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# Cobotic Assembly Line Design Problem with Ergonomics

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**Abstract.** Demands for smaller lot sizes of mass-customized products increased the need for flexibility and adaptability in production lines. Semi-automatic manufacturing systems that involve human operators as well as technological equipment increase the flexibility of manufacturing systems. Such systems combine the benefits of human flexibility and new industrial and assistive technology. The key combinatorial problem to solve in the design of semi-automatic manufacturing lines is the assembly line balancing problem with the selection of equipment. An efficient and sustainable line design requires a cost-effective choice of equipment, and the presence of human increase the importance of ergonomics. In this work, we propose a Multi-objective Mixed-Integer Nonlinear Programming (MO-MINLP) for the design of semi-automated assembly lines. The objectives are the optimization of the design cost and the ergonomics level, modeled with the fatigue and recovery of workers. We propose to solve the problem with a bi-objective local search algorithm, based on the Iterative Local Search metaheuristic. We apply the algorithm on a case study to illustrate the originality of the problem and the solving algorithm.

**Keywords:** Semi-automated manufacturing systems; Assembly Line Design Problem; ergonomics; Human-Machine collaboration; Industry 4.0

## 1 Introduction

The current industrial context is characterized by more and more demand for mass-customized products through high agility and flexibility of manufacturing systems. Flexibility and quick changes have become a critical factor in the design of manufacturing systems to adapt to the highly competitive global competition and changing demands. One of the factors that favorite the flexibility of manufacturing systems is the association of human and machine, with an adequate Level of Automation (LoA).

There are three types of manufacturing systems: manual; automated; and semi-automated systems. Even if a manual system is highly flexible and offers a better ability for complex parts assembly, the repetitive aspect of work and the manipulation of loads and heavy tools exposes industrial workers to work-related musculoskeletal disorders

(MSDs). Hence, manual lines require a high level of ergonomics and safety. On the other hand, an automated production system provides advantages such as work without break and systems without ergonomic risks, but automatic system flexibility is low due to programming issues, and difficulty in assembling complex and small parts, furthermore, a full level of automation investment cost is high compared to manual systems. Semi-automatic systems benefit from the advantages and strengths of both parts but require an adequate Human-Machine collaboration.

The interaction between humans and machines in semi-automated systems improves complex assembly processes, especially when a machine or equipment provides power assistance to the worker [1]. With the ongoing process of digital transformation in Industry 4.0, there is more and more technological support to enhance the hybridization of collaboration between humans and machines in manufacturing systems. Among the technological equipment used in industry, e.g.: the intelligent automation devices, touch-based admittance control of the robot, collaborative robot (cobot), and assistive exoskeleton technology. There is also an emerging concept of Operator 4.0 [2], this concept within the framework of Industry 4.0 push towards better Human-Machine work for better ergonomics and sustainability of manufacturing systems.

The combinatorial problem associated with the sustainable design of semi-automatic manufacturing lines is the Assembly Line Design Problem with the assignment of operations and the selection of adequate collaborative equipment. This is a strategic problem that involves substantial costs, that contain costs related to the purchase and maintenance of equipment, spare parts, and workers' training. On the other hand, equipment affects the level of ergonomics and productivity of the line through their effect on the physical load of operations and their processing times. Since the design of semi-automatic assembly lines involves conflicting objectives, a multi-objective trade-off between cost and ergonomics could assist decision-makers to choose the most suitable design configuration of the line, from a set of trade-offs between the cost and the ergonomics.

In this article, we propose a bi-objective approach for the Assembly Line Design Problem for semi-automated assembly lines. The first objective is the total design cost, and the second is an ergonomics criterion that considers the fatigue and recovery of workers. In the sequel, the next Section presents a brief literature review of the existing literature related to our work and open research questions. In Section 3, we present the problem description and formulation. In Section 4, we describe a bi-objective algorithm proposed to obtain potentially non-dominated points. Section 5 presents a didactical example to illustrate the novelty of the approach and its potential. Finally, the conclusion and perspectives in Section 6.

## 2 Literature Review

Assembly lines are manufacturing systems designed for the final assembly of products. This mode of production is suitable for mass production, or mass customization. Several decisions have to be made in the design of assembly lines, including the combinatorial optimization problem of assigning different operations to be performed for each workstation, denoted the Assembly Line Balancing Problem (ALBP). The problem raise interest in the literature, research has been made on different variants of ALBP and solutions approaches [3], [4]. The ALBP becomes more complicated with equipment selection that considers the assignment of operations and the selection of equipment for each workstation referred to as the Assembly Line Design Problem (ALDP) [5]. In the literature, several works have focused on the ALDP and the introduction of ergonomics into the assembly systems. In the next Subsection, we present some related works regarding the ALDP while in Subsection 2.2, we present works that integrate ergonomics into the assembly lines.

### 2.1 Assembly Line Design Problem

The articles that investigate the ALDP mainly consider the optimization of criteria related to the costs, such as in [6], [7]. Another related problem is the so-called Robotic Assembly Line Balancing Problem (RALBP), that extends the ALBP with the additional assignment of robots as workstations equipment [8], [9]. Other optimization problems that consider equipment selection are the transfer line balancing problem, these types of lines are fully automated in the majority of cases. In transfer lines, a machining tool (multi-spindle) performs machining operations by block [10], [11].

Since the ALDP present conflicting objectives, the problem was considered in a multi-objective approach, we refer particularly to the work of [12], [13], [14] and [15]. The literature review in [16] presents a more detailed review of cost and profit assembly line design and balancing problems.

Although the literature presents works that study the modeling and the resolution of the ALDP, usually, these works consider only automatic systems, without mention of human presence and consideration of ergonomics.

### 2.2 Assembly Lines with Ergonomics

MSDs are a significant source of disease and absenteeism, affecting the economics of the production system and resulting in high compensation and absenteeism costs [17], with a decrease in the overall system productivity and quality performance. Furthermore, the aging workforce aggravates the problem related to ergonomics, with two-third of the European Union workforce aged over 50 years old [14].

In the last decades, some works attempt to include ergonomics into the ALBP to mitigate the risks and reduce MSDs, but mainly focusing on manual assembly lines. Most articles in the literature consider the ergonomics with a risk assessment criteria, such as in [18], [19].

Quantitative and biomechanical models are used in some articles, e.g., in the work of [20] with the quantification of fatigue and recovery of workers in assembly lines. Energy expenditure and rest allowance models as quantitative criteria were used in the articles [21] and [22], and the equipment vibration was considered recently in ALDP [23]. We refer for more details, to a recent literature review [24].

Contribution including the safety of workers and ergonomics are recent, and they are not numerous. Furthermore, they only focus on fully manual assembly lines. New advanced equipment and intelligent assistive tools, allow introducing the human-machine collaboration in the design of semi-automatic assembly lines. In this work, we aim to include ergonomics in the challenging assembly line design problem.

## 3 Problem Description and Formulation

An assembly line is composed of a set of workstations arranged in a linear form, and connected by a material handling device such as conveyor that transport parts between workstations at the end of takt time. The takt time denoted $T$ represents the maximal amount of time sub-assembly products should be processed at a given workstation, often defined by customer demand. The assembly lines are paced without buffer, and the takt time or production rate $(\frac{1}{T})$ defines the pace of the line.

We consider the hypothesis of ALDP (cf. [5]). The decisions are the assignment of operations and the assignment of a unique set of equipment to each workstation. We consider semi-automatic assembly lines, with the presence of a worker in each workstation.

We suppose that equipment is composed of one or many components (e.g. basic manual tool and an exoskeleton). All operations could be executed with all equipment, and only one equipment could be assigned to each workstation. A given set of equipment could influence the physical load of operations and/or the processing time. Each set of equipment has an associated cost. The equipment influences the productivity and the level of ergonomics of a workstation.

The binary decision variable $x_{j,k}$ is used for the assignment of the operation $j \in V$ to a workstation $k \in W$, with $V = \{1, .., n\}$ the set of operations and $W = \{1, .., m\}$ the set of workstations. The binary decision variable $y_{i,k}$ is used for the assignment of an equipment $i \in E$ to workstation $k$ , with $E = \{1, .., r\}$ the set of equipment. $C_i$ represents the cost of equipment $i \in E$.

Equipment $i$ influences the deterministic processing time $t_{i,j}$ of operation $j$ and/or the physical load, defined with $Fload_{i,j}$. Operation time or processing time $t_{i,j}$ set the standard time in which a worker should complete a given operation $j$ when executed with the equipment $i$. $Fload_{i,j}$ represents the physical load of operation $j$ when executed with the equipment $i$. The assignment of operations to workstations must respect the takt time $T$.

### 3.2 Ergonomics Level

We use the fatigue and recovery model developed by [25] as a criterion for assessing the ergonomics level in a workstation $k$. The ergonomics level (i.e., the fatigue and recovery criterion) after one takt time in a given workstation is represented with the ALDP notations as in the following equation:

$$F_k = 1 + \left(e^{-K(\sum_{i\in E}\sum_{j\in V}\int_0^{t_{i,j}} Fload_{i,j}(u).x_{j,k}.y_{i,k}du)} - 1\right) e^{-R.(T-\sum_{i\in E}\sum_{j\in V} t_{i,j}.x_{j,k}.y_{i,k})} \quad \forall k \in W \tag{1}$$

$F_k \in [0,1]$ represents the level of ergonomics in workstation *k* after one takt time *T*, depending on a load of operation and the equipment assigned to that workstation. K and R are constant values, representing the worker's capabilities, which are considered as constant representing an average worker. We refer to the work of [20] and [26] for more details on the ergonomics model and its use in assembly lines, and on the assessment of ergonomics load of operations.

### 3.2 Multi-objective Mixed-Integer Nonlinear Programming

We present in the following the Multi-objective Mixed-Integer Nonlinear Programming (MO-MINLP). To include the ergonomics level in the ALDP.

$$OF\ 1: Maximize\{Min_{k\in W}\{F_k\}\};\ OF\ 2: Minimize\{\sum_{i\in E}\sum_{k\in W} C_i.y_{i,k})\} \tag{2}$$

$$\sum_{k\in W} x_{j,k} = 1 \quad \forall j \in V \tag{3}$$

$$\sum_{i\in E} y_{i,k} = 1 \quad \forall k \in W \tag{4}$$

$$\sum_{i\in E}\sum_{j\in V} t_{i,j}.x_{j,k}.y_{i,k} \le \mathrm{T} \ \forall k \in W \tag{5}$$

$$\sum_{k\in W} k.x_{h,k} \le \sum_{k\in W} k.x_{g,k} \quad \forall (h,g) \in P \tag{6}$$

$$x_{j,k}, y_{i,k} \in \{0,1\} \tag{7}$$

The Objective Function (OF1) maximizes the ergonomics level at the most charged workstation (i.e., workstation $k$ where the worker presents the lowest level of ergonomics: $Min_{k\in W}\{F_k\}$), while the OF2 minimizes the design cost of the assembly line. Constraint (3) assigns each operation to one workstation. Constraint (4) ensures that no more than one equipment can be assigned to the same workstation. Constraint (5) ensures the respect of takt time in each workstation. The respect of precedence constraints, defined with the set of precedence couple $P$ is ensured with the constraint (6). Finally, decision variables are binaries (7).

The MO-MINLP defined with the set of constraints {(2) to (7)} is non-linear due to the OF1 and the product of the two decision variables $x_{j,k}.y_{i,k}$. The problem is denoted Cobotic Assembly Line Design Problem (CALDP) to refer to the specificities of semi-automated assembly lines proposed in this paper.

## 4 Multi-objective Iterative Local Search

ALDP is an NP-Hard combinatorial problem [5], in addition to the combinatorial aspects of the problem, the MO-MINLP, denoted CALDP in Section 3 presents also conflicting objectives, which are the investment cost and the level of ergonomics. It is important to define a compromise between the two objectives and to offer a quick solution to decision-makers. We propose to solve the problem with a metaheuristic. The metaheuristic does not guarantee optimality but can achieve acceptable results in a reasonable computational time.

We propose a multi-objective metaheuristic, based on the well-known framework of Iterative Local Search (ILS) (cf. [27] for more details). ILS is a multi-start based metaheuristic that iterates a specific local search procedure from different starting solutions to sample various regions of the pool of solutions and avoid local optimum. We chose ILS to take advantage of the Cplex's built-in one-tree algorithm, details about the algorithm and its implementation are discussed in [28]. The one-three algorithm allows us to generate quickly multiple feasible solutions to the Robotic Assembly Line Balancing Problem or RALBP (i.e., a feasible balancing solution with operations and equipment assignment defined with a linear formulation from the literature [8]), all multiples solutions are stored in a set or pool of solutions. Since the objective is to improve the level of ergonomics and to reduce the cost, we can make local perturbation to all the solutions in the pool provided by Cplex to improve the values of objective functions.

```
Algorithm: Multi-objective Iterative Local Search
S=GeneratePool()
for each $s_i$ in S do
    do
        $s^{break}$=$s_i$
        LocalSearchTask($s_i$)
        LocalSearchEquipment($s_i$)
    while ($s^{break} \neq s_i$ )
end for
S=Filter(S)
return {S}
```

**Fig. 1.** Pseudo-code of the ILS algorithm

Figure 1 depicts the pseudo-code of the ILS algorithm. We start by generating a pool of feasible solutions S, with different ergonomics level and different cost values that constitute our initial search space. Afterward, for each solution in S, we apply sequential local search procedures. Local search explores the search space, moving from a solution to neighborhood solutions that improves the objective functions.

We start first with a neighborhood with operations, we apply sequentially the classical swap and shift neighborhood, as defined in [4]. The neighborhood applied in "LocalSearchTask" consists of all transformed solutions, which are obtained by a single feasible swap or shift move of operations, without changing the equipment already assigned in each workstation. A swap or shift select the operation to move from the critical workstation (i.e., the most charged workstation with the lowest ergonomics level) since it is likely what could maximize our ergonomics objective function. To improve the ergonomics level, we choose the steepest descent or best-fit procedure that chooses a move leading to the maximum improvement of the current ergonomics level.

Afterward, we apply a local search to optimize the cost "LocalSearchEquipment", without changing the assignment of operations and without decreasing the value of the ergonomics level. For all workstations, we swap the already existing equipment with another one, which is less expensive. The solution is kept when feasible, and when it improves the value of the OF2.

We apply the same two local search procedures as long as the solution stored at the beginning denoted $s^{break}$ is different (i.e, different objective functions) from the solution at the end of the two local search procedures, to ensure that no better solution is still possible.

A filtering stage is applied to keep in the set S only potentially non-dominated points. We use the Pareto Dominance rules to decide if a solution is better than another with respect to both objectives (i.e., a set containing points not dominated by any other points generated by the algorithm constraint so far and using the Pareto dominance rules).

## 5 Illustrative Case Study

We illustrate the approach proposed in this paper with a case study. We use the Buxey ALBP instance from the benchmark of Scholl [4], precedence graph, operation's processing time data are available in https://assembly-line-balancing.de/.

The Buxey's instance has 29 operations; the takt time is equal to 1500s with 14 workstations to assemble the product. Since there are no equipment and physical workload in the literature, we generate the missing data to apply our approach. We generate 10 equipment, with different corresponding costs. The most expensive equipment is better than the others in terms of productivity (lower processing times of operations $t_{i,j}$) and better ergonomics influence (lower physical load of operations $Fload_{i,j}$).

We apply the algorithm ILS to generate the potentially non-dominated points for this instance. We use Cplex V12.8.0 as a solver with default parameters. The application of the algorithm to the case has required computational time of 40s and has led to the solutions represented in Figure 2. First, the algorithm generated with the use of Cplex a pool of 30 feasible solutions, Figure 2 represents the set of initial solutions with bleu diamonds. This initial pool constitutes the input of the ILS algorithm.

With ILS, we obtain 4 potentially non-dominated points, represented with the orange square in the figure. The potentially non-dominated points are obtained with ILS by improving the initial pool of solutions.

By comparing the difference in each criterion between the average solution in the initial pool and the solutions obtained by ILS, we found that, on average, the ergonomics level obtained with ILS is 4.56% better than the average solution of the pool. Also, the average cost is 2.07% lower with ILS than the average solution of the pool.

The approach we proposed is promising to optimize the values of the ergonomics and the total investment cost of assembly lines. Besides, the results are obtained quickly, especially for medium and long term assembly line design problem.

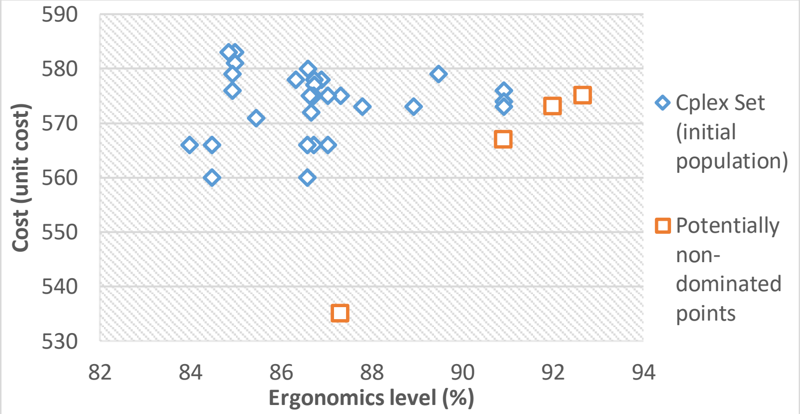

**Fig. 2.** Representation of solutions in the objective space; the x-axis represents the ergonomics level represented in percentage (%) that we seek to maximize, and the y-axis represents the total investment cost, represented in cost unit – Bleu diamonds represent the pool obtained in the generation of initial solutions set with Cplex; Orange square represents the potentially non-dominated points, obtained with the ILS algorithm.

## 6 Conclusion and Perspectives

The integration of ergonomics in manufacturing systems design has gained a growing interest in the last years, particularly for assembly lines. The present work has proposed a new approach with a CALDP model and solving approach, to design semi-automatic assembly systems by taking into account the ergonomics during the execution of operations, with the use of fatigue and recovery of workers as ergonomics criteria (i.e., ergonomics level). The objective functions aim at minimizing both the equipment total cost and the ergonomics level. The consideration of ergonomics in the design stage will also allow reducing the cost of future intervention on already existing systems, and enhance the Human-Machine collaboration. The application of the model to an illustrative case study from the literature shows its competitive computational time as well as its practical usefulness to define a set of potentially non-dominated points. The aim is to provide decision-makers with a model and fast multi-objective algorithm to identify the interesting trade-off between the conflicting objectives.

The Human-Machine collaboration in semi-automated assembly lines is motivated by the increased need for flexibility in manufacturing systems. An essential precondition for effective interaction between humans and machines is the ergonomics of the worker, not only physical but also cognitive. As perspectives, to enable safe sharing of the same physical space by humans and advanced robots and machines, cognitive ergonomics could be considered with the acceptability of new technologies by workers, to improve their acceptance and adoption of sophisticated technologies.

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