

## Assembly line balancing with ergonomics paradigms: two alternative methods

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**Abstract:** In this paper, the assembly line balancing problem when ergonomics principles are taken into account is considered. Two different approaches are presented and discussed with a numerical example to provide new insights on the field and to illustrate their use on a didactic example. The first one applies a multi-objective model based on the energy expenditure, used to estimate the ergonomics level. The second one transforms the energy expenditure rate in a rest time in order to reduce the multi-objective problem to a single objective one. The two methods are alternatively usable in practice and a numerical model demonstrates their foundation.

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**Keywords:** Assembly Balancing Problem, Ergonomics, Energy Expenditure, Rest Allowance, Pareto Frontiers.

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### 1. INTRODUCTION

In many industrial sectors, the production of high value and customized products is even today only feasible with a large involvement of a highly skilled workforce. Moreover, in many countries the increased presence of highly skilled elderly workers not easily substitutable with robots or machines requires the development of new strategies capable to integrate assembly system design with ergonomics and safety science. In this context, a poor ergonomic design of assembly and manufacturing systems can generate a large amount of sick leaves due to musculo-skeletal disorders (MSDs). Thus, it is even more necessary to design efficient assembly systems and enhance work related satisfaction of human operators. As also highlighted in the new European Horizon 2020 Program (i.e. the Factory of the Future calls), this will require new thinking both on scheduling of work and design of attractive and safe workplaces, taking into account the ageing workforce needs. In fact, in the European Union (EU), over 38% of occupational diseases are related to MSDs (EHSAW 2010) with a cost up to 2% of the Gross National Product in the EU. Bevan (2012) estimates more than 200 billion € for direct and indirect costs of MSDs. Thus, the ergonomics of the system needs to be deeply analyzed and coupled with the time and methods analysis in order to obtain a final assembly system really performant in the short and medium term. Recent research of the authors (Battini et al., 2011) has demonstrated a link between productivity and ergonomics in assembly systems. In particular, some recent studies are closely related and complementary to our work: Kazmierczak et al. (2007), Otto and Scholl (2011), Bautista et al. (2013), Cheshmehgaz et al. (2012) and Otto (2014) introduce new constraints and define ergonomics-objective functions in the ALBP formulations, supporting the analysis with traditional ergonomics evaluations techniques (observational methods). A large consensus is also given in the automotive industry community on the application of the

European Assembly WorkSheet (EAWS), which grants load points for unfavourable physical workload and due to the total score assigns a traffic light risk scheme to work situations (Schaub et al, 2013). However, the observational methods applied by EAWS and the other studies in the field are subject to the usual limitations of this category, first of all large amount of time required to reach a precise estimation and strong dependence on the analyst subjective perception during the observation phase and input parameters evaluation. In 2014, the authors have firstly introduced the ergo-balancing approach by applying the energy expenditure computation method and a multi-objective optimization approach (Battini et al, 2014). The novelty of this approach is the analysis of the integration of ergonomics on ALBP based on energy expenditure with two alternative methods. Using energy expenditure formulations simplifies the problem and speed up the solving process (Battini et al, 2104). Moreover it permits to convert the ergonomics evaluation into rest allowance (Rohmert, 1973), thus reducing the multi-objective problem to a single-objective one. In this new work, we aim to discuss by a methodological point of view two alternative methods applicable in order to obtain an optimized assembly system by taking into consideration both ergonomics and productivity paradigms. The first one applies a multi-objective optimization approach in order to distinguish the objective function linked with the assigned work load (the time dimension) from the objective function linked with the ergo-quality level of the workstations (thus the ergonomics dimension). Multi-objective optimization has been applied in many fields of science, where optimal decisions need to be taken in the presence of trade-offs between two or more conflicting objectives. Minimizing ergonomics risk while maximizing productivity is possible if we involve the necessary input data right from the beginning of the system design phase. In practical problems, there can be more than two objectives. By keeping the objective functions separated during the analysis it's possible to define how an

improvement in one of them could affect the others and viceversa. The second method here discussed transforms the original multi-objective problem into a simpler single objective optimization algorithm by transforming the energy expenditure amount during assembly task into a rest time in order to express the balancing and sequencing problems in a time-unit base. The two methodological approaches works well in practical environments and can be applied alternatively in accordance to the input data available. While the first one could often bring to a set of different feasible solutions and drive the designer towards a unique final solution only after an interactive analysis, the second one tries to simplify the problem to a unique objective function.

## 2. METHODS DESCRIPTION

### 2.1 Method n°1: multi-objective problem based on energy expenditure

The first approach proposed by the author applies a multi-objective problem with two objective functions: the solution is not a single optimum but instead it is represented by the set of balancing designs belongings to the Pareto frontier. The methodology could be easily extended to different kind of ALBP models and different objective functions, according to Scholl, A. (1999). The procedure is made up by 4 steps:

Step 1) Calculate the mean working time for each task by a times and method analysis technique.

Step 2) Calculate the energy expenditure to be assigned to each task by using formulas provided by Garg et al. (1978) and parametric maps provided by Battini et al. (2014).

Step 3) Express the same objective function in time and energy, thus defining two different objective functions.

Step 4) Solve the bi-objective problem by defining and mapping in a graph all the feasible solutions and the balancing designs belonging to the Pareto frontier.

In order to give an example of the methodology we here consider the so-called SALBP-2 method, which allows the minimization of the cycle time for a defined number of stations in order to increase the productivity of the assembly line when constrained by a trial cycle time  $c$ , known and fixed (Scholl, 1999). In the example following reported an assembly process consisting of  $n = 17$  tasks denoted A, B,...,Q is used. This example represents a real case regarding small cleaning equipment. Some simplifications, such as tasks grouping, have been made without any loss of information. Let's consider a set A of tasks to be assigned to work stations, the assembly times ( $t_j$ ) and the direct predecessors of the tasks are given. For each task  $j$  also the energy expenditure ( $e_j$ ) is computed and coupled with a task node in the precedence diagram in Figure 2. The  $e_j$  values are computed using the formulas provided the well-known study of Garg et al (1978), by using the analytical ergonomic measurement

systems based on oxygen or metabolic consumption, where each movement features specific energy expenditure. Such approach seems to be very useful in this context because it quickly calculates the ergonomics level of different assembly tasks without leave the evaluation to the subjective analyst interpretation. According to Garg et al. (1978) the net metabolic energy expenditure is influenced by: gender, body weight, load weight, vertical heights of lifting/lowering, lateral movements of arms in horizontal plane, speed of walking and carrying load, postures and time duration of the task. To help an easy and fast computation of the tasks' energy values a set of parametric tables have been recently provided by the authors in Battini et al. (2014). Thus, it is possible to define a generic SALBP-2 model that aims to jointly minimize two objective functions, the smoothness index in time and the smoothness index in energy expenditure between the different work stations. Based on the binary linear model (Scholl, 1999) in the single-model assembly line, the binary variable called  $x_{jk}$  is used to indicate the assignment and  $B_k$  is the set of task assignable to the station  $k$  (within a set of workstations from 1 to  $K$ ). We introduce the first objective function expressed in time, the Time Smoothness Index ( $SX - T$ ) to measure the equality of work distribution among the stations:

$$\min SX - T = \min \sqrt{\sum_{k=1}^N \left( c_r - \sum_{j \in B_k} x_{jk} \cdot t_j \right)^2} \quad (1)$$

where  $c_r = \max \left\{ \sum_{j \in B_k} x_{jk} \cdot t_j \mid k = 1 \dots m \right\}$ ,  $E_j$  is the earliest station of task  $j$  and  $L_j$  is the latest station of task  $j$  (Scholl, 1999), with the following constraints:

$$\sum_{k \in [E_j, L_j]} x_{jk} = 1 \quad \text{for } j = 1 \dots n \quad (2)$$

$$\sum_{j \in B_k} x_{jk} \cdot t_j = T_k \leq c \quad \text{for } k = 1 \dots K \quad (3)$$

$$\sum_{k \in [E_h, L_h]} k \cdot x_{hk} \leq \sum_{i \in [E_j, L_j]} i \cdot x_{ji} \quad \text{for } (h, j) \in A \text{ and } L_h \geq E_j \quad (4)$$

The second objective function expressed in energy, the Energy Smoothness Index ( $SX - E$ ), in order to reduce risks among the stations distributing physical load among workers at a similar low level (as underlined also by Otto and Scholl, 2011), is defined as follows (with the same constraints as the previous one):

$$\min SX - E = \min \sqrt{\sum_{k=1}^N \left( E_r - \sum_{j \in B_k} x_{jk} \cdot e_j \right)^2} \quad (5)$$

where  $E_r = \max \left\{ \sum_{j \in B_k} x_{jk} \cdot e_j \mid k = 1 \dots m \right\}$

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