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Delimiting the linear area on the problems of assembly line balancing with minimal ergonomic risk

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Abstract In this paper we propose to incorporate some working conditions to the assembly lines. For this, used a mathematical model to solve the assembly line balancing problem whose objective is minimizing the ergonomic risk, imposing the limitation of the cycle time, number of workstations and the maximum linear area for each station. A study is presented through a case study that corresponds to an assembly line from Nissan's plant in Barcelona.

Keywords: Ergonomic Risk; Linear Area; Assembly Line Balancing.

1 Introduction

During the last decades academic literature has defined ergonomics as the science that allows to study employees' working conditions and assess the risks they are exposed to so that measures seeking to alleviate these risks can be adopted. However, a wide array of factors should be taken into account when it comes to design ergonomic studies (e.g., jobs and workloads assessment and the analysis of working conditions and environment, among others) and this complicates the use of a single method for assessing risks at work.

The Spain's regulatory framework provides guidelines on how risks at work should be assessed as well as what measures should be adopted to protect workers

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and individuals who might be affected by work risks. This creates the conditions for adapting workplaces and minimizing monotonous and repetitive work tasks.

The primary objective of ergonomic studies is to minimize work risks, and this requires the identification of all hazards at the workplace including all factors that could potentially cause workrelated illnesses. The poor adaptation of the workplace and the lack of space available to workers to develop their tasks is one of the most commonly referred causes of work risk and/or illness.

Ergonomics should have the capacity to evaluate working area in order to provide adequate working space since workers' natural movements jointly with their diverse positions at work are essential elements to effectively develop work tasks. In this scenario, it is essential to understand that job positions should fit both the workers' physical conditions and the tools and devices so that the latter can be used as independently and naturally as possible.

Nevertheless, as mentioned above, the available space at the workstations should be adapted to both workers and products.

This research is based on a case study in which products are of great volume and weight (engines, bodyworks, etc.). This means that the analyzed product parts require adequate storage space at the workstation. When it comes to define the assembly line, different components should be taken into account and clearly delimitated, including: the place and storage space, the raw materials necessary to manufacture the product, and the movements and re-allocation of workers within their corresponding workstation.

Therefore, we should design an assembly line that adapts to all these conditions in each of the workstations in order to increase productivity and reduce the potential injuries that workers might be exposed to.

All the problems mentioned, can trigger multiple musculoskeletal disorders that cause inflammatory or degenerative lesions in the musculoskeletal system's tissues such as muscles, tendons, nerves and body joints.

Nowadays, and besides the abovementioned ergonomic problems, the automobile industry suffers from several aspects that interfere with the effective development and execution of labor activities.

Different scientific studies have analyzed aspects related to ergonomics (Salveson, ME, 1955 and Battaïa and Dolgui, 2013) and established different criteria for assembly lines balancing.

Bautista and Pereira (2007) introduced a new variable into the analysis, namely the available space or area (A) of working materials and tools for each workstation, and this led to develop a new family of problems labeled TSALBP (Time and Space Constrained Assembly Line Balancing Problems).

Bautista et al., (2013a) incorporate a new constraint into the TSALBP model that limits maximum and minimum ergonomic risks. The same authors conducted an analysis of the impact of reduced ergonomic risks over the number of workstations (Bautista et al., 2013b).

The works of Bautista et al., (2015a) and Bautista et al., (2015b) solve the problem of lines balancing in order to minimize the maximum ergonomic risk of stations.

Specifically, Bautista et al., (2015a) solve the problem using linear programming and Bautista et al., (2015b) with GRASP algorithms.

Note that both studies minimize ergonomic risk without considerer the impact area.

Therefore, in this work we extend the studies of Bautista et al., (2015a) and Bautista et al., (2015b) considering a linear area available in each station.

2 Ergonomic Risk Assessment

Debates on the design of assembly lines must take into account the factors characterizing the interaction between multiple elements, such as workers' body dimensions as well as their physical and mental attributes, physical movements at work, working tools, physical force demanded by work positions, the duration of tasks, vibration levels, and temperature, among others. The joint interaction of these elements might represent a risk factor for workers.

Existing literature incorporates ergonomic risks in the analysis of balanced lines in order to develop models that contribute to the reduction of these risks (Otto and Scholl, 2011 and Bautista et al., 2013a). Additionally, Bautista et al., (2013c) examine how an additional constraint dealing with the minimization of risks contribute to determine the optimal number of jobs necessary to maximize the lines' operating and production capacity.

By using the case presented by Bautista et al., (2013c) which depicts three types of problems (SALBP-1, TSALBP-1 and TSALBP-1_erg) we observe that increased constraining factors lead to a greater number of workstations.

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

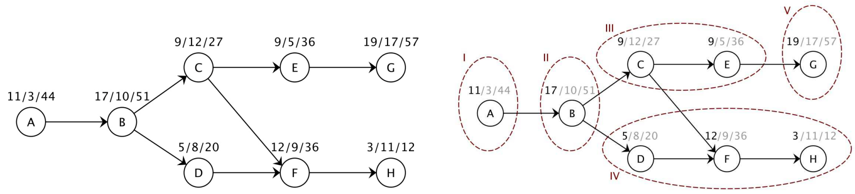

Fig 1. Precedence graph of tasks. At each vertex we can see the tuple $t_j / a_j / R_j$ corresponding to the task (left). Solution obtained by SALBP-1 (m = 5) (right).

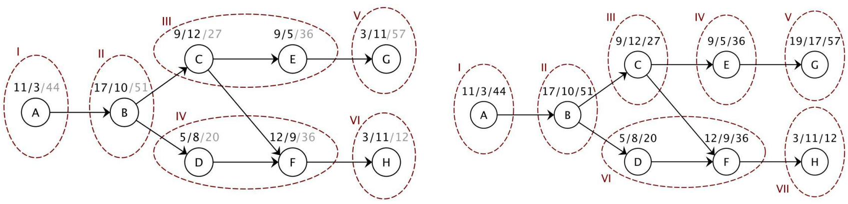

Fig 2 Solution by TSALBP-1 (m = 6) (left). Solution by TSALBP-1_erg (m = 7) (right).

The ergonomic risk presented a big variety of factors to which are exposed the workers, therefore not easy to obtain a single value associated the ergonomic risk. In this study we propose unify three ergonomic methods for obtain a only value for the ergonomic risk associated with each of the tasks.

The methods chosen are: OCRA (Colombini, et. al., 2002) method for analysis the repetitive movements, the NIOSH (Waters, et. al., 1994) method for manual handling and the RULA method (McAtamney and Corlett, 1993) for the postural load.

The determination the risk associated with each task can see in work presented by Bautista et al., (2015a).

In such conditions, the following model is proposed for the line balancing problems whose parameters and variables are:

Parameters

J	Set of elemental task $(j = 1,\ldots,\lvert J\rvert)$.
K	Set of workstations $(k = 1,\ldots,\lvert K\rvert)$.
Φ	Set of ergonomic risk factors $(\phi = 1,\ldots,\lvert\Phi\rvert)$.
t_j	Processing time of the task j $(j = 1,\ldots,\lvert J\rvert)$ at normal activity.
a_j	Linear area required by the elemental task j $(j = 1,\ldots,\lvert J\rvert)$.
$\chi_{\phi,j}$	Category of the task j $(j = 1,\ldots,\lvert J\rvert)$ associated to the risk factor ϕ $(\phi = 1,\ldots,\lvert\Phi\rvert)$.
$R_{\phi,j}$	Ergonomic risk of task j $(j = 1,\ldots,\lvert J\rvert)$ associated to the risk factor ϕ $(\phi = 1,\ldots,\lvert\Phi\rvert)$. Here, $R_{\phi,j} = t_j \cdot \chi_{\phi,j}$.

P_j	Set of direct precedent tasks of the task j $(j = 1,\ldots,\lvert J\rvert)$.
c	Cycle time. Standard time assigned to each workstation to process its workload (S_k)
m	Number of workstations. In this case, $m = \lvert K\rvert$.
A	Available space or linear area assigned to each workstation.

Variables	
$x_{j,k}$	Binary variable equal to 1 if the elemental task j $(j = 1,\ldots,\lvert J\rvert)$ is assigned to the workstation k $(k = 1,\ldots,\lvert K\rvert)$, and to 0 otherwise.
R_ϕ	Maximum ergonomic risk, associated to the risk factor ϕ $(\phi = 1,\ldots,\lvert\Phi\rvert)$, allowed to each workstations.
$\overline{R}(\Phi)$	Average ergonomic risk due to the set of factors Φ related to the production line.

TSALBP-R_erg:

$$\min \overline{R}(\Phi) = \frac{1}{|\Phi|}\sum_{\phi=1}^{|\Phi|} R_\phi \tag{1.1}$$

Subject to:

$$\sum_{\forall k\in K} x_{j,k} = 1 \qquad (j = 1,\ldots,|J|) \tag{1.2}$$

$$\sum_{\forall j\in J} t_j \cdot x_{j,k} \le c \qquad (k = 1,\ldots,|K|) \tag{1.3}$$

$$\sum_{\forall j\in J} a_j \cdot x_{j,k} \le A \qquad (k = 1,\ldots,|K|) \tag{1.4}$$

$$R_\phi - \sum_{\forall j\in J} R_{\phi,j} \cdot x_{j,k} \ge 0 \qquad (k = 1,\ldots,|K|)\wedge(\phi = 1,\ldots,|\Phi|) \tag{1.5}$$

$$\sum_{\forall k\in K} k\left(x_{i,k} - x_{j,k}\right) \le 0 \qquad \left(1 \le i,j \le |J| : i \in P_j\right) \tag{1.6}$$

$$\sum_{\forall k\in K} k \cdot x_{j,k} \le m \qquad (j = 1,\ldots,|J|) \tag{1.7}$$

$$\sum_{\forall j\in J} x_{j,k} \ge 1 \qquad (k = 1,\ldots,|K|) \tag{1.8}$$

$$x_{j,k} \in \{0,1\} \qquad (j = 1,\ldots,|J|) \wedge (k = 1,\ldots,|K|) \tag{1.9}$$

In the model, the objective function (1.1) expresses the minimization of the ergonomic risk of the line. This risk is measured as the average ergonomic risk due to a set of factors Φ. Constraints (1.2) indicate that each task can only be assigned to one workstation. Constraints (1.3) and (1.4) impose the maximum limitation of the workload time and the maximum linear area allowed by the workload of each workstation. Constraints (1.5) determine the ergonomic risk associated to the factor $\phi \in \Phi$ at each workstation. Constraints (1.6) correspond to the precedence task bindings. Constraints (1.7) and (1.8) limit the number of workstations and force that there is no empty workstation, respectively. Finally, constraints (1.9) require the assignment variables be binary.

3 Computational Experience

By means of the proposed model we analyze the influence of the constraint of maximum available area (A = 4m and A = 5m) on the maximum risk to which workers are subjected, given number of workstations and a cycle time for each of them.

For this was used a production plan corresponding to a Nissan's engine plant in Barcelona (NMISA: Nissan Motor Ibérica - BCN). In this plant are assembled nine different kinds of engines grouped in 3 families: p_1, p_2 and p_3 are engines for crossovers and SUVs; p_4 and p_5 are for vans; and p_6, p_7, p_8 and p_9 are intended for medium tonnage trucks; all this engines require 140 operations.

The formulation was solved with the CPLEX (v11.0) software, running on a Mac Pro computer with an Intel Xeon, 3.0 GHz CPU and 2 GB RAM memory under the Windows XP operating system. In all the executions, the CPU time was limited to 2 hours.

Computational experience initiates from a number of workstations that ranges between 19 and 25, inclusive, a cycle time of 180s and two values of available space for workers at the station (A = 4m and A = 5m).

The purpose is to observe how it affects the establish areas in relation to minimize ergonomic risks in the assembly line.

Figure 3 present a Pareto frontier (m versus $\overline{R}_\phi$) for three values of the linear area (4, 5 and ∞) assigned to each station.

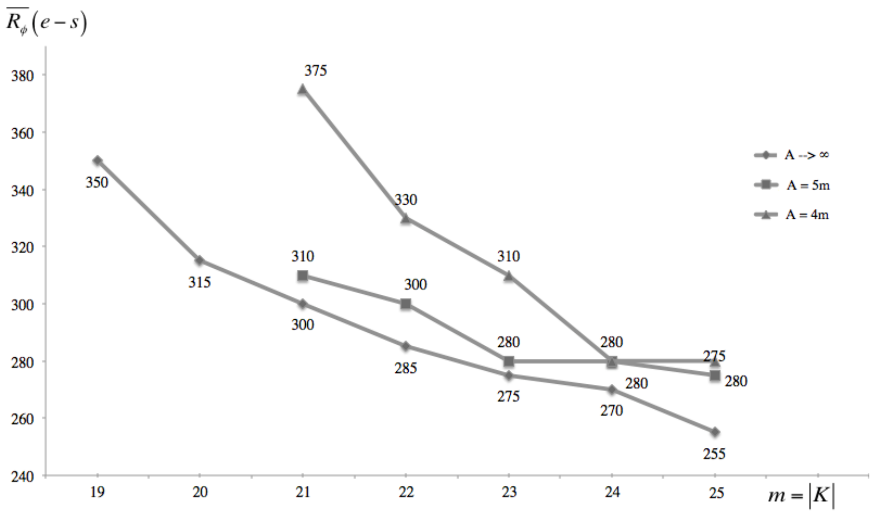

Fig 3 Pseudo-optimal solutions, *m* versus $\overline{R_\phi}$, without limiting the linear area and limiting it to 4 and 5 meters.

It is worth noting that increases in the number of workstations lead to a reduction in the maximum ergonomic risk in all cases. When the line comprises 19 stations only found solution for a infinite area; however, when the work area is limited to 4 and 5 meters feasible solutions materialize for 21 workstations.

The maximum risk for an infinite area is 350 e-s (a risk category value of 1.94) with 19 stations, whereas the minimum ergonomic risk found is 255 e-s (a risk category value of 1.42) with 25 stations.

When to analyze the results to limiting the area to 5 and 4 meters, we find a maximum ergonomic risk of 310 e-s (a risk category value of 1.72) and 375 e-s (a risk category value of 2.08) with 21 stations and the minimum ergonomic risk found is 275 e-s (a risk category value of 1.53) and 280 e-s (a risk category value of 1.55) respectively.

4 Conclusions

Given the increased relevance of all movements and postures performed by employees at work, it is desirable to establish a workspace that meets a number of requirements regarding occupational health and safety conditions. Thus, the adaptation of job position to the operator dimensions is required to enhance mobility, to delimit sufficient space for equipment, tools, and work materials. In this way the security and accessibility are guaranteed.

On the above and drawing upon the family of models TSALBP, we propose a new model to balance assembly lines minimizing ergonomic risks and complying the constraints in regard with the linear workspace by workstation.

To analyze the space effects on workers' occupational health conditions, we have used a case study in Nissan's engine plant in Barcelona. The obtained results allow us to conclude, for this experiment, that both a greater number of stations on the line and increased available space reduce the ergonomic risk of the assembly line without changing its production capacity.

In future works it would be interesting to analyze other case studies in order to extend the conclusion of this work to different industrial sectors.

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