Incorporating Ergonomics Factors into the TSALBP

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Joaquín Bautista[1], Cristina Batalla[1], and Rocío Alfaro[1]

[1] Universitat Politècnica de Catalunya, Avda. Diagonal 647, 7th floor, 08028 Barcelona, Spain
{joaquin.bautista; cristina.batalla; rocio.alfaro}@upc.edu

Abstract. Mixed-product assembly lines have ergonomic risks that can affect the worker productivity and lines. This work proposes to incorporate ergonomic factors to the *TSALBP* (*Time and Space constrained Assembly Line Balancing Problem*). Therefore, we present several elements for new models to assign the tasks to a workstation considering technological, management and ergonomic factors.

Keywords: Manufacturing, Assembly Line Balancing, Somatic and Psychic Factors.

1 Preliminaries

Circulating units in an assembly line are not identical in manufacturing systems with mixed-product assembly lines, such as in the automotive industry. This difference between product units leads to a change in use of resources (workers, tools, etc.) as well as in consumption of components. Therefore, the assembly line design must deal with balancing. Obviously, technological and management constraints should be considered in the line balancing, according to real situations.

The Assembly Line Balancing Problem (*ALBP*) is a classic problem [1] related to flow-oriented production systems. The problem deals to assign a set of elementary tasks (which may correspond to the assembly or disassembly of a product: motors, batteries, cars...) to a set of workstations or modules. The workstations are usually associated with teams of workers and/or robots, and they apply some of the work that will serve to complete the final product.

Typically, the workstations are arranged in a row, one behind another, and connected by a transport system, which allows movement of the work in progress at constant speed. Each workstation is given a constant time (cycle time, c) to complete the work that has been assigned.

Baybars [2] divided the *ALBP* into two classes:

1. The Simple Assembly Line Balancing Problem (*SALBP*).
2. The General Assembly Line Balancing Problem (*GALBP*).

The *SALBP* class contains assembly problems that attempt to minimize the total idle time considering exclusively only two kinds of task assignment constraints:

1. Cumulative constraints, associated with the available time of work in the stations.
2. Precedence constraints, established by the order in which the tasks can be executed.

Other problems with additional considerations are included in the GALBP class [3], like the case in which the assignment of tasks is restricted [4] or when certain tasks must be assigned in block [5].

Some of the limitations in literature [6-7] take into account factors such as: the number of workstations (*m*); the standard time assigned to each workstation (*c*), which is calculated through an average of the processing times of all tasks according to the proportions, of each type of product, that are present in the demand plan, and the available space or area (*A*) to materials and tools to each workstation.

In these conditions we can define a family of problems under the acronym TSALBP (Time and Space constrained Assembly Line Balancing Problems) [6-7] that consist on: given a set J of $|J|$ tasks with their temporal t_j and spatial a_j attributes ($j = 1,\ldots,|J|$) and a precedence graph, each task must be assigned to a single station, such that:

- All the precedence constraints are satisfied.
- No station workload time is greater than the cycle time (*c*).
- No area required by the station is greater than the available area per station (*A*).

Then, if we consider the types of limitations defined above, we have eight types of problems, according to the objective of each one of them [6]. For example, the model to the *TSALBP-1* is the following:

$$Min\ z_1 = m \tag{1}$$

Subject to:

$$m - \sum_{k=1}^{m_{\max}} k\, x_{j,k} \geq 0 \qquad (j = 1,\ldots,|J|) \tag{2}$$

$$\sum_{j=1}^{|J|} t_j x_{j,k} \leq c \qquad (k = 1,\ldots,m_{\max}) \tag{3}$$

$$\sum_{j=1}^{|J|} a_j x_{j,k} \leq A \qquad (k = 1,\ldots,m_{\max}) \tag{4}$$

$$\sum_{k=1}^{m_{\max}} x_{j,k} = 1 \qquad (j = 1,\ldots,|J|) \tag{5}$$

$$\sum_{k=1}^{m_{\max}} k\left(x_{j,k} - x_{i,k}\right) \geq 0 \qquad \left(1 \leq i,\ j \leq |J| : i \in P_j\right) \tag{6}$$

$$x_{j,k} \in \{0,1\} \qquad (j = 1,\ldots,|J|) \wedge (k = 1,\ldots,m_{\max}) \tag{7}$$

Where, $x_{j,k}$ is a binary variable that is equal to 1 if a task j ($j = 1,\ldots,|J|$) is assigned to the workstation k ($k = 1,\ldots,m_{\max}$), and 0 otherwise; P_j is a parameter that indicates the set of precedent tasks of the task j ($j = 1,\ldots,|J|$) and the objective is to minimize the number of workstations ($m = |K|$).

2 The Ergonomic in assembly lines

One of the main objectives of the ergonomic is to adapt the operations that the workers must perform to guarantee their safety, welfare and to improve their efficiency.

Although the problems of a poor design of a workstation, in ergonomic terms, affect all areas of employment, manufacturing is one of the most affected. Specifically, the ergonomic risk is present and may affect the performance of workers and the line, in manufacturing assembly lines with mixed-products.

In such environments, ergonomic risk is given basically by the components related to somatic comfort and psychological comfort.

The somatic comfort determinates the set of physical demands to which a worker is exposed throughout the working day. To analyze this type of ergonomic risk, three factors, among others, can be analyzed. These are:

- Postural load: During working hours the workers may adopt repeatedly, inappropriate or awkward postures that can result in fatigue and musculoskeletal disorders in the long run [8].
- Repetitive movements: A workstation may involve a set of repeated upper-limb movements by the worker. This may cause musculoskeletal injuries at long term [9].
- Manual handling: Some tasks involve the lifting, moving, pushing, grasping and transporting objects [10].

By the other hand, the psychological comfort refers to the set of necessary mental conditions that the workers must have to develop their tasks. These conditions are: autonomy, social support, acceptable workloads and a favorable work environment.

3 The TSALBP with ergonomic

Our proposal is to incorporate into the *TSALBP* or in other assembly lines problems the factors that imply these ergonomic problems.

Otto and Scholl [11] employ several techniques to incorporate the ergonomic risks to the problem *SALB-1*.

In a first approximation, given the set K of stations, to each workload S_k assigned at workstation k ($k = 1,\ldots,|K|$), the ergonomic risk $F(S_k)$ is determined. Moreover, a maximum value is established for that ergonomic risk, Erg. Consequently, we can add to the original models the following constraints, satisfying: $F(S_k) \leq F(S_k \cup \{j\})$ ($\forall S_k, \forall j \in J$).

$$F(S_k) \leq Erg \qquad \left(k = 1,\ldots,|K|\right) \tag{8}$$

Alternatively to the conditions (8), Otto and Scholl propose the *ErgoSALBP-1* with a new objective function composed by two terms [11]; that is:

$$Min\ K^{'}(x) = K(x) + \omega \cdot \xi\left(F\left(S_k\right)\right) \tag{9}$$

Where $K(x)$ is the number of workstations; ω is a weight non-negative and $\xi\left(F\left(S_k\right)\right)$ is a function that includes the ergonomic risk factors $F(S_k)$ $\left(k = 1,\ldots,|K|\right)$.

Logically, the constraints (8), presented by [11], can be completed if we take into account, in the design of the line, a minimum value to the ergonomic risk. In addition we can consider that this risk depends on the factor (somatic or psychic) that we want. In this situation, we have:

$$F_{\phi}^{\min} \leq F_{\phi}\left(S_k\right) \leq F_{\phi}^{\max} \qquad \left(k = 1,\ldots,|K|\right);\ \forall \phi \in \Phi \tag{10}$$

Where Φ is the set of factors, $F_{\phi}^{\min}$ and $F_{\phi}^{\max}$ correspond to the minimum and maximum ergonomic risk to the factor $\phi \in \Phi$, and $F_{\phi}\left(S_k\right)$ is the ergonomic risk at workstation $k \in K$.

Other way to treat the problem is to classify the workstations in several categories (e.g. from 1 to 4) depending on different factors, such as movements, loads, duration, etc. From this point, we can condition the design of the line to the different categories of workstations that are present in a minimum and maximum percentage.

Then, if we define H as the set of ergonomic risk components, in our case, somatics (σ), psychics (φ) or both ($\sigma \cup \varphi$), we can find a new classification for the *TSALBP*, that is (see table 1):

Table 1. *TSALBP_erg* typology. The suffixes 1, 2, and 3 refer to the minimization of *m*, *c* and *A*, respectively. The suffix F refers to a feasibility problem. The post-suffix η refers to the type of the restriction linked to the human aspects, psychic and somatic, being the element $\eta \in$ H where $\eta = \{\varnothing, \sigma, \varphi, \sigma \cup \varphi\}$. The column "Type" indicates if the problem is one of feasibility (F), mono-objective (OP) or multi-objective (MOP).

Name	m	c	A	Type
TSALBP-F- η	Given	Given	Given	F
TSALBP-1- η	Minimize	Given	Given	OP
TSALBP-2- η	Given	Minimize	Given	OP
TSALBP-3- η	Given	Given	Minimize	OP
TSALBP-1/2- η	Minimize	Minimize	Given	MOP
TSALBP-1/3- η	Minimize	Given	Minimize	MOP
TSALBP-2/3- η	Given	Minimize	Minimize	MOP
TSALBP-1/2/3- η	Minimize	Minimize	Minimize	MOP

In addition to the above proposals, the assembly line balancing problems with ergonomic conditions can be treated as multi-objective problems.

4 An example

To illustrate the *SALBP-1*, the *TSALBP-1* and the *TSALBP-1-*σ, we present the following example.

Given a set of eight tasks ($|J| = 8$), whose operation times, t_j ($j = 1,\ldots,|J|$), required space, a_j ($j = 1,\ldots,|J|$), ergonomic risk $F(\{j\})$ ($\forall j \in |J|$) and which precedence graph are shown in figure 1, each task must be assigned to a single stations satisfying the limitations: (1) c = 20 *s*; (2) A = 20 *m*; and (3) $F^{\max}$ = 60 *e-s* (ergo-seconds).

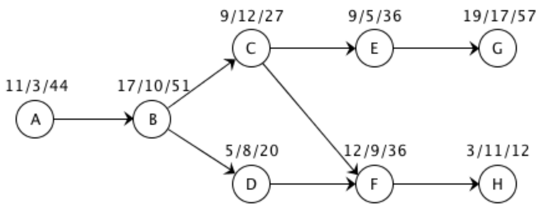

Fig. 1. Precedence graph of tasks. At each vertex we can see the tuple $t_j / a_j / F(\{j\})$ corresponding to the task.

Solving the *SALBP-1*, *TSALBP-1*, *TSALBP-1-*σ we obtain the following results (see Figure 2, Figure 3 and Figure 4, respectively).

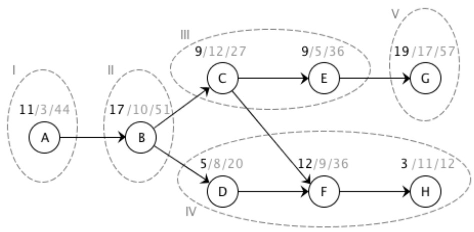

Fig. 2. Solution obtained by *SALBP-1* (m = 5).

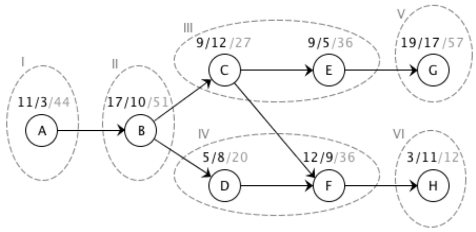

Fig. 3. Solution obtained by *TSALBP-1* (m = 6).

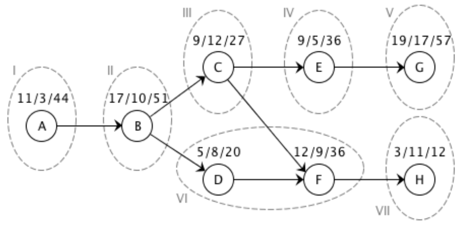

Fig. 4. Solution obtained by *TSALBP-1-*σ (m = 7).

Considering the *SALBP-1*, the obtained result is (see figure 2) a number of workstations of 5. By other hand, considering the *TSALBP-1* the obtained result is one workstation more that with the *SALBP-1* (figure 3). Finally, if we consider that the ergonomic factor are additive, we can group tasks taking into account, in addition to the cycle time and the area, this factor. Then, we can obtain a result for the *TSALBP-1-*σ (figure 4).

As we can see from the examples, depending on the limiting factors that we consider, the resulting number of stations will be one or other. Obviously, a greater number of conditional factors, means a greater number of workstations.

5 Case study

To evaluate the proposed model and to contrast the influence of constrains relative to the ergonomic factors on the number of workstations of the line, required *for SALBP-1* and *TSALBP-1*, we have chosen a case study that corresponds to an assembly line from Nissan's plant in Barcelona. In fact, the 378 tasks (including the rapid test), that are required in the assembly of a motor (Pathfinder), have been grouped into 36 operations. After to set consistently the potential links, predecessors and successors, between the 36 operations, considering the potential links of the 378 original tasks, and taking into account a cycle time of 180 *s*; an available longitudinal area of 400 *cm*; and a maximum ergonomic risk of 400 *e-s*, we have solved, using the CPLEX solver, the three problems that are the focus of this study (*SALBP-1*, *TSALBP-1* and *TSALBP-1-*σ).

In table 2 we can see the optimal solutions obtained, and the need of more workers when are taken into account more realistic conditions in the assembly line problems. In addition we can see the process time of the operations (t), the required area (a), the risk factor (F) and the workstation where each task has been assigned, for each problem.

In our case, 19 work teams are necessary when only is taken into account the limitation of the cycle time, 21 when the constraints of area are included and 24 when a maximum ergonomic risk must be respected at each workstation.

Table 2. Obtained solutions by CPLEX from *SALBP-1*, *TSALBP-1* and *TSALBP-1-σ*.

j	*t*	*a*	*F*	*P*	*SALBP-1*	*TSALBP-1*	*TSALBP-1-σ*
1	100	400	200	-	1	1	1
2	105	400	210	1	2	2	2
3	45	100	90	1	3	3	3
4	113	300	226	1, 2	3	3	3
5	168	400	336	1, 2, 4	4	4	4
6	17	150	34	2, 4, 5	5	5	5
7	97	250	194	6	5	5	5
8	50	200	100	2, 3, 7	5	6	6
9	75	200	150	2, 8	19	6	6
10	30	100	90	8	6	7	7
11	65	300	195	8, 10	6	7	7
12	35	350	105	10, 11	6	8	8
13	65	50	195	11, 12	7	8	8
14	115	300	345	12, 13	7	9	9
15	60	50	180	14	8	9	10
16	115	100	345	14, 15	8	10	11
17	60	150	120	13, 14, 16	9	10	12
18	105	250	210	16, 17	9	11	12
19	60	150	120	18	10	11	13
20	100	400	200	18, 19	10	12	14
21	100	400	200	19, 20	11	13	15
22	75	200	150	21, 22	11	14	16
23	75	175	225	21, 22	12	14	16
24	105	150	315	23	12	15	17
25	15	100	45	23, 24	17	15	17
26	35	150	105	24, 25	19	15	20
27	175	250	350	24	13	16	18
28	5	0	15	27	14	17	18
29	165	250	330	27, 28	14	17	19
30	5	0	15	27, 28	14	17	19
31	115	150	230	5, 29	15	18	20
32	60	200	120	29, 30, 31	15	18	21
33	85	200	170	5, 31	16	19	22
34	70	200	140	32	16	19	21
35	160	375	320	31, 33, 34	17	20	23
36	165	150	330	35	18	21	24

6 Conclusions

From the family of problems *TSALBP*, we propose an extension to these problems attending to the need to improve working conditions of workers in production and assembly lines. The result of this extension is the family of problems *TSALBP_erg*. Specifically, we formulate the problem *TSALBP-1-σ*, corresponding to the somatic risks, that considers the constraints of cycle time, available area and, in addition, the maximum ergonomic risk to which the workers, assigned to each station, may be subjected.

Through a case study linked to Nissan, we observe that the improvement of the working conditions increases the minimum number of required workers to carry out the same work. By other hand, the reduction of the maximum ergonomic risk admissible, supposes a reduction of the labor cost due to injuries and absenteeism, whose valuation will be object studied in future research.

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