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Assembly Line Balancing Problem with ergonomics: a new fatigue and recovery model

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ABSTRACT

Assembly lines are production lines used to manufacture products, ranging from mass-production products to mass-customization with low unit products. Assembly lines consume the largest parts of investment funds and involve the largest proportion of companies' labor force. However, workers in assembly lines are exposed to work-related musculoskeletal disorders (MSDs) and ergonomics problems. Poor distribution of workloads reduces the performance of assembly lines and causes workers MSDs and injuries, largely affecting the economics of production systems and resulting in high workers' compensation and absenteeism costs. Furthermore, ergonomics problems and MSDs impact product quality and decrease productivity. We propose a methodology for taking physical ergonomics into account as early as in the design phase of assembly lines. This methodology is based on Integer Linear Programming for the assembly line balancing problem with consideration of ergonomics with a quantitative fatigue and recovery criterion. As solving approach, we develop a dedicated exact algorithm, denoted Iterative Dichotomic Search, to solve low and medium-size instances of the problem. We validate our approach by proposing numerical experiments and analysis on instances from the literature.

KEYWORDS

Assembly Line Balancing Problem; Design of Manufacturing systems; Ergonomics; Exact algorithm; Fatigue and Recovery model

1. Introduction

Assembly lines are production lines used to manufacture products, ranging from mass-production products to mass-customization with low unit products, varying from big-size products such as aircraft to medium and small size products such as electronic goods. Assembly lines don't only consume the largest parts of investment funds but also involve the largest proportion of companies' labor force. Hence, the understanding and improvement of assembly systems would enhance the

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production firms' performance, with positive effects on the global economy and safety and health of the labor force (Finco et al. 2021). The assignment of operations in assembly lines plays a significant role in ergonomics, even with a fixed cost.

Despite the advance observed in the last decades in the safety and ergonomics of workplaces, workers are still exposed to work-related musculoskeletal disorders (MSDs) and injuries. Prevention of MSDs depends upon the identification and control of risk factors in the workplace and on the application of good ergonomic choices. Studies have shown that MSDs lead to loss of productivity due to higher error rates, injury rates, and absenteeism (Calzavara et al. 2018; Battini et al. 2016). The issue of ergonomics is related to the design of efficient, productive, profitable, and safe production systems for workers. Keep in mind that both performance and human health are central to sustainable manufacturing systems design. According to Bevan (2015), the cost of MSDs is consuming almost 2% of the European Union's gross domestic product, affecting about 44 million EU workers per year. Likewise, the U.S. Bureau of Labor Statistics reported that in 2016, MSDs counted for 32% of private-sector days away from work in the USA.

An analysis of 250 case studies by Goggins et al. (2008) concluded that ergonomics intervention includes a reduction in the number of reported MSDs as well as related lost workdays and workers' compensation costs. Additional benefits reported were mostly positive on the systems productivity, turn-over, and absenteeism, with a typical payback period of less than one year. Besides, numerous studies showed a direct link between poor work environment and ergonomics with the under-performance of manufacturing systems (Yung et al. 2020). In the work of Thun et al. (2011), 55 companies in the automotive industry are analyzed, and companies with ergonomic practices show a better economic performance.

In the first place, the objective in the design stage of manufacturing systems is the optimization of economic efficiency with the sole consideration of cost and profit. Physical ergonomics considerations are usually taken into account later on existing systems with adjustment of posture or investment in equipment to mitigate risks of injuries. However, the original approach of considering ergonomics from the design phase through decision support tools and methods provides more leeway for decision-makers and helps to prevent costly interventions later in already existing systems.

In the literature, there is a promising trend to include ergonomics and workers' health in operations research models for the design phase of assembly lines with the optimization of ergonomics (Savino et al. 2020; Battini et al. 2017; Calzavara et al. 2018). In their literature review, Otto and Battaïa (2017) stated that most ergonomic methods are designed for existing assembly lines, this has led to a simplification of estimation and lack of rigor, only a few ergonomics criteria are suitable for the design stage of assembly lines. Moreover, the majority of ergonomic criteria are non-linear and are difficult to formulate with the linear formulation of ALBP. The non-linearity of criteria and the large number of possible assignments of ALBP raise the question of the algorithm and their efficiency to find an optimal or near-optimal solution. In their survey, Otto and Battaïa (2017) stated that most articles recommend metaheuristics to solve problems but fail to provide a good quality gap to the optimal solution and information about the bounds. Furthermore, Otto and Battaïa (2017) stated that to compare different ergonomics criteria from the literature, an exact solution for the balancing problems is the more neutral base to assess the efficiency of a given approach.

Research opportunities identified in the survey by Otto and Battaïa (2017) suggested addressing two main challenges: the first is the adaptation of ergonomics estimation methods to the needs of preventive planning, and the second is the advancement of modeling and solution approaches. To the best of our knowledge, those challenges have not been addressed. To address those challenges, we propose in this paper an original approach to model and solve the SALBP with an advanced non-linear ergonomics criterion related to physical fatigue and recovery. To solve the problem, we propose a new linearized model which can be solved using a dichotomic search.

In this work, we consider the corresponding optimization problem associated with the assignment of operations into workstations, denoted the Simple Assembly Line Balancing Problem (*SALBP*). Although our findings can be generalized to more General Assembly Line Balancing Problem or *GALBP*, we focus in this paper on the *SALBP* (Battaia and Dolgui 2013).

In the following, we present in Section 2 a literature review of work considering *ALBP* with ergonomics. In Section 3, we present the problem definition and formulation with an explanation of the fatigue and recovery criteria considered to measure the ergonomics level in this work. We propose in Subsection 3.2 the new ILP and show that fatigue and recovery can be formulated as a linear decision problem and an exact solving algorithm in Subsection 3.3. In Section 4, we validate the proposed approach with instances from the literature. Finally, Section 5 contains the conclusion and future research.

2. Literature review

The recent literature highlight the preventive reduction of physical ergonomic risks in operational and tactical planning optimization problems. In their survey, Otto and Battaia (2017) review articles that consider ergonomic risks and propose optimization models and algorithms for the assembly line balancing and job rotation problems. The job rotation scheduling describes the assignments of workers to workstations (Bhadury and Radovilsky 2006; Botti et al. 2021; Asensio-Cuesta et al. 2012). With the appropriate assignment of tasks and workers, ergonomic risks could be smoothed and mitigated (Otto and Battaia 2017).

In this paper, we consider the Simple Assembly Line Balancing Problem *SALBP* hypothesis. The *SALBP* is the core problem in line balancing and is studied in several articles in the literature (Battaia and Dolgui 2013). *SALBP* is known to be NP-hard (Karp 1972; Scholl 1999), the problem complexity and the number of possible assignments raised the question of the physical load and ergonomics evaluation of solutions while balancing an assembly line.

Ergonomics criteria are classified by Chengalur (2004) as qualitative, semi-quantitative, and quantitative methods. Qualitative assessment methods gather observational data about the work and are generally used to screen the work. Semi-quantitative assessment methods use a mix of judgment data and/or quickly obtained quantitative data (e.g., OCRA, RULA, REBA, QEC, etc. (Chengalur 2004; Baykasoğlu et al. 2017)). Semi-quantitative methods may be used for more detailed information about the risk factors of the work and identify necessary future interventions and require mainly objective data. In the literature, only semi-quantitative and quantitative methods are used for the assessment of ergonomics in assembly lines.

2.1. *Semi-quantitative methods*

The work in Otto and Scholl (2011) proposes semi-quantitative methods to incorporate risk assessment tools from the literature such as OCRA, Job Strain Index (JSI), and the European Assembly Worksheet (EAWS) into *ALBP* as constraints or objectives. OCRA for risk assessment of upper extremities in assembly lines was also used by Akyol and Baykasoğlu (2019) and Tiacchi and Mimmi (2018).

Baykasoğlu et al. (2017) proposed a systematic approach for the main assembly line balancing problem and assembly layout problem while considering ergonomic with OCRA as a risk factor.

Choi (2009) proposes different risks element for three categories: environment criteria, postural criteria, and physical loads. Likewise, Özcan Mutlu and Özgörmüş (2012) considers the physical load with an estimation of risks on a defined scale for the optimization of ergonomics in assembly lines.

Some other papers consider more than one criterion in an integrated manner. Xu et al. (2012)

propose to measure ergonomics of the upper extremity in an integrated manner, based on the guideline from the American Conference of Governmental Industrial Hygienists (ACGIH) concerning physical exposures of workers. Ergonomics criteria are exertion frequency, duty cycle, normalized peak force, and vibration. Kara et al. (2014) consider in an integrated way, several industry-originated restrictions such as energy expenditure, workers skills, working conditions, and illumination levels. The objective function considers an aggregation of several costs to minimize, such as workers and equipment costs.

Ergonomic risks are also quantified in several papers by a semi-quantitative customized set of criteria instead of assessment methods available in the literature. Bautista et al. (2016) and Bautista et al. (2017) propose to optimize customized risks of injuries and the linear space given to workers to execute their jobs.

2.2. Quantitative methods

Only a few works in the literature used quantitative-based methods such as energy expenditure (Finco et al. 2021), fatigue (Abdous et al. 2018), and vibration analysis (Finco et al. 2019).

Battini et al. (2016, 2015) proposed a method to estimate the energy expenditure called Pre-determined Motion Energy System; this method helps to estimate the energy expenditure values. Worker's energy expenditures are considered as ergonomic aspects and integrated into the SALBP through the rest allowance evaluation in the work of Finco et al. (2020). The objective is an economic objective with the production rate optimization, ergonomics is considered as a constraint, and the balancing solution must assign a sufficient rest period to allow complete recovery after the effort for workers (Finco et al. 2020).

Physical fatigue and reduction of the ability to execute assembly operations are studied in the work of Carnahan et al. (2001). In this paper, the fatigue and recovery model for the assessment of grip strength was used with SALBP. The objective considered is a weighted sum of takt time and fatigue after several cycles of work and recovery. This work only considers the fatigue of grip strength and proposes only heuristics to solve the problem, while the approach we propose in this paper used more general fatigue and recovery criteria and propose an exact solving approach.

Quantitative assessment methods are more suitable for the design of work and the objective assessment of the ergonomics level (Chengalur 2004). We propose in this work to include ergonomics with a quantitative analytical model of fatigue and recovery. Indeed, the load and repetitiveness of operations in assembly lines can lead to muscle fatigue (Ma et al. 2009), which has been shown to reduce the performance and the product quality and leads to MSDs (Elmaraghy et al. 2008; Kulus et al. 2018). Most of the time, in assembly lines, a high effort, and intensity lead to the fatigue of workers (Givi et al. 2015; Ferjani et al. 2017). Besides, workers can initiate several cycles on several products without the benefit of sufficient rest time to recover and reduce fatigue. To design such work-rest patterns in assembly lines, we propose to consider ergonomics with a quantitative analytical model of fatigue and recovery. In the next Section, we present the problem definition and the quantitative model used as ergonomics assessment criteria with its integration in a linear form with the SALBP classical formulation.

3. Problem definition and exact algorithm

3.1. SALBP with fatigue and recovery model

The SALBP consist of a set of operations $V = \{1, \dots, n\}$ that should be assigned to a set of workstations $W = \{1, \dots, m\}$. t_j represents the processing time of operation j . The technological constraints between operations are represented with the set of precedence $Prec$. With $(h, g) \in P$, operation h is a predecessor of g , the operation g is also called the successor of h . The takt time

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. The takt time is composed of two physical quantities $T = AT + TT$. With AT , the adjusted takt time, which is the strict time to respect when assigning operations to a workstation. The second component of the takt time is the transfer time TT , which represents the time required to transport a product from one station to another, the TT is often of low value or completely negligible. However, in many cases, non-negligible transfer time is observed to transport a product from a workstation to another.

Fatigue is different from posture analysis, even with the right posture and movements, workers would still endure muscular fatigue. Furthermore, the work-rest schedule is important to recover after the work completion. To represent the evolution of fatigue level in assembly lines, we choose the quantitative fatigue and recovery model proposed by Ma et al. (2009, 2010). We choose this fatigue and recovery model since the model's mathematical properties are suitable for the evaluation of workload in assembly lines. Also, we choose this model since it is a general model for a single or group of muscles and was validated experimentally and theoretically with a series of articles in the last decade (Ma et al. 2009; Liu et al. 2018). In this fatigue and recovery model, the evolution of the fatigue depends on the external load and duration of operations, workers' factors or characteristics, and the length of the recovery time at the end of working time, workers benefit from idle and transfer time to decrease fatigue.

The discussion of the exact mechanism of muscle fatigue is beyond the scope of this work. However, the fatigue and recovery model considered is general and considers the dynamic load of operations.

We define the data to include the ergonomics criterion into SALBP.

MVC: Maximum voluntary contraction. Unit [N] or [N.m]. It represents the maximal muscular power output generation, which represents the maximum level of muscular strength expressed as a percentage (i.e., $MVC = 100\%$). The percentage is used to simplify the comprehension of the measure and to make it unit-independent;

Fload_j: the magnitude of operation intensity. Unit [N] or [N.m]. This measure would be expressed relative to MVC with $MVC=100\%$. For example, if the magnitude or intensity of operation $j \in V$ is $Fload_j = 20\%$, it means that the operation load represents 20% of the maximum force capability;

K: Worker fatigability or fatigue rate; unit [s^{-1}]; positive constant that represents the fatigability and worker's characteristics;

R: Worker recovery rate [s^{-1}]; a positive constant that equals and represents the recovery rate of workers.

We assume that workers belong to the 50% percentile of the population, and hence, we consider average physical characteristics. The average worker's characteristics are used since SALBP does not consider the assignment of workers. Besides, in the design stage of assembly lines, workers' characteristics could not always be available to designers, a consideration of a percentile of the working population is a reasonable assumption at this stage (Greig et al. 2018).

Figure 1 represents an example of the working and recovery time in an assembly line of 3 workstations (WS1, WS2, WS3) in two successive takt times. Parts to assemble in paced lines are transported between workstations at the end of the adjusted takt time AT with conveyors. In the example of the figure, the working time filled with black dots patterns in each workstation represents the sum of operations times assigned to that workstation, and the recovery time is composed of the idle time in gray and the transfer time TT with the crosshatches.

As for the ergonomics criterion, we consider the evolution of the muscular capacity in each workstation k at the end of one takt time T . Let $F_k \in [0, 1]$ defined in Equation (1) be a function representing the level of muscular capacity of the worker in the workstation k at the end of takt

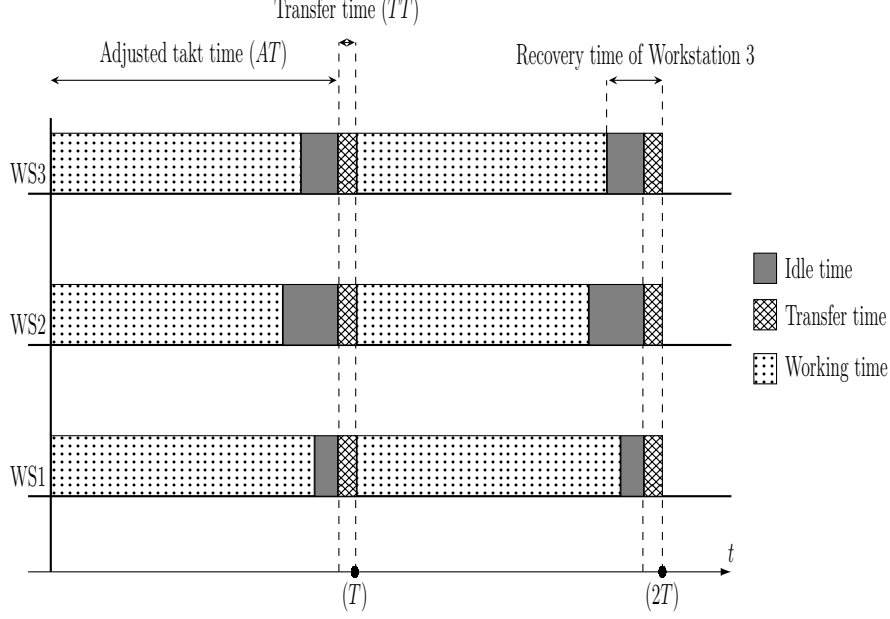


Figure 1. Working and recovery time for two successive takt time

time.

$$F_k = 1 + \left(e^{-\left(\frac{K}{MVC}\right) \int_0^{AT} \text{Load}_j(u) \cdot x_{j,k} du} - 1 \right) e^{-R(T - \sum_{j \in V} t_j \cdot x_{j,k})} \quad \forall k \in W \quad (1)$$

Figure 2 represents the evolution of the muscular capacity in working and recovery time in an assembly line after one takt time. The fatigue is accrued in working time when the worker executes the assembly operations, represented in the figure with the exponential decrease in the muscular capacity until the end of the working time, it depends on the worker's fatigability K and

Afterward, in recovery time (idle time and transfer time), the worker recovers from fatigue. In recovery times, the worker in a given workstation k benefits from the recovery process, the latter depends on the worker's recovery rate R , the length of recovery $T - \sum_{j \in V} t_j \cdot x_{j,k}$ and the fatigue level at the beginning of the recovery period. We can observe the exponential recovery in the figure during the recovery time.

At the end of takt time, the difference between the initial level without fatigue (100%) and the final F_k (%) represents the fatigue level after the first takt time in a workstation k .

In a balancing solution, a workstation k is called *critical* if the muscular capacity of the worker in that workstation is the worst among other workers in the assembly line. i.e., $\text{Min}_{k \in W} \{F_k\}$. We define $F = \text{Min}_{k \in W} \{F_k\}$ that represents the *ergonomics level* of the critical workstation. Non-critical workstations are called *slack* workstations. For the sake of clarity, in the rest of this paper, F would be referred to as the *ergonomics level*, which is used to refer to the state of the muscular capacity in a critical workstation at the end of one takt time. Fatigue and recovery are important to balance the workload in assembly lines, the consideration of a fatigue and recovery model to improve ergonomics level in critical workstations would result in an overall better workload balance and better work-rest schedule in the assembly lines.

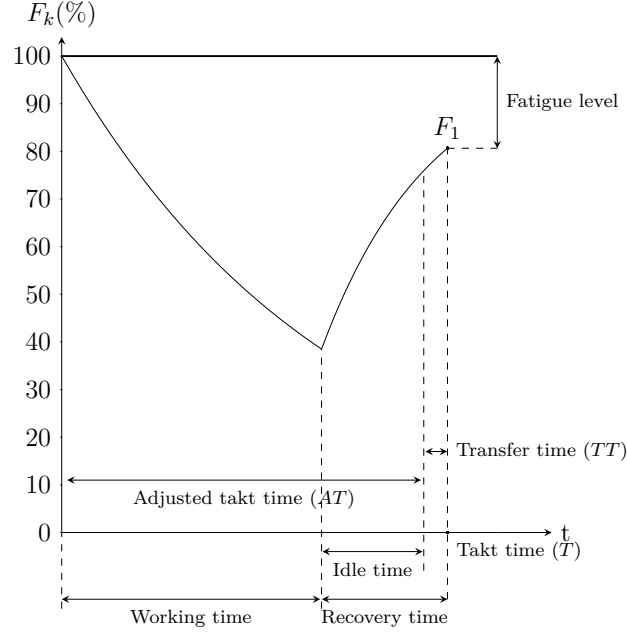


Figure 2. Evolution of the muscular capacity for a worker in workstation k in the work and recovery time after one takt time (T)

3.1.1. Illustration on numerical example

To illustrate the use of the ergonomics level in the assembly line balancing problem with the fatigue and recovery model, we present the following numerical example.

Figure 3 presents an example of a precedence graph with 10 operations, each node represents an operation, arcs represent the precedence relation between operations, processing time in second, and the magnitude of operations intensity F_{load} in percentage are represented above the node, we assume a static load along the processing time. The takt time in this example is $T=900s$ without transfer time.

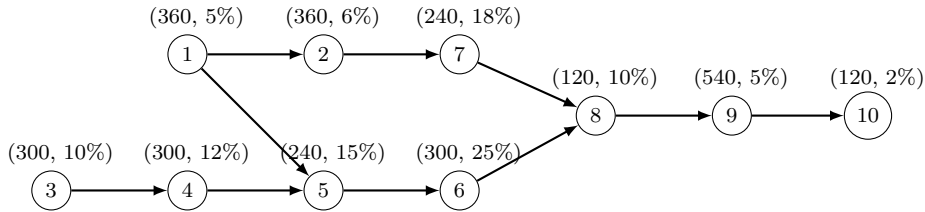


Figure 3. Precedence graph

The optimal number of workstations is 4. To illustrate the ergonomics level, we compare two possible balancing solution. The assignment of solution 1: $\{(1,2), (3,4,5), (7,6), (8,9,10)\}$ with task 1 and 2 assigned to the first workstation, task 3, 4 and 5 to the second workstation, and so on. The assignment of solution 2: $\{(1,3), (2,4), (5,6,7), (8,9,10)\}$. Since the workload is static, I_j is equal to $\frac{K}{MVC} F_{load_j} t_j$. The muscular capacity of the first workstation is $F_1 = 1 + (e^{-(I_1+I_2)} - 1)e^{-R(T-(t_1+t_2))} = 97.6\%$, with $R = K = \frac{1}{60}$ are constants representing workers characteristics, and $MVC = 100\%$. In Table 1, we compute the muscular capacity F_j of a worker in workstation j after one takt time with Equation (1), F represent the ergonomics level ($Min_{k \in W} \{F_k\}$), considered as objective function.

Table 1. Comparison of two balancing solutions

	Solution 1	Solution 2
Workstation 1	97.6%	99%
Workstation 2	69.9%	98.9%
Workstation 3	99.8%	87.5%
Workstation 4	93.3%	93.3%
F	69.9%	87.5%

Solution 2 presents a better ergonomics level than solution 1, we can observe that even for this simple example, strong variation could be observed between two balancing solutions. Even though we considered the optimal number of workstations, the ergonomics level may have considerably varying values.

3.2. Mixed Integer Linear Program formulation

To introduce the ergonomics in SALBP, we formulate an Integer Linear Program (ILP) using the notations and definition presented in Subsection 3.1. The main structure of this ILP, apart from the objective function, corresponds to a SALBP-F (i.e., a feasibility problem with a fixed takt time and a fixed number of workstations, cf. Boysen et al. (2007)). The goal here is to maximize the *level of ergonomics* for an assembly line for one takt time with the optimal number of workstations (m). The nonlinearity of the objective function (i.e., the ergonomics level) is a considerable limitation and puts a brake on the use of linear programming. The reason linear programming models are given more attention in comparison to nonlinear models is the ease of their resolution.

3.2.1. Linearization of the fatigue-recovery objective function

We start by defining I_j expressed in Equation (2) that represents the integral of the operation's load, the integration by part allows us to aggregate a subset of operations $V' \subseteq V$ assigned to the worker in a given workstation $k \in W$.

$$I_j = \frac{K}{MVC} \int_t^{t+t_j} Fload_j(u) du \quad (2)$$

We introduce $\underline{F} \in [0, 1[$ that represents a lower bound on the ergonomics level. Hence, Equation (3) is valid for all $k \in W$.

$$\underline{F} \leq 1 + (e^{-\sum_{j \in V} I_j \cdot x_{j,k}} - 1) e^{-R(T - \sum_{j \in V} t_j \cdot x_{j,k})} \quad \forall k \in W \quad (3)$$

To transform Equation (3) into Equation (4), we subtract 1 from each side of the inequality, then we multiple both sides by the positive term $e^{R(T - \sum_{j \in V} t_j \cdot x_{j,k})}$:

$$(\underline{F} - 1) e^{R(T - \sum_{j \in V} t_j \cdot x_{j,k})} \leq e^{-\sum_{j \in V} I_j \cdot x_{j,k}} - 1 \quad \forall k \in W \quad (4)$$

We developed Equation (4) into Equation (5) by applying the logarithm function and with respect to its definition domain.

$$\ln \left(\underline{F} - 1 \right) e^{R(T - \sum_{j \in V} t_j \cdot x_{j,k})} + 1 \leq - \sum_{j \in V} I_j \cdot x_{j,k} \quad \forall k \in W \quad (5)$$

Equation (5) is valid when $0 < (\underline{F} - 1)e^{R(T - \sum_{j \in V} t_j \cdot x_{j,k})} + 1$ and is equivalent to Equation (6).

$$\sum_{j \in V} I_j \cdot x_{j,k} \leq \ln \left(\frac{1}{(\underline{F} - 1)e^{R(T - \sum_{j \in V} t_j \cdot x_{j,k})} + 1} \right) \quad \forall k \in W \quad (6)$$

In Equation (6), we obtain a constraint on the workload to obtain an ergonomics level that respect the bound \underline{F} , the domain of definition depends on the length of recovery time $(T - \sum_{j \in V} x_{j,k} \cdot t_j)$. Since the t_j are integers, we introduce a decision variable $z_{l,k}$ for the recovery time with $U = \{0, 1, \dots, T\}$ the set of possible recovery time.

$$z_{l,k} = \begin{cases} 1 & \text{if recovery time of workstation } k \text{ is equal to } l, \text{ with } l \in U \\ 0 & \text{Otherwise} \end{cases}$$

Equation (6) is developed in Equation (7), with $l = (T - \sum_{j \in V} x_{j,k} \cdot t_j)$.

$$\sum_{j \in V} I_j \cdot x_{j,k} \leq \ln \left(\frac{1}{(\underline{F} - 1)e^{R \cdot l} + 1} \right) \quad \forall k \in W \quad (7)$$

To respect the definition of the logarithm function, we should respect the condition $0 < (\underline{F} - 1)e^{Rl} + 1$ in Equation (7), which is equivalent to: $l < \frac{1}{R} \ln \left(\frac{1}{1 - \underline{F}} \right)$.

Finally, we developed Equation (7) into Equation (8) with the use of $z_{l,k}$:

$$\sum_{j \in V} I_j \cdot x_{j,k} \leq \sum_{l \in U \mid l < \mathcal{D}} \ln \left(\frac{1}{(\underline{F} - 1)e^{R \cdot l} + 1} \right) \cdot z_{l,k} + \left(\sum_{j \in V} I_j \right) \cdot \sum_{l \in U \mid l \geq \mathcal{D}} z_{l,k} \quad \forall k \in W \quad (8)$$

When the value of recovery time l is strictly inferior to the value $\mathcal{D} = \frac{1}{R} \ln \left(\frac{1}{1 - \underline{F}} \right)$, the natural logarithm function in Equation (8) is defined and specifies a bound on the load in workstations to respect the lower bound \underline{F} on the ergonomics level. On the other hand, when the value of the recovery is equal or exceeds \mathcal{D} (i.e., $l \geq \mathcal{D}$), no matter which load value is assigned to the workstation, the ergonomics level will respect the bound \underline{F} , in this case, a maximum load $\sum_{j \in V} I_j$ can be used as a bound on the load.

3.2.2. SALBP-FR: Simple Assembly Line Balancing Problem with workers Fatigue and Recovery

Finally, the complete ILP model is presented in {Equation (9a) to Equation (9h)}. This model is denoted SALBP-FR: Simple Assembly Line Balancing Problem with workers Fatigue and Recovery.

$$\sum_{k \in W} y_k = m \quad (9a)$$

$$\sum_{k \in W} x_{j,k} = 1 \quad \forall j \in V \quad (9b)$$

$$\sum_{j \in V} t_j \cdot x_{j,k} \leq AT \cdot y_k \quad \forall k \in W \quad (9c)$$

$$\sum_{k \in W} k.x_{h,k} \leq \sum_{k \in W} k.x_{g,k} \quad \forall (h, g) \in Prec \quad (9d)$$

$$\sum_{j \in V} I_j.x_{j,k} \leq \sum_{l \in U \mid l < \mathcal{D}} \ln \left(\frac{1}{(\underline{F} - 1)e^{R.l} + 1} \right) . z_{l,k} + \left(\sum_{j \in V} I_j \right) . \sum_{l \in U \mid l \geq \mathcal{D}} z_{l,k} \quad \forall k \in W \quad (9e)$$

$$T - \sum_{j \in V} t_j.x_{j,k} = \sum_{l \in U} l.z_{l,k} \quad \forall k \in W \quad (9f)$$

$$\sum_{l \in U} z_{l,k} = 1 \quad \forall k \in W \quad (9g)$$

$$x_{j,k}, y_k, z_{l,k} \in \{0, 1\} \quad (9h)$$

Constraint (9a) precise the number of workstations, and constraints (9b) defines the occurrence constraint that all operations must be processed. The total processing time of a given workstation should not exceed the adjusted takt time as defined by constraint (9c). Constraint (9d) represents the technological precedence between operations. Constraint (9e) defines the level of ergonomics that is respected by the solution. To define the value of the recovery time, constraint (9f) makes sure that the recovery time l in workstation k is equal to the difference between the takt time and working time. Constraint (9g) ensures the uniqueness of the recovery time in each workstation k .

SALBP-FR is a decision problem, such problems, as mentioned in Garey and Johnson (1979), have only two possible solutions, either the answer feasible or the answer infeasible. Decision problems arise from optimization problems by replacing the objective function by the question of whether or not a feasible solution exists with an objective function value (in the case of maximization) exceeding a particular value defined in the set of constraints (Scholl 1999). The format of the decision problem we will use for specifying the ergonomics level in the assembly lines problems consists of a set of constraints, without an objective function, since the non-linear objective function was transformed into constraints.

Solving the decision problem SALBP-FR does not guarantee to maximize the ergonomics level in the assembly line since we only get an ergonomics level better than a given threshold or lower bound (defined with \underline{F} in Equation (9e)). We present in Subsection 3.3 an exact algorithm, denoted Iterative Dichotomic Search, dedicated to solving the SALBP-FR formulation.

3.3. Iterative dichotomic search algorithm

The decision problem SALBP-FR tries to find a solution that is better than a fixed target on the ergonomics level defined with the bound \underline{F} in constraint (9e). The iterative improvement of the target leads to the optimal solution and the improvement of the overall ergonomics condition.

We propose an algorithm that operates on the difference between the ergonomics level of an initial solution and an upper bound of the ergonomics level. The algorithm denoted Iterative Dichotomic Search (IDS) fixes a target on the level of ergonomics and solves each time the decision problem SALBP-FR to find a better solution. The dichotomy is used to reduce the search space quickly, particularly since the number of decision problems to be solved will increase logarithmically compared to the initial difference between the lower and the upper bounds.

The interest of this method is to quickly find the optimal solution by solving the decision problem SALBP-FR and by updating the value of the bounds at each iteration until the optimal value is obtained. The dichotomic procedure has been successfully applied to another assembly line balancing problem (Kovalev et al. 2017).

Algorithm 1 Iterative Dichotomic Search

```

1:  $S = \emptyset; i \leftarrow 0$ 
2: Solve SALBP; set  $m$ .
3: Compute  $F$  from the solution of SALBP-1
4: Set  $\underline{F}_i \leftarrow F$  ▷ Initial lower bound
5:  $S \leftarrow S \cup \{\underline{F}_i\}$ .
6: Compute  $\overline{F}_i$  with Equation (10) ▷ Initial upper bound
7: while ( $\epsilon \leq |\overline{F}_i - \underline{F}_i|$ ) do
8:   Compute  $F_i^{target} \leftarrow \underline{F}_i + \frac{\overline{F}_i - \underline{F}_i}{2}$ 
9:   Set  $\underline{F} \leftarrow F_i^{target}$  in Equation (9e)
10:  Solve SALBP-FR ▷ Solve return the status of the solver
11:   $i \leftarrow i + 1$ 
12:  if Feasible then
13:    Compute the new  $F$  from the solution
14:    Set  $\underline{F}_i \leftarrow F$ 
15:     $S \leftarrow S \cup \{\underline{F}_i\}$ 
16:  else if Infeasible then
17:     $\overline{F}_i \leftarrow F_i^{target}$ 
18:  end if
19: end while
20: return  $Max_{i \in S} \{\underline{F}_i\}$  ▷ return the best found lower bound

```

IDS operates on the difference between the ergonomics level of an initial solution, for instance with an existing known solution, or with the solution of the SALBP-1 which solves the Simple Assembly Line Balancing Problem with a fixed takt time and seeking to minimize the number m of workstations. From the initial balancing solution, we determine the value of \underline{F} , which represents the ergonomics level of the initial solution.

We define an upper bound of the ergonomics level that can be obtained using Equation (10). \overline{F} represents the maximal ergonomics level and is important to shorten quickly the search space.

$$\overline{F} = \text{Min}_{j \in V} \left\{ 1 + (e^{-I_j} - 1)e^{-R(T-t_j)} \right\} \quad (10)$$

The search space is defined with the interval $[\underline{F}, \overline{F}]$, at each iteration, the algorithm divides the interval and sets a target F^{target} in constraint (9e) and looks for a feasible solution. If it exists, we obtain a better lower bound. We update the value of the target, and we iterate the same procedure. In the case where there is no feasible solution, we update \overline{F} to reduce the search space. We execute the same steps described before for the new interval. The algorithm converges to the optimal solution when the length of the interval of search $[\underline{F}, \overline{F}]$ is below a small fixed precision, denoted ϵ , i.e., $|\overline{F} - \underline{F}| \leq \epsilon$. We depict in Algorithm 1 the pseudo-code for the IDS algorithm.

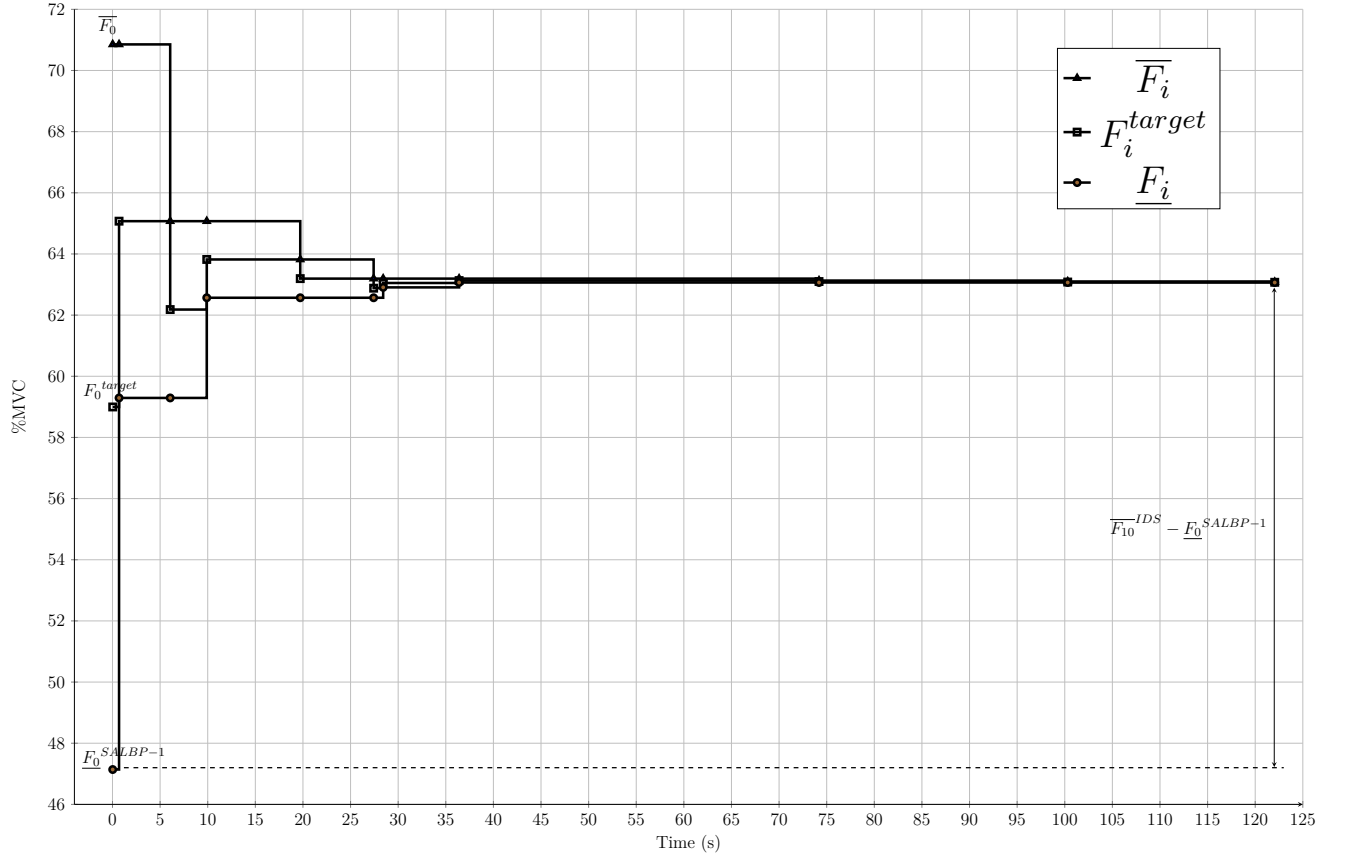


Figure 4. Example of the evolution of upper-lower bounds and the target value in the execution of IDS algorithm

3.3.1. Example of exact resolution

In Figure 4, we represent the evolution of the upper and lower bounds and the target in the execution of the IDS on the instance of Hahn ($n = 53$) from the literature (cf. Subsection 4.1 for experimental conditions). The initial solution is obtained with SALBP-1 and denoted $\underline{F}_0^{SALBP-1}$ which represents the first lower bound, \overline{F}_0 represents the initial upper bound computed with Equation (10). The first target F_0^{target} which is the middle of the interval $[\underline{F}_0^{SALBP-1}, \overline{F}_0]$ set the target value used to solve SALBP-FR in the first initial step of IDS. In this example, the solution obtained with IDS is optimal. The difference between the initial solution of SALBP-1 and the final upper bound ($|\overline{F}_{10}^{IDS} - \underline{F}_0^{SALBP-1}|$) gives a relative gap of 25.25%.

4. Numerical experiments

4.1. Experimental conditions

All the experiments were performed with a single node of a cluster with a CPU Intel(R) Xeon(R) CPU E5-2660, 2.60GHz, and 65GB of RAM. The algorithms are developed in C++. We used Cplex V12.6 as a solver with default parameters.

Even if the algorithm presented in Subsection 3.3 is described in the case when we succeed to obtain solutions, we fix a time limit to keep the algorithm running time compatible with practical application. The line balancing problem presented in this paper is a tactical planning problem, and we can allow setting a relatively high time limit. A time limit of 3,600s is set for each iteration of the IDS algorithm. Similarly, 3,600s for each call of Cplex as a solver. For the IDS algorithm,

we fix a precision of $\epsilon = 10^{-5}$.

4.2. Data and characteristics of instances

We use for our experiments a selection of instances for SALBP, namely those of Scholl and Otto (available on the website: <https://assembly-line-balancing.de>). Due to the lack of available instances in the literature (to the best of our knowledge) for the line balancing problems with the physical operations load (*Fload*), we randomly generate the physical loads of operations for our instances (cf. Subsection 4.2.2).

We solve instances of SALBP-1 with Cplex and discard instances that were not solved within the time limit from our dataset. This phase of selection is used to eliminate the instances which are already difficult to solve for SALBP-1 since the problem considered in this paper is harder to solve.

We end up with 42 starting instances from the Scholl dataset, with the minimal and medium value of adjusted takt time from the benchmark and a number of operations between 7 and 148. Also, we selected 24 instances from the Otto dataset with a number of 20, 50, and 100 operations.

4.2.1. Workers characteristics

We consider anthropometrics, and physical constants values for a worker belonging to the 50th percentile of the working population, i.e., a worker with average characteristics. Experimental regression in Liu et al. (2018) and Ma et al. (2015) shows that the average workers' fatiguability and recovery rate are $K = 0.017s^{-1}$ and $R = 0.017s^{-1}$.

4.2.2. Operation physical load

Operation physical load or exertion intensity denoted *Fload* is a measure of operation's physical intensity and expressed in percentage, relative to MVC. For practitioners, methods and tools to predict physical workload and data from assembly lines workstations to apply the proposed approach are presented in Greig et al. (2018) and Abdous et al. (2018).

In our experiments, we generate a load distribution for operations, we assume that the effort is static for the duration of the effort (i.e., $I_j = \frac{K}{MVC} \cdot Fload_j \cdot t_j$). The proposed modeling is not restrictive to static load and is suitable also for dynamic load. The static assumption is only considered for the numerical experiments. The load follows a statistical beta distribution with integer percentage values between [2%,60%] with statistical parameters α and β specified by making values between 2% and 25% more likely and values further from 25% less likely.

The beta law seems to represent the distribution of load in manual lines as it was observed in real data from industrial lines. With the beta distribution, most operations are in a low and medium-range of difficulty, but there is also a proportion of operations with a high physical load. This assumption is also observed in the distribution of energy expenditure values in assembly line case studies (Finco et al. 2020).

For each instance, we generate four physical loads according to the beta law. We end up with 264 instances.

4.2.3. Transfer time

Transfer time, denoted *TT* is the time required for transport between workstations in paced assembly lines. In our experiments, we tested two values of transfer time, $TT = 0$ when the transfer time is negligible, and when $TT = 5\%AT$, which means that the transfer time represents 5% of the adjusted takt time. We end up performing experiments on 528 instances in this paper.

4.3. Numerical results

Since we performed numerical experiments on instances from the literature, we focus in this analysis on the evaluation of the quality of solutions and computational times, rather than the values of the ergonomics level.

4.3.1. Iterative Dichotomic Search and resulting bounds

For instances that we cannot solve within the time limit, we evaluate the quality of the approximation with the gap between the upper and lower bound, using the following equation:

$$Gap = \frac{|\overline{F}^{IDS} - \underline{F}^{IDS}|}{|\overline{F}^{IDS}|} \quad (11)$$

With \overline{F}^{IDS} the upper bound and \underline{F}^{IDS} the lower bound at the end of the execution of the algorithm.

From the results, IDS solves more than 98% of instances with less or equal than 50 operations and 60% of instances with more than 50 operations from the Scholl dataset. IDS does not solve optimally any instances with 50 or 100 operations from the Otto dataset.

4.3.2. Results analysis and comparison

In this Subsection, we evaluate the performance of IDS. We always calculate the gap with the best upper bound obtained by the IDS resolution. To simplify and by abuse of language, we also refer to the solution obtained from SALBP-1 with Cplex as an algorithm.

Table 2. Average Gap in % of all algorithms presented according to the category of instances, adjusted takt time and transfer time

	Adj. Takt time	Transfer time	Avg Gap (%)	Avg Gap (%)
			SALBP	IDS
Scholl	Min	0%	14.73	3.75
		5%	4.95	0.33
	Median	0%	19.83	5.95
		5%	7.61	3.62
Otto	-	0%	74.52	42.78
		5%	23.07	18.3

We present in Table 2 the average gap in % of different algorithms, clustered in categories according to the adjusted takt time and transfer time for Scholl instances and transfer time for Otto instances since, in the dataset of Otto, only one value of the adjusted takt time is available. The average gap indicated is calculated on all the instances, by counting a gap of 0 for the instances solved optimally.

Overall, gaps are lower with a transfer time of 5% both in Otto and Scholl datasets. In the Scholl dataset, the median adjusted takt time is more challenging than the minimal adjusted takt time. Overall, the most challenging subset of instances seems to be the dataset of Otto with a transfer time of 0%. The average gap for IDS is 13.29%, IDS is practical to provide overall good results and to improve the starting solution efficiently.

Similarly, in Table 3, we analyze computational times with a comparison similar to the one we just made for gaps. We present the average computational times in seconds (s) for different algorithms represented according to different categories of instances.

Table 3. Averages computational times in seconds (s) of all algorithms presented according to the category of instances, adjusted takt time and transfer time

	Adj. Takt time	Transfer time	Avg Time (s)	Avg Time (s)
			SALBP	IDS
Scholl	Min	0%	1.56	667.47
		5%	1.58	712.71
	Median	0%	0.89	1141.55
		5%	1.01	777.15
Otto	-	0%	1.75	2805.23
		5%	1.54	2760.33

For IDS, instances of Scholl with a median adjusted takt time consume more computational times, especially those with a transfer time of 0%. Otto instances are the ones that consume the most computational time on average and seem to be more challenging.

In these numerical experiments, on average 5 SALBP-FR sub-problems had to be solved per instance, with a maximum of 13 resolutions and a minimum of 1 resolution. The proportion of time devoted to the resolution of the initial SALBP with Cplex (i.e., Step 2 of the IDS algorithm) is on average 1.5s for the instances we have considered, which represent a tiny fraction of time (0.06% on average) compared to the total computational time. We conclude that computational time to obtain the initial solution is negligible compared to the total computational time. This conclusion emphasizes that solving the SALBP is not the blocking element for the instances we have considered.

These numerical experiments made it possible to highlight the interest of the IDS algorithm, in particular, to obtain an upper bound to evaluate the quality of a solution. Indeed, IDS proves its effectiveness to improve an initial solution and obtaining a better quality solution. We succeed in solving almost all instances with less than 50 operations, we also have good quality results for instances with several operations greater or equal than 50 operations, and we can solve some instances up to a size of 148 operations. Computational times are competitive and suitable for long-term optimization problems such as assembly line balancing.

4.4. Managerial insights

Based on the numerical experiments, we make the following recommendations for practitioners and assembly lines managers. First of all, it is important to consider ergonomics aspects right from the design stage of manufacturing systems, as this preventively reduces MSDs and improves the ergonomics level for workers. The optimization algorithm developed in this paper can find solutions better than the classical assignments of operations with SALBP-1 within acceptable computational times. The proposed approach has improvements in the following managerial areas:

- The approach with the consideration of ergonomics with the fatigue and recovery criteria improve the ergonomics level in 58% of instances. The difference between SALBP-1 solutions without ergonomics consideration and the proposed approach is on average 7.1 percentage points. This result highlights the significance of the gain and its impact on MSDs risk and ergonomics issues.
- The improvement of the ergonomic level does not require higher takt time or additional workstations and thus the assembly line productivity indicators have not deteriorated. This result is relevant for industries in highly competitive environments that cannot allow deterioration in assembly line performance. The solutions obtained induce no additional cost nor decrease in performance, which is an advantage by comparison with approaches requiring to invest in specific equipment. Furthermore, we can identify cases where investment in equipment is necessary to improve the ergonomics level.

5. Conclusion

To avoid MSDs and to fit the needs of workers, the subset of operations and the recovery period assigned to each workstation in assembly lines should consider a target level of ergonomics. The approach proposed here is a decision-aid method to assist engineers and decision-makers to evaluate simultaneously economic cost, and the load inherent in the line balancing solution and reduce the physical experimentation with new production layouts.

In this work, we proposed a model for the problem of balancing assembly lines with the consideration of ergonomics. The criterion for ergonomics is based on the muscular fatigue and recovery of workers. The non-linearity of the criterion requires a methodological approach to introduce it with the assembly line balancing problem. For this, we proposed a linearization and an exact algorithm denoted Iterative Dichotomic Search or IDS. Subsequently, IDS is validated throughout an experimental protocol on a set of instances of various characteristics and sizes coming from the literature for the assembly line balancing problem.

Some areas of research are worth exploring further in the future. Workers' assignment to a workstation (i.e., the different percentile of the working population (Calzavara et al. 2020; Katirae et al. 2021)) and the manual aspects of work raise the question of variability which could significantly impact both the productivity of the line and the recovery time of workers. A perspective of this work could be to consider a stochastic version of the problem.

The exact algorithm presented in this article consider the optimal number of workstation and satisfy a lexicographic optimization, giving priority to a criterion of economic performance compared to the ergonomics level. A perspective of this work would be the improvement of the proposed Iterative Dichotomic Search by utilizing state-of-the-art algorithms to solve the initial problem and the feasibility sub-problems instead of using Cplex (Li et al. 2021; Morrison et al. 2014; Sewell and Jacobson 2012). An additional perspective would be the consideration of the problem with a multiobjective approach including the criterion of fatigue and recovery in addition to a criterion of economic performance and a dedicated solving approach (Cerqueus and Delorme 2019).

A metaheuristic could be developed to deal with large-scale industrial and practical problems in reasonable computational time. A metaheuristic that gives results in a short computational time is appealing for industrial applications. In the literature, numerous and various metaheuristics are developed for assembly lines problems (Battaia and Dolgui 2013), particularly neighborhood methods (Otto and Scholl 2011), evolutionary approaches (Tasan and Tunali 2008), and Swarm intelligence-based metaheuristic (Oesterle and Lionel 2018).

The development of Industry 4.0 change the demands and the role of human factors in assembly systems (Golan et al. 2020). The modern industry grows toward a human-robot collaboration (cobot) to benefit from the automation and the flexibility of workers. A perspective of this work is the consideration of the decision of equipment selection (i.e., the denoted Assembly Line Design Problem) and their effect on the level of ergonomics. Also, this fourth industrial revolution raises questions about cognitive ergonomics, especially the worker's technology acceptance and human-machine interactions. Future works should address those issues and develop frameworks to design new assembly systems and to select equipment that considers worker demands.

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