Multi-manned production Lines with labor Concentration

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Abstract: In many real world assembly lines the work-piece is of large size and there are several workers operating on the same work-piece in each station. This type of lines is called multi-manned assembly line (MAL). In the previous studies on MALs it is assumed that task times are deterministic and independent of other factors. But in many real world MALs task time are affected by other factors; one of these factors is the number of operators in the station. In other words intense concentration of workers in a station increases the task processing times because of operators blocking each other or waiting times for facilities to be released by other operators in the station. In this paper the multi-manned assembly line balancing problem in which task times are dependent on the number of workers in the station is introduced. A mathematical model is developed to solve this problem with the aim of minimizing the number of workers as the first objective and number of stations as the secondary objective. To illustrate the proposed model a numerical example is solved using Lingo 11 software.

Key words: Production line; Multi-manned workstation; labor concentration;

INTRODUCTION

Assembly lines are flow-oriented production systems used to produce high volume of a single product and even gain importance in producing low quantity of customized products. An assembly line consists of m consecutive stations arranged along a conveyor belt or similar material handling equipment. The conveyor carries the production units through the line with a constant transportation speed. The production rate is determined by the cycle time which is the time between completions of two consecutive production units. The cycle time restricts the duration of the work content of each station in the line. The total work needed to produce the final commodity is divided into n elementary operations V = {1, 2... n}, these elementary operations are called tasks. Every task j requires tj units of time to be performed; this duration is called task time. In addition, there are some precedence relations between the tasks. These precedence relations can be presented in a precedence graph, vertices of this graph represent the tasks and every arc represents a precedence relation between task i and j, in other words each arc (i,j) indicates that task j can’t be started before finishing task i.

The decision problem of assigning tasks to stations with the aim of optimizing some objective functions is called assembly line balancing (ALB) problem. Simple assembly line balancing problem (SALBP) is the most studied problem in the field of ALB and has the following assumptions: (Baybars, 1986; Scholl and Becker, 2006; Scholl, 1999)

- Mass production of one homogenous commodity.
- Given production process.
- Paced line with a fixed cycle time C.
- Each task j has a Deterministic and integer operation time tj.
- No assignment constraints besides precedence constraints.
- Serial line layout with m stations.
- All stations are equally equipped with respect to machines and workers.
- Maximize the line efficiency: Eff = \( \frac{t_{\text{sum}}}{m \times C} \) in which m is the number of stations and is the sum of processing time of all tasks.

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Since the assumptions of SALBP are very restrictive with respect to real world assembly lines, researchers have recently focused on modifying or releasing some of them. The resulting problems are called generalized assembly line balancing problems (GALBPs) (Boysen et al, 2007).

Several generalizations have been considered for the ALBP. Some examples are considering U-shaped assembly lines balancing (Miltenburg and Wijngaard, 1994), parallel workstations (Buxey, 1974), two sided assembly lines (Bartholdi, 1993) and considering process alternatives (Pinto et al, 1983). Some recent surveys of generalized assembly line models are Erel & Sarin, 1998; Scholl, 1999; Rekiek et al, 2002 and Scholl & Becker, 2006.

In many real world assembly lines the work-piece is of large size. Therefore there can be more than one worker working on the same work-piece in each station. This resulted in considering multi-manned assembly line balancing problem (MALBP), which is first introduced and modeled by Dimitriadis, 2006. In a multi-manned assembly line balancing problem (MALBP) more than one worker can be assigned to each station. MALBs have several advantages over simple assembly lines. Some examples of these advantages are reducing the length of line, the cycle time, the cost of tools and fixtures, material handling and setup times (Fattahi, 2011).

Due to the high competition in the production environment, reducing the production overheads and increasing the utilization of current resources are very important issues for manufacturing managers. Therefore reducing the number of stations by parallel working of several operators in multi-manned workstations to reduce the costs of facilities can be beneficial to obtain these aims. On the other hand reducing the number of stations result in reducing the length of the line and better utilization of the current space specially if there are space restrictions due to building design. Additionally an assembly line with lower number of stations result in reducing the throughput time and work in process which is of high importance for production managers.

In spite of the fact that MALBs are very common in real world assembly line systems, very few research papers have considered multi-manned assembly line balancing problems. The most related problem considered in the literature of ALB is the two-sided line proposed by Bartholdi, 1993. In a two-sided line there are two serial lines in parallel. Instead of single stations, pairs of opposite stations on either side of the line work in parallel on the same work-piece. The distinction between this problem and the problem considered in this paper is that in the problem considered in this paper there may be more than two workers in each station and these workers may perform tasks on either sides of the work-piece. There are some studies considering collaboration of many workers on the same product and the same task to reduce the cycle time. This situation is different from the MALs in which several workers carry out different tasks on the same work-piece. Also the problem considered in this study is different from problems that consider parallel stations in which many workers carry out the same tasks on different work-pieces (Buxey, 1974; Akagi et al, 1983; Pinto et al, 1981). Dimitriadis, 2006, addressed the multi-manned assembly line balancing problem (MALBP) for the first time. He developed a heuristic assembly line balancing procedure to solve the problem. Cevikcan et al, 2009, presented a mathematical programming model to create assembly physical multi-manned stations in mixed model assembly lines. They also proposed a scheduling-based heuristic to solve the problem. Chang & Chang, 2010, discussed a mixed-model assembly line balancing problem with multi-manned workstations and developed a mathematical model for the mixed-model assembly line balancing problem with simultaneous production (MALBPS) to decide the optimal number of workstations. They also developed a coding system, Four-Position Code (FPC), to re-code the tasks to deal with this issue, and provided a computerized coding program written in C++ to generate those FPCs. Fattahi et al, 2011, proposed a mixed integer programming model for MALBP. Since the MALBP is NP-hard, they also developed an ant colony meta-heuristic approach to efficiently solve the medium- and large-size scales of this problem.

In this paper task times are assumed to be dependent on the number of workers in the station. In the previous studies on MALBP it is assumed that the number of workers assigned to a station doesn’t have any effect on the duration of the tasks assigned to it. The number of workers in a station is constrained by the maximum feasible ‘worker concentration’. This value is provided by the system designer according to the product dimension. But in many real world assembly lines the number of workers in the station has a major effect on the duration of the tasks assigned to the workstation. For example there may be a certain number of a specific tool in a station, if the number of operators surpasses the number of tools, waiting time for the tool to be released by other operators are to be considered. Another issue is the essential space to perform the tasks i.e. the task time may increase if there is not adequate space to carry out the task. These examples and many other pragmatic situations emphasize the significance of considering task times which are dependent on the concentration of workers in the station. To the best of our knowledge this type of task times hasn’t been considered in the literature of MALBP so far. For the rest of this paper the introduced model is called
The rest of this paper is as follows: in section 1 a mathematical model is proposed to solve the problem. In section 2 a numerical instance is developed and solved using Lingo 11 software. The main conclusions of the paper are presented in sections 3.

Proposed Model and Mathematical Formulation:

In this paper the paced assembly line with multi-manned workstations is considered which is very familiar in real world assembly lines but a few research papers have considered this category of assembly line. The work-piece stays at each workstation for a certain amount of time called cycle time. In each station there are many operators performing different tasks on the same work-piece. Each worker starts the tasks assigned to him (or her) as soon as it is technically possible. The major objective in this type of assembly line is to reduce the length of line while maintaining the effectiveness of the line in terms of the number of workers and total idle time. This type of multiple workers working on the same work-piece at the same time requires the work-piece to be of large size e.g. final assembly of vehicle. Customarily in simple assembly lines all of the tasks assigned to a worker can be performed continuously if the precedence relations are observed. But in multi-manned lines some tasks assigned to a worker may be postponed by the tasks assigned to other workers in the same workstation this postponement is called unavoidable delay. Traditionally in MAL literature the task times are assumed to be constant. But in the proposed model task times are assumed to be dependent to the number of workers in the station. Specifically duration of task \( j \) when there are \( k \) workers in the station is assumed to be equal to \( p_{ik} \).

The objective is to minimize the number of workers as the primary objective and then minimize the number of stations as the secondary objective. The decisions involved in GMALBP include the followings: (1) first how many workers should be assigned to each station then (2) which tasks to be performed by which worker.

The notations used to model the problem are shown in table 2.

<table>
<thead>
<tr>
<th>( i, h )</th>
<th>( j )</th>
<th>( k )</th>
<th>( I )</th>
<th>( K )</th>
<th>( J )</th>
</tr>
</thead>
<tbody>
<tr>
<td>task</td>
<td>station</td>
<td>worker</td>
<td>Set of tasks</td>
<td>Set of workers</td>
<td>Set of workstations</td>
</tr>
</tbody>
</table>

\( P(P^\prime) \): Set of direct (all) predecessors of task \( i \)

\( F(F^\prime) \): Set of direct (all) successors of task \( i \)

\( C \): Cycle time

\( m \): Number of stations

\( M \): A big number

\( MC \): Maximum concentration of workers in a station

\( N \): Number of tasks

\( p_{ik} \): Processing time of task \( i \) when there are \( k \) workers in the station

\( t_{ij} \): Processing time of task \( i \) in station \( j \).

\( x_{ijk} \in \{0,1\} \): Equals 1 if task \( i \) is assigned to worker \( k \) in station \( j \).

\( y_{ih} \in \{0,1\} \): Equals to 1 if task \( i \) and \( h \) is assigned to the same worker and task \( i \) is performed earlier than task \( h \).

\( w_{jk} \in \{0,1\} \): Equals to 1 if \( k \) th worker is used in station \( j \).

\( ws_{jk} \in \{0,1\} \): Equals to 1 if \( k \) workers are used in station \( j \).

\( s_i \): Start time of task \( i \)

The problem is formulated as follows:
In this model (1) is the objective function which is minimizing the number of operators as the first objective and the number of stations as the second objective. In this equation, the first term represents the number of workers in all stations. The second term is the number of station multiplied by a factor which is used to ensure that the second term is always less than one. It is assumed that the last task (N) is successor of all other tasks and consequently is assigned to the last station. If the task N is not a successor of all of tasks then a fictitious task must be considered. Therefore the number of stations is considered as the secondary objective. Equations (2) entail that each task is assigned to one and only one operator in one workstation. Constraints (3) guarantee that precedence constraints are observed. Constraints (4) make sure that all tasks must be finished before the end of cycle time. Equations (5) imply that if tasks \(i\) and \(h\) are assigned to the same station and task \(h\) is a immediate predecessor of task \(i\), then starting time of task \(i\) must be after...
finish time of task $h$, if these tasks are not allocated to the same workstation or don’t have direct precedence relation, the constraint (5) becomes redundant. The constraint pair (6) and (7) is disjunctive due to the sufficiently large number $M$ and it becomes active only when tasks $i$ and $h$ don’t have direct precedence relation and are assigned to the same worker. If $y_{ih}=1$ then task $i$ is performed before task $h$, the equation (7) becomes redundant and equation (6) leads to $st_i-st_h$, this means that task $h$ must start after task $i$ is completed. On the other hand if $h$ is assigned earlier than $i$ then $y_{ih}=0$ and equation (6) becomes redundant and equation (7) leads to: $st_i-st_h$. Equations (8) ensure that if the $k$th worker hasn’t been assigned to workstation $j$, then no task can be assigned to it. Constraints (9) ensure that of $ws_j$ is set to be 1 if the number of workers in station $j$ is equal to $k$. Constraints (10) mean that the workers are loaded in increasing order of their indexes. With constraints (11) $t_i$ assumes the processing time of task $i$ in station $j$ according to the number of workers in the station. Equations (12) ensure that starting times are non-negative. Constraints (13) through (16) imply that variables $x_{ijk}$, $y_{ih}$, $w_{jk}$ and $ws_j$ are binary variables.

**Numerical example:**
To illustrate the model an example is presented, this example is generated from the well-known example of Mertens. The precedence graph for this instance is shown in fig.1 and the task times for each task and number of workers in are presented in table 1. Cycle time is assumed to be 6.

**Table 2: task times**

<table>
<thead>
<tr>
<th>task</th>
<th>Number of workers in the station</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
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<tr>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>3</td>
<td>4</td>
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<td>4</td>
<td>3</td>
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<td>5</td>
<td>5</td>
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<tr>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>7</td>
<td>5</td>
</tr>
</tbody>
</table>

At first it is aimed to minimize the number of workers as the first objective and then the number of stations is minimized as the second objective. An optimum solution for this example is presented in fig. 2. For each task, starting time and finishing time are shown next to its bar. Shaded rectangles specify idle time at the end of the cycle time. As it can be seen from fig. 2 four workstations and 6 operators are needed to carry out the tasks in a multi-manned assembly line system.

**Fig. 1:** precedence graph of Mertens instance

**Fig. 2:** Optimum solution found by GMALBP model

Comparing GMALBP to SALBP, in the multi-manned approach the major goal is to reduce the length of the line with respect to simple lines while maintaining the efficiency of the line.
One of the main priorities of production managers is reducing the costs of production in order to minimize the total costs of one production unit while optimizing the efficiency of the line in terms of cycle time and idle time of workers. This objective can be obtained by using multi-manned workstations. One of the main factors in determining production costs are the costs of machinery and tools. These costs can be reduced by using multi-manned workstations and parallel working of several operators in the same station. In other words, several operators working in each station results in more usage of the available resources by sharing the current resources among more than one operator.

On the other hand additional production rate can be made available in many cases by increasing equipment utilization rates instead of adding units of equipment. This adds up to important savings because the base cost of many types of equipment exceeds $1 million per unit (Committee on Analysis of Research Directions and Needs in U.S. Manufacturing, Manufacturing Studies Board, 1991). For example in fig. 2 there are 6 operators working in 3 stations. In the SALBP for each operator one station is needed, therefore 6 stations is needed. However in the multi-manned approach 3 stations are required. The throughput time is reduced from 36 to 18, this leads to a decrease in the amount of work in process.

Another significant factor which has a major priority for manufacturing managers is the utilization of available space. This issue is of special importance when there are space limitations in the production floor because of building design. This issue may happen in redesigning the line for producing a new commodity. The amount of floor space required is dependent on the size of machines, the number of equipment in the manufacturing process and the number of stations needed.

The multi-manned system results in a shorter physical line length and improves the space utilization. Because in this system the same number of workers can be allocated to fewer stations comparing to the traditional approach.

Space utilization can be defined as ratio of the total space required for multi-manned approach to the total space required for the traditional approach and can be calculated by the following equation (Dimitriadis, 2006; Fattahi et al, 2011):

\[
f = \frac{m}{tw}
\]

In this equation \( f \) is the space utilization factor, \( m \) is the number of stations and \( tw \) is the number of workers. The utilization factor ranges between 1, when each station has one worker assigned to it, and 1/\( tw \), when all of the workers are assigned to one station. This factor can be used to compare the multi-manned approach to the traditional approach. For example in fig. 2 this factor is equal to 1/2, which has been improved from the value 1 for the traditional approach. It can be inferred from this example that using multi-manned assembly lines can be very beneficial in reducing the production costs and improving space utilization.

In order for being able to compare the current model with the traditional MALBP, the optimum solution found by Fattahi et al, 2011, for the example presented in this paper is presented in fig. 3.

As seen in figures 2 and 3, both conventional multi-manned model and the GMALBP have obtained the same number of operators and workstations. However because of high concentration of operators in the solution obtained by traditional model, cycle of this solution has increased to 7. This highlights the importance of considering the effect of worker concentration on task times. Not considering this concept may result in unwanted increase in the cycle time.

Fig. 3: Optimum solution for the traditional multi-manned model
It is interesting to compare the proposed model with the traditional MALBP in terms of space utilization and throughput time. For this aim the calculations of space utilization and throughput time for optimum solutions found by MALBP and GMALBP models are presented in Table 3. In this table $I^*_j$ is the set of tasks assigned to worker $l$ in station $j$, $pr_j$ is the sum of durations of tasks assigned to the worker $l$ in station $j$, and finally $f_j$ is the finish time of tasks assigned to worker $l$ in station $j$.

As seen in this table both solutions have the same space utilization factor. However since the cycle time obtained by MALBP model is 7 (which is 1 unit more than the cycle time obtained by GMALBP model) the throughput time for this solution is equal to 21. While the throughput time for GMALBP is equal to 18. This lower throughput time result in lower work in process, which is an important issue for production managers. This highlights the importance of considering the effect of worker concentration on task times.

**Table 3: Optimum solutions for MALBP and GMALBP**

<table>
<thead>
<tr>
<th>Station</th>
<th>Worker</th>
<th>MALBP optimal solution</th>
<th>GMALBP optimal solution</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$I^*_j$</td>
<td>$st_j$</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>{1,4}</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>{2}</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>{5}</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>{7}</td>
<td>0</td>
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<tr>
<td>3</td>
<td>1</td>
<td>{6}</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Cycle time</td>
<td>7</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>$m$</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$Tw$</td>
<td>6</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>$f$</td>
<td>3/6</td>
<td>3/6</td>
<td></td>
</tr>
<tr>
<td>Throughput time</td>
<td>21</td>
<td>18</td>
<td></td>
</tr>
</tbody>
</table>

**Conclusions and Future Research:**

In this paper the MAL model presented by Dimitriadis, 2006, is extended. Specifically it is assumed that task times are dependent on the number of workers in the station. A mathematical formulation is developed to solve this problem with the objective of minimizing the number of workers as the primary objective and the number of stations as the second objective. Multi-manned assembly lines have several advantages over the traditional lines which includes reducing the length of the line and therefore improving the space utilization. On the other hand this type of lines results in reducing the work in process and throughput time which is of major priority for production managers. However intense concentration of operators in a workstation increases the task processing times because of workers blocking each other or waiting times for facilities to be released by other workers in station. Not considering this effect may result in unsuitable line balances and increasing the cycle time. Considering this effect is an important issue for high volume production systems and could be used as a basis for more realistic production systems with various types of assembly line, such as mixed-model lines. Developing heuristic or meta-heuristics such as ant colony or simulated annealing to solve the proposed model and considering multiple-objective optimization problem by taking into account many other objective, such as smoothing and load balancing are recommended for future research in this area.

**REFERENCES**


