

Optimization of the Allocation of Material Resources in a Production Line: Workstation Load Balancing by Analogy with the Bin Packing Problem

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Abstract: The obligation to use resources in an optimal way in production lines requires industrials to use the tools and methods of operational research and to mathematically model their resource allocation problems in order to find optimal configurations of their assembly lines. The objective of this paper is the implementation of a decision support tool to help manage and optimize the allocation of material resources of companies during the product launch phase. This tool must be able to be used at several levels: strategic and operational. The assembly lines balancing problem, which we study in this article, is distinguished by its configuration (constraint and hypothesis) related to the business environment studied, finally, for the resolution of the problem we made an analogy with the bin packing problem and then proposed a solution adapted to our case study.

Keywords: Resource Allocation, Assembly Line Balancing, Load Balancing, Bin Packing, Algorithm First Fit Decreasing.

1. Introduction

The current situation of the world economy, as well as the strong concurrence, puts manufacturing companies with large production capacity in front of several challenges. The success of a company is directly related to its ability to use its resources in an optimal way while producing the quality required by the customer. Any underutilization in production dynamics involves additional costs. So, the decision of choosing the configuration of the assembly lines has become increasingly important, and severely impact the product cost. The complexity of the problems of this decision requires the use of optimization methods for resolution.

One of the main objectives of assembly line balancing is the optimization of material resources, in fact, it is a complex decision problem due to its combinatorial complexity and its impact on the cost and performance of the production system implemented.

2. State of the Art

2.1. Assembly Line Balancing

Several bibliographical researches on the balancing of assembly lines have been done: (Ignall, 1965; Mas-tor, 1970; Buxey et al., 1973; Baybars, 1986; Ghosh et al., 1989; Erel et al., 1998; Tal-bot et al., 1986; Ponnambalam et al., 1999; Scholl, 1999; Rekiek et al., 2002a; Scholl et al., 2006).

In the literature there are two types of assembly line balancing problem:

- SALBP (Simple Assembly Line Balancing Problem)
- GALBP (Generalized Assembly Line Balancing Problem).

The classification of the ALB problem is mainly based on the objective functions and the structure of the problem. Different versions of ALB problems are introduced due to the variation in objectives (Fig 1).

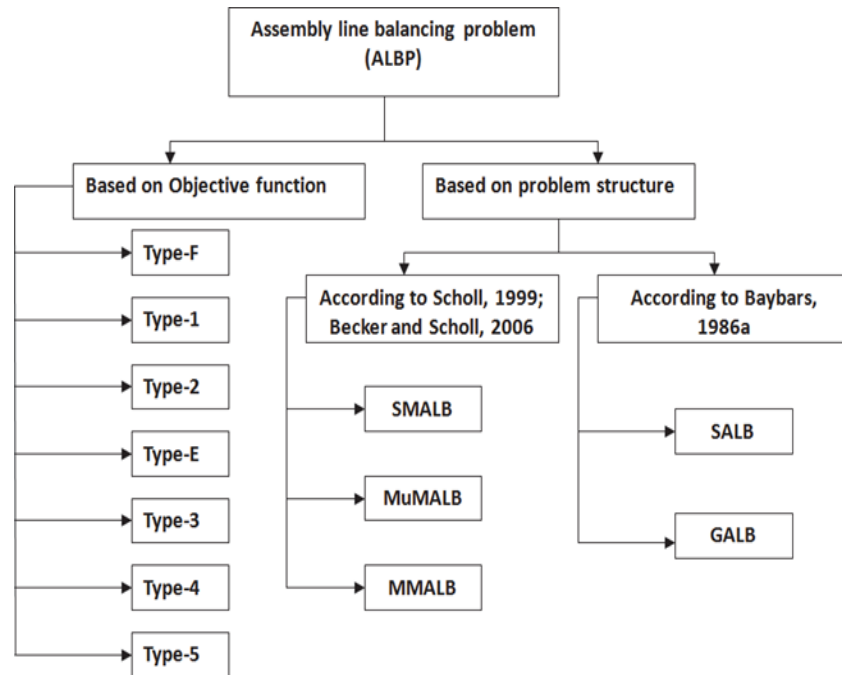


Figure 1. Classification of ALBP (Scholl & Boyesen, 2006)

2.2. The Bin Packing Problem

The bin packing problem considers N objects each having a defined size and several boxes of the same capacity. The goal is to place all objects in a minimum number of boxes by ensuring that the sum of the sizes of the objects placed in each box is less than the capacity of the box by allocating each object in one and only one box.

For example, in Figure 2, objects 1 and 2 are stored in box m_1 , objects 3 and 5 in box m_2 and object 4 in box m_3 .

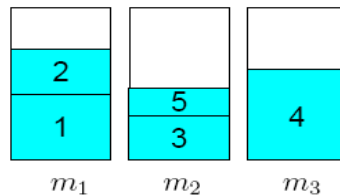


Figure 2. A Solution to the 1D Bin Packing Problem

Since its introduction in 1973 by Johnson (Johnson, 1973), the problem of bin packing has been studied by several researchers (Cohen, Johanne, 2001; Klement, 2015; Wee, T. S., et M. J. Magazine 1982). This problem is an NP-Complete decision problem as demonstrated by (Garey and Johnson, 1979). The associated optimization problem is NP-difficult: what is the minimum number of boxes needed to assign each object to one and only one box, while respecting the capacity constraints of the boxes? Given the size of the actual problems handled, many approximate methods have been developed to solve it.

Heuristics have been introduced, as well as meta-heuristic methods of resolution. The bin packing problem is still a hot topic, both in terms of the study of inferior bounds (Balogh et al., 2012) and the proposal of a new meta-heuristic resolution (Bin et al., 2012).

3. Context and Problematic

Our case study concerns a manufacturing company with a large operator-oriented production capacity; this company operates in the automotive sector and specializes in the design and manufacture of car seats. The objective of the process engineers is to provide the manufacturer with an assembly line that is as balanced as possible, which requires complex work and generates additional costs if the line is not optimally balanced.

3.1. Criteria

The occupancy rates of each Production Line and each workstation in the line must be at the maximum in order to be as economical as possible and to ensure the optimal use of resources.

3.2. Constraints

The constraints of the problem can be expressed as follows:

- Precedence: The assignment must satisfy the constraint of precedence between operations.
- Compatibility between equipment and operation: The assignment must satisfy the given list of incompatibilities between operations and pieces of equipment.
- Each operation must be assigned to only one machine.
- The time sum of the operations assigned to a machine must not exceed the cycle time.

3.3. Hypotheses

- The following hypotheses are considered:
- The times of the operations are defined and fixed.
- Machine of the same types has the same parameters.
- The cycle time is a fixed data.

3.4. Objective

The objective is the minimization of the number of workstations,

$$\text{Min } z = \sum P_j$$

4. Formalization of the Problem of Assembly Line Balancing

4.1. Notations

- The index i corresponds to the operation or task.
- The index k corresponds to the Production Line.
- The index l corresponds to the Equipment or Machine.
- The index t corresponds to the opening time.

4.2. Data

The data used in this model are as follows.

N : the set of Operations or tasks to be assigned in the production line.

L : the set of equipment or Machines available in the line.

T : the set of times.

t_i : the execution time of operation $i \in N$.

T_0 : Product cycle time.

$$c_{i,l} = \begin{cases} 1 & \text{if operation } i \in N \text{ can be assigned to the work station } l \in L \\ 0 & \text{if not} \end{cases}$$

4.3. Criteria

The variables considered are:

- The assignment of an operation to a machine:

$$x_{i,l} = \begin{cases} 1 & \text{if operation } i \in N \text{ is assigned to the machine } l \in L \\ 0 & \text{if not} \end{cases}$$

- Using a machine to execute operation i .

$$l_j = \begin{cases} 1 & \text{if the machine } l \in L \text{ contains an operation } i \\ 0 & \text{if not} \end{cases}$$

- Maximization of machine occupancy

$$F = \max \sum_{l \in L} \sum_{i \in N} t_i * x_{i,l}, \forall i \in N, \forall l \in L$$

4.4. Constraints and Hypothesis

- Each operation is assigned to a machine according to the Equation:

$$\sum_{l \in L} x_{i,l} = 1, \forall i \in N$$
- Each operation is assigned to a compatible machine according to the Equation:

$$\sum_{l \in L} x_{i,l} (1 - C_{i,l}) = 0, \forall i \in N$$
- Equipment may be required to carry out an operation (in the case of regulatory and safety operations: the Airbag Zone in which specific machines must be used). The constraint "the machine l2 must be used to carry out operation i" is finite by the Equation :

$$\sum_{l \in L} x_{i,l} = 1, \forall i \in N$$
- The binary constraints are defined by the equation:

$$x_{i,l} \in \{0, 1\}, \forall i \in N, \forall l \in L,$$
- The non-negative constraints are defined by the Equation:

$$G_{l,t} \geq 0, \forall l \in L, \forall t \in T$$
- The sum of the execution times of the operations assigned to a machine must not exceed the cycle time T0, according to the equation :

$$\sum_{i \in N} t_i * x_{i,l} \leq T_0, \forall l \in L$$
- The precedence constraint is expressed by:

if $i, j \in L, i < j$ and $i \in I_x, j \in I_y$, so $x \leq y$;

4.5. The Objective Function

Minimize the number of machines to be installed in the assembly line, according to the Equation:

$$\text{Min } Z = \sum_{j \in L} l_j$$

5. Solving the Alb Problem by Analogy with the Bin Packing Problem

5.1. Analogy with the Bin Packing Problem

The bin packing problem considers N items each with a defined size and several boxes of the same capacity. The objective is to place all the objects in a minimum number of boxes, ensuring that the sum of the sizes of the objects placed in each box is less than the capacity of the box by assigning each object in one and only one box. This problem also exists in two and three dimensions. Only the one-dimensional case is considered.

The problem consists in assigning operations to machines. The machines must be occupied as much as possible, so the objective is to minimize the number of machines l to be installed in the assembly line, i.e. to minimize the number of boxes in the case of the bin packing problem.

The table (1) below summarizes the analogies between the bin packing problem and the problem of assigning operations to machines.

Our problem considers an additional constraint: before assigning an operation i to a machine L, the constraints must be verified:

- Compatibility: verify that $c_{i,l} = 1$.
- The precedence constraint between operations:

if $i, j \in L, i < j$ and $i \in I_x, j \in I_y$, so $x \leq y$;

Table 1. Analogy of Our Problem with the Bin Packing Problem.

	Bin packing problem	Our ALB Problem
Data	Objects	Operations
	boxes	Machines or Equipment
	Size of object	Executing time of an operation
	Size of box	Cycle time of product
Problem	Assigning Objects to the boxes	Assigning operations to a machine
	Box size constraint	Capacity: Machine open time constraint (Cycle time)
	-	Compatibility
	-	Precedence constraint between operations.
Objective	Minimizing the number of boxes	Minimizing the number of machine

The concept of compatibility between operation and equipment is directly defined and can be inferred as follows:

An operation i is compatible with a machine l if and only if the operation i can be executed in the machine l which is of type A .

5.2. Algorithm to Solve the Problem

5.2.1. Algorithm First Fit Decreasing

Decreasing or sorting algorithms are applied to an ordered list of operations. Considering that the main criterion is the order defined by the method engineers, this order of operations takes into account the precedence constraint between operations. That is to say, the operations with the highest priority are the first to be assigned to the current equipment, so that they are carried out first. The compatibility constraint between operation and equipment is always checked before the assignment.

The coupling of list algorithms with basic bin packing heuristics guarantees high performance results. As tested in reference (Klement, Nathalie, 2015; Elaassiri, 2019), the best fit and first fit heuristics give equivalent results (tested on bin packing instances in the literature) and Next fit gives the worst results, and when these heuristics are coupled with decreasing list algorithms, the First Fit Decreasing heuristic is the one that gives the best results, at a factor 2 of the optimal as shown by (Johnson et al., 1974). Subsequently, we will use the First Fit Decreasing heuristic with incompatibility to solve the assignment problem for a real instance.

$$FF(L) \leq (17/10) \cdot OPT(L) + 2, \forall L$$

5.2.2. Assignment Procedure

The procedure for assigning operations to equipment is as follows:

- Initially update all the available operations: the list of operations must be ordered and classified according to priority and precedence criteria. This initial classification is given by the methods engineers and defined during the prototype phase.
- The operations whose immediate predecessors have been assigned: the operations with the highest priority are the first to be assigned to the current equipment after verification of the compatibility constraint between operation and equipment.
- Successively assign the operations available in the first piece of equipment where the precedence, capacity and compatibility constraints are met.
- The next set of available operations is updated and the assignment continues.
- The updating and assignment process continues until all operations have been assigned.

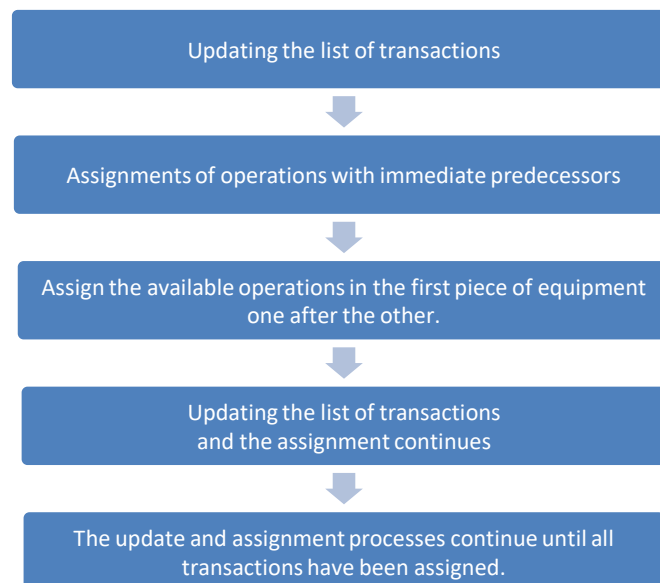


Figure 3. Transaction Assignment Process

5.2.3. Proposal of an Algorithm for Our Problem

Data: list of operations $(a_i) i \in N$;

C_l : equipment capacity, $\forall l \in L$;

t_i : execution time of operation, $\forall i \in N$;

Tab_k $k=1 \dots n$ tables of operation execution times ;

1. Sort $t_i, \forall i \in N$ in increasing order of priority and then put them in Tab_i .
2. $F_l := 0, \forall l \in L$,
3. for all $i \in N$ do
4. $l := 1$, affected := false
5. as long as $(l \leq L)$ & (affected = false) do
6. if the Tab_{ai} operation is compatible with equipment l ($c_{i,l} = 1$) then
7. if the Tab_{ai} operation fits in the equipment l ($F_l + t_{ai} \leq C_l$) then
8. if $\forall a_j$ such as $tab_{aj} \leq tab_{ai}$, and $l_{aj} \leq l$ (equipment that holds a_j less than or equal to l)
9. Assign operation Tab_{ai} to equipment l : $x_{i,l} := 1$
10. $F_l := F_l + t_{ai}$
11. affected := True
12. $l := l + 1$

6. Conclusions

The objective of our research is the optimization of the allocation of material resources in a production line, this work and the result of a long research carried out on the problematic of optimization of the tools of the allocation of human resources and materials for a production line (khabir et al. 2019; khabir et al. 2020).

The problem studied in our article has been mathematically formalized in the form of integer linear problems. Many methods of resolution exist to solve this type of problem, and given the complexity and the size of the studied problem, there is no algorithm to solve it in polynomial time. That is why there are many approximate methods.

Many heuristic resolution methods have been proposed. Many of them are tedious to apply. The end use of our tool is made by industry personnel, so we have thought of the simplest methods possible. In our article, we proposed a new method of resolution easy to develop and to use based on the method of solving the problem of bin packing (one dimension).

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