautista et al., 2000).
- Large products (e.g. cars, automatic machines, white goods) require different mounting positions to be handled by workers. As suggested by Lapierre and Ruiz (2004) each position enables certain tasks to be assigned to the station and disables some others.

**Equipment requirement.** Assembly operations could require specific tools, machines or worker technical capabilities to be performed (Boysen et al., 2007):
- Rekiek et al. (2002) and Bukchin and Tzar (2000) propose algorithms to assign a set of resources to each station and allow it to handle a certain group of tasks. Similarly, Boysen and Fleischner (2008) and Nicosia et al. (2002) treat this problem considering which device has to be assigned to each station. Each device type is able to perform different tasks and consequently it defines a multipurpose flexible station.
- A complementary approach suggested by Amen (2000) considers the worker specialization as a constraint for the tasks to be assigned. Each worker can handle only the tasks that require a lower or equal specialization level.
- The branch and bound algorithm developed by Bukchin and Rubinovitz (2003) overcomes the distinction between human and equipment resources. They define several equipment alternatives that has to be chosen to define a station. A station is classified accordingly to its intensity of labor and equipment.

**Parallel workers.** Assembly lines that have to deal with large products can benefit from assigning multiple workers per station. They execute different tasks simultaneously respecting the mounting positions, avoiding any interference (Boysen et al., 2008):
- The first study on parallel worker is carried out by Akagi et al. (1983). He suggests a two-phase heuristic method for small scale problem. In the former phase the tasks are assigned to the stations, enabled to have one or more workers. In the latter one, for each station, the allotted tasks are divided among the workers.
- The problem dimension is partially overcame by Bukchin and Masin (2004). They present a backtracking branch and bound algorithm and a related heuristic version for large scale problems. Nevertheless tasks partitioning among workers of the same station is not considered.
- Cevikcan et al. (2009) propose an integer programming model that assigns the tasks to each worker that belongs to a station. Due to the complexity of the model an heuristic algorithm is developed for large scale problems.

In the last years various researchers deal with parallel workers assembly line balancing problem:
- Dimitriadis (2006) establishes the term multi-manned station, to indicate a station with parallel workers that simultaneously handle different tasks.
- Roshani et al. (2013) and Fattahi et al. (2011), as the previous author, validate respectively their simulated annealing and ant colony heuristic algorithms exploiting the problems collected by Talbot and Patterson (1984). This data set presents small and medium size problems, since only one precedence diagram has more than 100 tasks (Arcus, 1963).
- Big size problems are tackled by Becker and Scholl (2009) and Kellegöz and Toklu (2012). The authors suggest two different branch and bound procedures able to define the optimal solution for small and medium size ALBP. For large scale one an heuristic version of the procedures is developed.

Nevertheless all these approaches are limited: the main lack is the problem dimension of the analyzed case studies that is always limited in term of task number. In fact, the aforementioned approaches are tested only for two big size problems: Bartholdi (1993) and Lee et al. (2001). They propose two scenarios with more than 100 tasks, the largest available in the literature. However these are too simple if compared to real world problems.

In this context, aim of this paper is to model and define an effective solution procedure for the balancing problem well applicable in the real world considering assignment restriction, equipment requirement, parallel workers and numerous tasks. A procedure able to solve ALBP handling all these aspect simultaneously is missing in the literature and it is strongly encouraged by industries (Falkenauer, 2005).

The remainder of this paper is organized as follows: Section 2 proposes a Mixed Integer Programming model for the Assembly Line Balancing Problem with Parallel
Worker and Equipment Requirement (PAWERALBP). Section 3 analyzes an heuristic algorithm as an effective solution procedure for the balancing of these assembly lines. Section 4 adopts the algorithm presented to solve a well-known problem in the literature, proposing the key inputs and the results as well as the assembly line configuration. Finally Section 5 proposes the conclusions and suggests further research opportunities.

2. Mixed Integer Programming model for PAWERALBP

A Mixed Integer Programming (MIP) model is developed for the balancing of assembly lines with assignment restriction, equipment requirement and parallel workers.

Indices

- \( j, h \) indices for task
- \( w, v \) indices for worker
- \( k \) index for station
- \( m, l \) indices for mounting position
- \( e \) index for equipment

Decision variables

\[
x_{iw} = \begin{cases} 1, & \text{if task } j \text{ is assigned to worker } w \\ 0, & \text{otherwise} \end{cases}
\]

\[
z_{wk} = \begin{cases} 1, & \text{if worker } w \text{ belongs to station } k \\ 0, & \text{otherwise} \end{cases}
\]

\[
y_{ew} = \begin{cases} 1, & \text{if worker } w \text{ is equipped with equipment } e \\ 0, & \text{otherwise} \end{cases}
\]

\( s_j \) starting time of task \( j \)

\( u_{ij} \) time at the same station

Parameters

- \( c \) cycle time
- \( t_j \) operation time of task \( j \)
- \( p_{hj} \) immediate predecessor of task \( j \)
- \( b_{je} \) equipment to be handled
- \( d_{jm} \) handled in mounting position \( m \)
- \( a_{ml} \) compatible mounting position \( m, l \)
- \( mw \) maximum number of workers per station
- \( me \) maximum equipment size per worker
- \( mi \) maximum worker idle time

Objective function

\[
\text{Min } \Phi = \sum_w \sum_k z_{wk}
\]

Constraints

\[
\sum_k z_{wk} \leq 1 \quad \forall w
\]

\[
\sum_w z_{iw} = 1 \quad \forall j
\]

\[
x_{iw} \leq \sum_k z_{wk} \quad \forall w, \forall j
\]

\[
x_{iw} \cdot b_{je} \leq y_{ew} \quad \forall w, \forall j, \forall e
\]

Objective function (1) forces to minimize the workers number of the entire assembly line. Constraint (2) ensures that each worker belong exclusively to one station. Constraint (3) forces each task to be assigned uniquely to one worker. Constraint (4)fastens the tasks to be assigned only to the workers that belong to any station. Constraint (5) enables a worker to handle a task only if equipped properly.

Constraints (6) and (7) limit the task handling period: the former ensures that any assembly operation has to be finished within the cycle time, the latter guarantees the precedence relations among the tasks. Constraints (8), (9) and (10) represent the restrictions of the environment where the line has to be installed, as well as the designer preferences. The maximum number of worker per station could depend on space or interference constraint, the maximum equipment size per worker preempts the resource duplication and the maximum worker idle time ensures a certain workers saturation.

Constraints (11)-(15) ensure the feasibility of the balancing, considering that several tasks are handled simultaneously by different workers in the same station. Constraint (11) guarantees that two tasks can not precede each other simultaneously. Constraint (12) limits the handling period of the tasks that has an additional precedence relation represented by the decision variable \( u_{ij} \). Constraint (13) ensures that each worker can handle one task at a time. Constraint (14) guarantees each mounting position to receive one task at a time. For the duration of any task that requires a mounting position that disables some others, constraint (15) disables the incompatible mounting positions.

3. Heuristic algorithm for PAWERALBP

The MIP model previously described for PAWERALBP is NP-hard, consequently an heuristic algorithm for balancing of this category of assembly line is developed. The algorithm opens one station at time, determines the number of workers allocated to it, the equipment and the tasks assigned to each worker. Figure 1 presents how the generic k-th station is designed.
For each k-th station the algorithm selects one worker at time (r) and evaluates the tasks assignment considering each cycle time unit of time (i) consecutively, both for workers (in, ir) and for mounting positions (im, i).

The tasks available to be handled at a certain i-th instant (AT) are decreasing ordered with respect to their positional weight or resource index (ri), whose value is as high as the task require equipment already assigned to the worker considered and depends on parameters na and nb. Considering the ordered AT, one task at time is evaluated to be assigned at instant i, to the required mounting position m and to worker r. A task is assigned if it can be completed within the cycle time, if the worker, the mounting and the incompatible positions are available for the entire task duration and if the worker equipment size, considering old and new resources, is within the bound. The task assignment involves the updating of the worker equipment (yr), available task set (AT), worker, mounting position and tasks available instants (in, im, sj), as well as new worker r to consider for handling operation. He is the one with the highest idle time.

If any available task is assignable to worker r at instant i, worker time index ir will be increased by one unit of time and the assignment evaluation repeated. At time that ir is greater than cycle time the worker considered is replaced by the one with the highest idle time and index ir is set to 0.

The algorithm ends after that all workers and available tasks have been evaluated. However if the maximum worker idle time constraint does not hold even for one worker, the maximum number of worker per station is decreased by one and the algorithm computed again.

The algorithm is implemented in a Visual Basic application to facilitate the assembly line balancing. Varying the value of the algorithm parameters (mw, me, mi, na, nb and available task ordering priority rule) is possible to determine different assembly line configurations and evaluate them with respect to four significant key performance indices: equipment requirements, employed workers, workers saturation and number of assembly stations.

3. Case study and results

To test the proposed algorithm the 148 tasks ALBP presented by Bartholdi (1993) is used with some modifications: tasks equipment requirement are shown in Table 1, whereas Table 2 illustrates tasks mounting configurations and evaluate them with respect to four significant key performance indices: equipment requirements, employed workers, workers saturation and number of assembly stations.
bound), indeed the sum of workers idle time is lower than the cycle time. Furthermore the algorithm fastens the workers utilization and prevents the equipment duplication: 13 workers on 15 are distinguished by an idle time lower or equal to 6% of cycle time and just 6 workers on 15 are equipped with all the available resources (X, Y, Z).

<table>
<thead>
<tr>
<th>Tasks</th>
<th>Equipment required</th>
</tr>
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<tbody>
<tr>
<td>1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17</td>
<td>X</td>
</tr>
<tr>
<td>18 19 20 21 22 23 24 25 26 27 28 29 30 31</td>
<td>Y</td>
</tr>
<tr>
<td>32 33 34 36 41 42 48 49 55 56 57 58 59</td>
<td>Z</td>
</tr>
<tr>
<td>60 61 62 63 64 65 66 67 68 69 70 71 72 73</td>
<td>X, Y</td>
</tr>
<tr>
<td>74 75 82 83 84 85 86 87 88 89 90 91 92 93</td>
<td>Z</td>
</tr>
<tr>
<td>94 95 96 97 98 101 102 103 104 105 110</td>
<td>X, Y, Z</td>
</tr>
<tr>
<td>111 114 115 120 121 122 123 124 125 126</td>
<td></td>
</tr>
<tr>
<td>127 128 129 130 135 136 137 138 139 140</td>
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<td>143 146 147 148</td>
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<td>35 37 38 39 40 43 44 45 46 47 112 113</td>
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<tr>
<td>141 142 144 145</td>
<td></td>
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<td>50 51 52 53 131 132 133 134</td>
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</tbody>
</table>

4. Conclusions and further research

This paper deals with the balancing of assembly line that presents real world characteristics such as assignment restriction, equipment requirement, parallel workers and numerous tasks.

A mixed integer programming model is proposed: objective function forces to minimize workers number subject to equipment size, incompatible mounting positions, workers idle time and number of workers per station constraints.

Due to model intrinsic infeasibility (NP-hard) an heuristic algorithm is developed to solve the Assembly Line Balancing Problem with Parallel Worker and Equipment Requirement (PAWERALBP). The algorithm is implemented in a Visual Studio application: varying the algorithm parameters is possible to obtain several assembly line configurations and evaluate them with a set of key performance indices.

The aforementioned algorithm is tested with a real assembly line balancing problem proposed by the literature. The suggested line configuration is distinguished by the minimum number of worker, a negligible workers idle time and limited equipment duplication.

Further research has to validate the algorithm with additional real world case studies, even with a greater number of tasks, as well as to propose a cost objective functions, to consider simultaneously worker salary, equipment purchase and station cost.
References


