European Journal of Operational Research 251 (2016) 814–829

Contents lists available at ScienceDirect

European Journal of Operational Research

journal homepage: www.elsevier.com/locate/ejor

Production, Manufacturing and Logistics

Models for assembly line balancing by temporal, spatial and ergonomic risk attributes

Joaquín Bautista*, Cristina Batalla-García, Rocío Alfaro-Pozo

ETSEIB UPC, Universitat Politècnica de Catalunya, Avda. Diagonal 647, 08028 Barcelona, Spain

ARTICLE INFO

Article history:
Received 11 February 2014
Accepted 18 December 2015
Available online 29 December 2015

Keywords:
Manufacturing
Ergonomic risks
Flexible manufacturing systems
Assembly line balancing
Linear programming

ABSTRACT

Assembly lines with mixed products present ergonomic risks that can affect productivity of workers and lines. Because of that, the line balancing must consider the risk of injury in regard with the set of tasks necessary to process a product unit, in addition to other managerial and technological attributes such as the workload or the space. Therefore, in this paper we propose a new approach to solve the assembly line balancing problem considering temporal, spatial and ergonomic attributes at once. We formulate several mathematical models and we analyze the behavior of one of these models through case study linked to Nissan. Furthermore, we study the effect of the demand plan variations and ergonomic risk on the line balancing result.

1. Introduction

Manufacturing and/or assembly lines are common in product-oriented production systems. This is the case of the automotive sector, where the use of the same line to process different product types is very common. In such cases, the products although be similar, differ in the use of resources and components' consumption. For that reason, once the product, the process, and the line layout configuration have been established, the first step to design a mixed-product assembly line is to average the processing times of operations that are required by the different product types, according to the proportions of each product type in the demand plan. Then, the second design decision is the line balancing.

The Assembly Line Balancing Problem (*ALBP*) is a classic problem from literature (Salveson, 1955). The problem focuses on assigning the set of elementary tasks, necessary to assemble or disassemble a product (e.g., engines, batteries, cars), to the set of workstations or modules that compose the line, consistently and efficiently. These workstations (commonly associated with teams of workers and/or robots) are typically arranged in series, one behind another, and connected by a transport system that allows the movement of the work in progress at a constant speed. Thus, each workstation has a constant time (cycle time, c) to complete the assigned workload.

* Corresponding author. Tel.: +34 93 4011703; fax: +34 934016054.
E-mail addresses: joaquin.bautista@upc.edu, joaquin.bautista@prothius.com (J. Bautista), cristina.batalla@upc.edu (C. Batalla-García), rocio.alfaro@upc.edu (R. Alfaro-Pozo).

http://dx.doi.org/10.1016/j.ejor.2015.12.042
0377-2217/

Depending on the constraints taken into account, the problem can be divided. Indeed, Baybars (1986) classified the *ALBP* family into two types of problems:

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

The *SALBP* class contains assembly problems that attempt to minimize the total idle time when two types of task assignment constraints are exclusively considered:

(1) Cumulative constraints associated with the available work time at workstations.
(2) Precedence constraints established by the order in which the tasks must be executed.

On the other hand, the *GALBP* class (Becker & Scholl, 2006) contains problems with additional considerations, such as (1) the restricted assignment of tasks (Scholl, Fliedner, & Boysen, 2010); or (2) the assignment in block of certain tasks (Battaïa & Dolgui, 2012).

However the original problems have been extended in the literature in the last decades (Battaïa & Dolgui, 2013), resulting in problems that consider, in addition to the cycle time (c) and the number of workstations (m), other attributes, such as spatial conditions and ergonomic parameters.

Problems that consider the space or area (A) available for materials and tools at each workstation are included in the family problems whose name is Time and Space Constrained Assembly Line Balancing Problems (*TSALBP*) (Chica, Cordón, Damas, & Bautista, 2010; Chica, Cordón, Damas, & Bautista, 2011). Given a set J of $|J|$ tasks, with their temporal t_j and spatial a_j attributes

Table 1
SALBP and *TSALBP* typology.

Name	m	c	A	Type
SALBP-F	Given	Given	–	F
SALBP-1	Minimize	Given	–	OP
SALBP-2	Given	Minimize	–	OP
SALBP-E	Minimize	Minimize	–	OP
TSALBP-F	Given	Given	Given	F
TSALBP-m	Minimize	Given	Given	OP
TSALBP-c	Given	Minimize	Given	OP
TSALBP-A	Given	Given	Minimize	OP
TSALBP-m/c	Minimize	Minimize	Given	MOP
TSALBP-m/A	Minimize	Given	Minimize	MOP
TSALBP-c/A	Given	Minimize	Minimize	MOP
TSALBP-m/c/A	Minimize	Minimize	Minimize	MOP

($\forall j = 1, \ldots, |J|$) and a precedence graph, these problems focus on assigning each task to a single workstation, such that:

(1) All precedence constraints are satisfied.
(2) No workstation with workload time greater than the cycle time, (c).
(3) None workstation requires an area greater than the available area per station (A).

In short, considering the incorporation of the different attributes of tasks defined above into the balancing problems and the optimization criterion, both families of problems, *SALBP* and *TSALBP* (Bautista & Pereira, 2007), include a set of four and eight problem types, respectively (Table 1).

For both typologies, the column “Type” indicates if the problem is one of feasibility (F), mono-objective (OP) or multi-objective (MOP); and the columns “m”, “c” and “A” indicate if these attributes are variables (Minimize) or parameters (Given). It should be noted that *SALBP* family do not consider the spatial attribute.

Similarly, some precedents in literature incorporate ergonomic parameters into the line balancing problems, in addition to the technological and managerial restrictions discussed so far. Indeed, Otto and Scholl (2011) proposed two ways to consider the ergonomic risk in the workstations of a line for the *SALBP-1*. The first one consists of adding constraints that limit the maximum allowed ergonomic risk; and the second proposal defines a new objective function that minimizes the number of workstations and the global ergonomic risk of the line using a weighting coefficient. In both proposals, they incorporated the ergonomic risk of an assembly line by means of three methods; the revised *NIOSH* (the National Institute for Occupational Safety and Health) equation and the job strain index; the *OCRA* (Occupational Repetitive Action) method; and the *EAWS* (European Assembly Worksheet) method, which was created for assembly production systems.

In the same vein, other authors have also incorporated ergonomic parameters into line balancing problems. Bautista, Batalla, and Alfaro (2012, 2013) used constraints to limit the maximum and minimum risk allowed at each workstation of the line within the *TSALBP* family of problems. Thus, the authors proposed a new family of problems called *TSALBP_erg*. Specifically these authors (Bautista et al., 2012, 2013) consider that ergonomic risk, within manufacturing environments, is given basically by the components related to both somatic and psychological comfort.

The psychological comfort refers to the set of mental conditions required by workers toper form their work. These conditions are autonomy, social support, acceptable workloads and a favorable work environment. There are several methods to evaluate this component of ergonomic risk, such as the *COPSOQ* (Copenhagen Psychosocial Questionnaire) that was adapted and validated in Spain with the name of *ISTAS 21*, the *LEST* method that was developed by the “Laboratoire d’Economie et Sociologie du Travail” and other methods with less reliability.

Table 2
Classification of the level of risk by categories and actions to consider.

Level of risk	Category (χ)	Suggested action
Acceptable	1	No action is required because there is no risk to the worker.
Minor/moderate	2	An analysis of the workstation is necessary. In the future, corrective actions for its improvement are recommended.
High	3	An analysis and improvement of the workstation and medical supervision are immediately required. Regular checks are also recommended.
Unacceptable	4	Immediate modification of the workstation is required because of the worker presents serious illness

The somatic comfort concerns the set of physical demands to which a worker is exposed throughout the workday; physical demands that can potentially cause muscle contractions that compress nerve and vascular structures and induce chronic pain. In most cases, this pain is located in the upper extremities and back. There are several specific methods that analyze different risk factors to assess these types of ergonomic risk, such as postural loads, repetitive movements and manual handling.

- *Postural loads*: the workers may adopt inappropriate, asymmetric or awkward postures throughout the workday. These postures can cause certain stress to one or more anatomical regions. Some of these postural loads are hyper-extensions, hyper-flexions and hyper-rotations that may result in fatigue and musculoskeletal disorders over the long term. The methods found in the literature to analyze these types of ergonomic risk factors are the *RULA* (Rapid Upper Limb Assessment) (McAtamney & Corlett, 1993), the *REBA* (Rapid Entire Body Assessment) (Hignett & McAtamney, 2000) and the *OWAS* (Ovako Working Analysis System) (Karhu, Kansi, & Kuorinka, 1977).
- *Repetitive movements*: the worker can perform several operations or activities involving effort and rapid or repetitive motion of small muscle groups. This set of repeated upper-limb movements may cause long term musculoskeletal injuries. To assess the ergonomic risk that involves this type of movement we use the *OCRA Check List* (Occupational Repetitive Action) (Colombini, Occhipinti, & Grieco, 2002).
- *Manual handling*: some tasks performed by workers involve the object lifting, movement, push, grip and transport that may be physically harmful. The *NIOSH equation* (National Institute for Occupational Safety and Health) (Waters, Baron, & Kemmlert, 1997) and the Tables from Snook and Ciriello (1991) are methods to analyze this risk factor.

Despite the large number of available methods to assess ergonomic risks, one of the major drawbacks found is the lack of unification of these methods. The specialization of each method into a single muscle disorder, complicates the assessment and granting of an ergonomic risk level given a job with all musculoskeletal disorders (*TME*) that are caused by postural loads, repetitive movements and manual handling. For this reason, we propose the following unified classification of the risk levels (Table 2).

The above classification (Table 2) allows us to determine the risk level of tasks in regard with the somatic comfort, considering postural loads, repetitive movements and manual handling simultaneously. In this way, we can obtain an only risk value for all the set of tasks assigned to a workstation, from the ergonomic levels