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Multi-objective optimization of assembly lines with workers fatigue consideration

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Abstract: The work-related musculoskeletal disorders (MSDs) occur when the worker's capabilities do not match the physical demands of work. In assembly lines, with the execution of repetitive tasks, workers are exposed to fatigue and ergonomics risks. Thus, there is a need to find compromises between assembly lines performance and physical demands and ergonomics.

In this work, we introduce a general fatigue criterion for assessing workers fatigue. We propose a multi-objective mixed-integer linear programming model for the assembly line balancing problem with consideration of workers fatigue. We use ϵ-constraint approach to address both objectives and present the Pareto front. Experiments on instances from the literature are performed and discussed to highlight the trade-off between the numbers of workstations and fatigue.

Keywords: Assembly Line Balancing Problem, Multi-objective, Ergonomics, Fatigue, Human Factors.

1. INTRODUCTION

Prolonged exposure to ergonomic risks factors can damage the body of workers and lead to musculoskeletal disorders (MSDs). The work-related MSDs are a significant source of diseases and injuries, resulting in workers compensation costs and a decrease in overall productivity. According to the European Union survey on the labor force in 2013, musculoskeletal disorders represent 60% of all work-related health problems. By 2030, the age of a quarter of the total workforce in EU will be over 60 (European Commission (2017)). The analysis estimates the costs of MSDs in European economy around 240 billion euros, up to 2% of the gross national product (Bevan, 2015). In the strategic vision of the European Commission (Health and Safety at work 2014-2020), work-related diseases and aging of workers represent a significant challenge of the European Union and requires taking into account the ergonomics in work environment.

Assembly lines are among work activities with highest ergonomic risks, the most efficient way to prevent hazards is to consider ergonomics at the design stage (Battini et al., 2011), particularly in manual assembly lines. Ergonomics in the design phase of assembly systems should be addressed in conjunction with the performance and productivity. The aim is to develop methods and framework to consider both productivity and ergonomics in assembly system design.

In this work, we consider assembly line balancing problem with workers fatigue. The fatigue here mentioned is introduced by the general fatigue model of Ma et al. (2009). This model assesses muscle or group of muscles fatigue, depending on the external load, its magnitude, and the time of effort. This method is based on nonlinear function. We propose a multi-objective mixed-integer linear programming (MILP) approach and incorporate the fatigue evaluation with state-of-art simple assembly line balancing model. The first objective considers performance and the second one fatigue as ergonomics criterion. To figure out the trade-off between workstations numbers and fatigue, we use ϵ-constraint algorithm to solve instances from the literature.

The paper is structured as follows. Section 2 provides a literature review of related works. Section 3 presents the fatigue model and provides the linear formulation. In section 4, we present the multi-objective optimization model and the solving method. Some numerical experiments are reported in section 5. Finally, conclusions and future works are presented in section 6.

2. LITERATURE REVIEW

Assembly lines are workstations connected by a parts transfer system, or conveyors, in which a set of tasks are assigned to assemble a manufacturing product. Each task has an execution time and precedence relationship between tasks. This type of line is designed for the manufacture of standardized products. The problem of balancing the

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total workload on all stations to optimize one or more criteria is called the problem of assembly lines balancing. This paper will focus on Simple Assembly Line Balancing Problem (SALBP). The assumptions behind this problem were first introduced by Baybars (1986). Simple assembly line concerns one type of product under deterministic condition. This problem gives rise to several versions depending on the objective to be optimized. In this paper, we consider the so-called SALBP-1, when we minimize the number of workstations, given a fixed takt time. This type of problem is widely investigated in the literature, we refer to the surveys Battaïa and Dolgui (2013), Becker and Scholl (2006), Rekiek et al. (2002).

Physical workload and ergonomic risks are evaluated by many risks assessment methods, such as observational measurement techniques. Dempsey et al. (2005) and Li and Buckle (1999) provide surveys of some tools and methods used by ergonomists. Several works include these ergonomic risks in assembly line balancing. Otto and Scholl (2011) introduce the ERGO-SALBP with several widely used ergonomics estimation techniques and underline the nonlinearity of most ergonomics and risks assessment. They propose two-stage heuristic using the bidirectional branch and bound SALOME in the first stage and a simulated annealing in the second phase. OCRA index was used in the work of Tiacci and Mimmi (2017) as ergonomic risks with asynchronous assembly lines, the objective of this work is to minimize the design cost corrected for OCRA index.

Other authors consider ergonomics risks, such as the works of Bautista et al. (2016). This work introduces a family of ergonomic hazards method with the Time and Space constrained Assembly Line Balancing Problem (TSALBP). This formulation is applied to an automotive engine plant case study. The work of Kara et al. (2014) proposed an integrated cost-oriented model with psychological and physical strain. The objective function considers an aggregation of costs, Cplex is used to solve an example to illustrate the approach. Choi (2009) propose a zero-one programming approach that combines assembly line balancing problem and physical workload with various risk elements. Goal programming approach is used in this paper with Cplex as a solver.

Ergonomics can be assessed by analytical metabolic model and energy expenditure rate, Battini et al. (2015) propose two models for assembly line balancing problem. The first one introduces a bi-objective model with time and energy expenditure objectives to estimate the ergonomics level. This program is investigated with the Pareto approach. The second alternative proposes a single objective model with rest allowances time. Battini et al. (2016) provide a multi-objective assembly line balancing program, with four different objective functions. This paper introduces a new technique, called Predetermined Motion Energy System to estimate the energy expenditure. Pareto frontier is used with an industrial case study to illustrate the multi-objective approach.

Biomechanical models as physical fatigue evaluation are also used as ergonomics measure, Vøllestad (1997) defines muscular fatigue as any reduction in maximal ability to generate strength or power, thereby defining fatigue through its effects, namely the reduction of work capacity and power generation. The fatigue manifest when the necessary force to execute an effort is no longer possible. Wood et al. (1997) provide a fatigue model to assess grip strength in repetitive jobs. The model proposes a general formulation for fatigue after several cycles of work and rest. Carnahan et al. (2001) integrate the grip strength model in assembly line balancing problem type 2 when the objective is to minimize cycle time for a given number of workstations. In this proposition, the ergonomic fatigue model and cycle time were formulated in a weighted sum, two genetic algorithms and one ranking heuristic was used to solve large sets of benchmark problems.

We suggest the reader a recent article by Otto and Battaïa (2017) that survey existing optimization approaches used in assembly line balancing problem with consideration of physical demand and ergonomic risks. In the literature, fatigue models are nonlinear, their integration in state-of-art assembly line balancing is not straightforward. In the following section, we provide a linearization of a general fatigue model and a formulation with SALBP-1 in a multi-objective approach.

3. FATIGUE MODEL

Muscle fatigue reduces the ability to exert a force in a voluntary effort. Reduction of forces and fatigue lead to ergonomic risks and work-related MSDs. We consider in this part the general muscle fatigue model introduced by Ma et al. (2009). This model is based on the motor mechanism pattern of muscles and studies the influence of external load on fatigue level. The cognitive component of fatigue is not considered in this model. The load is expressed in integral, and thus, the mathematical property of this model can be used to aggregate the tasks physical workload in the context of assembly line.

The current capacity of muscle depends on the maximum voluntary contraction (MVC) and the external load or the forces to which the muscle is subjected. The MVC is defined by Vøllestad (1997) as the maximum generation of force, with a maximum will, when the worker believes he is doing his best during physical exertion, this measurement can vary, from one muscle group to another and from one individual to another. The parameters used are listed below.

MVC : Maximum voluntary contraction, represent the workers factors. Unit [N]
$Fcem(t)$: The current capacity of muscle at time t. Unit [N]
$Fload(t)$: External load or the forces to which the muscle is subjected to at time t. Unit [N]
k : Constant value. Unit [1/min].
$C = \frac{k}{MVC}$: Constant that represent the worker's factors.
The current capacity of muscle is expressed as a differential equation as presented in (1):

$$\frac{\partial Fcem(t)}{\partial t} = -CFcem(t)Fload(t) \quad (1)$$

The solution of (1) is (2):

$$Fcem(t) = MVC\mathrm{e}^{-C\int_0^t Fload(u)du} \quad (2)$$

The mathematical formulation remains valid if we consider torque instead of force in the above formulation. This fatigue model was theoretically validated and compared with the 24 existing static endurance time models in Imbeau et al. (2006) and also with dynamic models of the literature. The validation result proves that this dynamic fatigue model is precise when it comes to the evaluating of muscle fatigue in static and dynamic works. Several articles investigate this model and give details on parameters of the model (e.g. k and MVC) and experimental validation (Ma et al., 2011) (Zhang et al., 2014), (Ma et al., 2013). The model was also used in virtual and physical prototyping in Ma et al. (2010). To consider the fatigue model in an assembly line balancing problem, we introduce the following notation.

$j = \{1..n\}$: Index of tasks.
V: Represents the set of tasks.
$V' \subseteq V$: Subset of V.
t_j : Deterministic time of task j.
$t_{j,start}$ and $t_{j,end}$ respectively the starting and ending time of task j.
$Fload_j \in \mathbb{R}^+$: Load of task j.
$Fcem_{V'}$: State of force after execution of set of tasks V'.
I_j : Load integral of task j as expressed in (3):

$$I_j = \int_{t_{j,start}}^{t_{j,end}} Fload_j(u)du \tag{3}$$

We use the integration by parts propriety to aggregate the tasks and hence, we can formulate the fatigue after execution of sets of tasks as specified in (4):

$$Fcem_{V'} = MVC\mathrm{e}^{-C\sum_{j\in V'} I_j} \tag{4}$$

$Fcem_{V'}$ is the state of muscle capacity after the execution of a subset of tasks V'; the fatigue level is defined as the difference between MVC and $Fcem_{V'}$.

In order to maximize muscle capacity of workers, we need to consider this formulation with assembly line balancing problem. Thus, we can write the ergonomic objective as specified in (5). In this study, we consider an average value of k that represent an average workers characteristics from experimental results of Ma et al. (2013).

$$Max(Fcem_{V'}) \iff Min \sum_{j\in V'} I_j \tag{5}$$

In order to optimize the level of fatigue expressed in (4), we consider the equivalence equation (5). Indeed, the maximisation of the current capacity of workers is equivalent to the minimization of load as expressed in (5).This linearization is considered as an ergonomics measure in our multi-objective MILP approach.

4. PROBLEM FORMULATION

We formulate the SALBP-1 with consideration of the fatigue in a multi-objective model, the problem notations are defined below.

4.1 Sets and Parameters

$k = \{1..K\}$: Workstations index.
W : Set of workstations.
A : Set of precedences between tasks
c_r : Takt time
E_j, L_j : Earliest and latest station for task j.

4.2 Mixed-integer linear programming

$$x_{j,k} = \begin{cases} 1 & \text{if task } j \text{ is assigned to workstation } k \\ 0 & \text{otherwise} \end{cases}$$

$$y_k = \begin{cases} 1 & \text{if workstation } k \text{ is open} \\ 0 & \text{otherwise} \end{cases}$$

$$Min\left(\sum_{k\in W} y_k; F_{max}\right) \tag{6}$$

$$\sum_{k\in W} x_{j,k} = 1 \qquad \forall j \in V \tag{7}$$

$$\sum_{j\in V} t_j.x_{j,k} \le c_r.y_k \qquad \forall k \in W \tag{8}$$

$$\sum_{k\in[E_h,L_h]} k.x_{h,k} \le \sum_{k\in[E_j,L_j]} k.x_{j,k} \qquad for(h,j) \in A \tag{9}$$

$$\sum_{j\in V} I_j.x_{j,k} \le F_{max} \qquad \forall k \in W \tag{10}$$

$$x_{j,k}, y_k \in \{0,1\} \qquad \forall k \in W; \forall j \in V \tag{11}$$

$$F_{max} \ge 0 \tag{12}$$

The multiobjective function (6) optimize the number of workstations and F_{max}. Constraints (7) ensure that each task is assigned to only one workstation. Constraints (8) ensure the respect of takt time. Constraints (9) state the precedence relation between tasks. Constraints (10) ensure that F_{max} represent the maximum load among all workstations.

4.3 ϵ-constraint algorithm

To solve the multi-objective mathematical model, we use the ϵ-constraint method. We optimize the F_{max} objective using the number of workstations $\sum_{k\in W} y_k$ as a constraint. By parametrical variations of workstations, solutions of the problem are obtained. The first problem is noted $SALBP-1$ that correspond to the minimization of $\sum_{k\in W} y_k$ subjected to (7)-(11). The second problem noted $SALBP-F_{max}(m)$ minimize F_{max} subjected to (7)-(13).

$$\sum_{k\in W} y_k = m \tag{13}$$

Where m is the number of workstations. Constraints (13) ensure that we use a specific number of workstations. We present below the ϵ-constraint method used to determine Pareto front.

Step 1: Solve the problem $SALBP-1$.
Step 2: Let m be the optimal value obtained in Step 1.
Step 3: Solve $SALBP-F_{max}(m)$.
Step 4: If $F_{max} = Max\{I_j\}$, stop. Otherwise, $m \longleftarrow m+1$; go to Step 3.

The stopping criterion is met when the task with the highest physical load is assigned alone to a workstation. Therefore, no better solution can be obtained for the ergonomics criterion. In the following section, we test ϵ-constraint algorithm with sets of instances from the literature.

5. NUMERICAL EXPERIMENTS

We generate the ergonomics load and implement the ϵ-constraint algorithm with C++ programming language. The $SALBP-1$ and $SALBP-F_{max}(m)$ problems were solved with IBM ILOG Cplex Optimization Studio, Version 12.7.0.0, with default parameters. All computational experiments were conducted on a personal computer with Intel(R) Core(TM) i7-6700HQ 2.60Ghz and 16 Gbit RAM.

For $SALBP-1$, we consider the sets of data from Scholl (1993). We conduct two types of experiments in order to examine the trade-off between ergonomics and number of workstations. First with the lowest takt time, and second with the highest takt time in the benchmark. This numerical experiment was conducted to check the efficiency of the algorithm and the difference between the $SALBP-1$ resolution and the additional ergonomics criterion in the multi-objective model. We conducted the test with two statistical distribution for task load.

5.1 Experiments and instances generation

In the first experiment, we solve the 25 $SALBP-1$ instances with the lowest takt time of the benchmark. We set a computational time limit of 900s and we kept only the instances that we solved within the time limit. We obtain 21 instances from this selection phase. We have generated tasks load with the assumption of static load, which means that the load of the task is expressed according to (14).

$$I_j = \int_{t_{j,start}}^{t_{j,end}} Fload_j(u)du = Fload_j t_j \quad \forall j \in V \tag{14}$$

We generate for each instance, 5 sets of tasks load following the uniform law, and 5 following the Beta law. The range of $Fload_j$ is taken from the interval [2%MVC, 30%MVC] which seems to represent the range of industrial tasks in assembly lines. Beta distribution parameters are set to get more tasks load in the interval [2%MVC, 20%MVC], with only a few values larger than 20%MVC. The constant C allows the normalization of force and time units. In this experiment, we solve the 210 instances using the algorithm described in 4.3, for every iteration of the algorithm, the time limit was set to 900s.

In the second experiment, we use the highest takt time of the benchmark (Scholl, 1993). From the $SALBP-1$ selection, we obtained 23 instances that we solve within the time limit. Task load generation and time limit follow the same procedure described above in the first experiment. We solve 230 instances in this experiment.

5.2 Results discussion

Statistics obtained in the experiments are presented in Appendix A. The second (resp. sixth) column represents the average number of non-equivalent solutions in Pareto front for uniform (resp. Beta) distribution. the third (resp. seventh) column represents the percentage of Pareto optimal solutions for uniform (resp. Beta) distribution. The average time of resolution per instance is represented in fourth (resp. eighth) column. We calculate in fifth (resp. ninth) the hyperarea ratio HR, this metric was first proposed by Zitzler and Thiele (1998), the metric definition is defined in (15).

$$HR = \frac{H_1}{H_2} \tag{15}$$

H_1 and H_2 represent the area of coverage enclosed by the Pareto Front and the axes. H_1 is calculated by the solutions obtained with ϵ-constraint algorithm, and H_2 with lower bounds (LB) provided by Cplex. For minimization problems, HR is larger or equal than 1.

The second experiment appears to be more difficult than the first one. Additional workstations needed to improve the ergonomics are higher in the second experiment compared to the first one. From statistics, there are no significant differences between uniform and beta distribution of load.

Resolution time varies from instance to another but stay compatible with practical uses. Instances that cannot be solved within the time limit shows good hyperarea ratio value. We present in Fig. 1 the Pareto front of ARC111 with a uniform distribution of load. Hyperarea ratio gives $HR = 1.00029$; this front is obtained in 16 iterations of the algorithm. In Fig. 1, the abscissa represents the fatigue level $(MVC - F_{cem})$ expressed as a percentage. In the ordinate, we represent the number of workstations to illustrate the trade-off between the number of workstation and the level of fatigue after takt time.

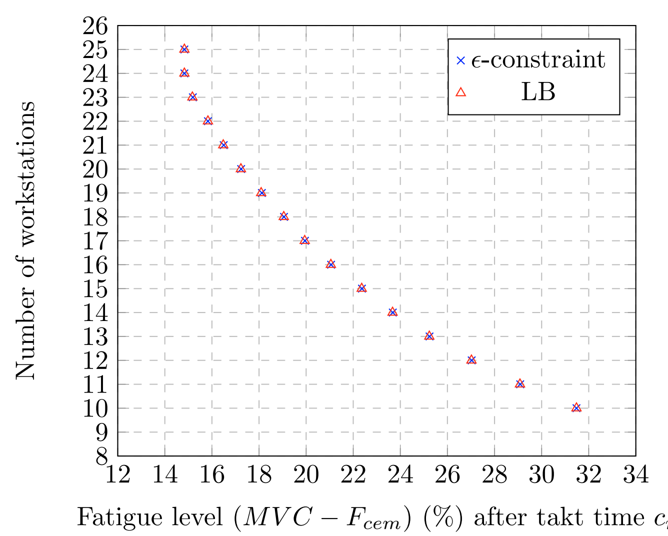

Fig. 1. Pareto feasible solutions

6. CONCLUSION

In this paper, we proposed a multi-objective MILP model for SALBP-1 with consideration of workers fatigue. Ergonomics consideration was formulated in linear form and experiments were conducted on benchmarks from the literature. We use ϵ-constraint algorithm to solve the problem, Pareto frontier was used to illustrate the trade-off between workstations numbers and fatigue to help practitioners in the design phase of assembly systems.

Overall, this method finds more than 80% of Pareto efficient solutions. For instances where our approach fails to give all the Pareto efficient solutions, the metric value HR shows the good quality of the results obtained. The proposed method makes it possible to balance line with less fatigue for workers. A small increase in cost can reduce the threshold of fatigue.

Future research will focus on fatigue and recuperation of workers with a new muscle fatigue and recovery model (Ma et al., 2010) to take into account the idle and transfer time for workers recuperation. Further works should consider other assembly line problems with different situation observed in the industrial environment.

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Appendix A. EXPERIMENTS RESULTS

Here below, we report the results of the experiment as described in Section 5. First table (A.1) concern the 21 instances with the lowest takt time of the benchmark and the second table (A.2) concern the 23 instances with the highest takt time.

Table A.1. Experiment 1 : Lowest takt time

	Uniform Distribution				Beta Distribution			
	Avg Nb of sol	Pareto Opt sol (%)	Avg time per inst (s)	Hyperarea ratio	Avg Nb of sol	Pareto Opt sol (%)	Avg time per inst (s)	Hyperarea ratio
ARC83	4.40	31.82	2771.97	1.1179	1.00	54.55	965.24	1.0057
ARC111	1.20	83.33	182.70	1.0048	4.50	100.00	8.54	1.0000
BARTHOLD	2.80	50.00	1356.38	1.0178	1.67	20.00	3605.56	1.0726
BOWMAN8	2.00	100.00	0.07	1.0000	1.33	100.00	0.02	1.0000
BUXEY	1.40	100.00	0.27	1.0000	1.17	100.00	0.30	1.0000
GUNTHER	1.20	100.00	0.24	1.0000	2.00	100.00	0.12	1.0000
HAHN	1.60	100.00	0.12	1.0000	1.83	100.00	0.18	1.0000
HESKIA	1.20	100.00	0.14	1.0000	1.17	100.00	0.23	1.0000
JACKSON	1.00	100.00	0.02	1.0000	1.00	100.00	0.02	1.0000
JAECHKE	1.00	100.00	0.01	1.0000	4.00	100.00	0.01	1.0000
KILBRID	2.80	100.00	87.82	1.0000	4.00	73.68	1287.72	1.0002
LUTZ1	3.60	100.00	0.76	1.0000	2.00	100.00	1.71	1.0000
LUTZ3	2.00	100.00	41.41	1.0000	2.33	100.00	20.17	1.0000
MANSOOR	1.80	100.00	0.04	1.0000	1.00	100.00	0.07	1.0000
MERTENS	1.00	100.00	0.03	1.0000	2.17	100.00	0.02	1.0000
MITCHELL	3.20	100.00	0.23	1.0000	1.00	100.00	0.13	1.0000
MUKHERJE	1.00	100.00	2.13	1.0000	2.00	100.00	29.45	1.0000
ROSZEIG	2.60	100.00	0.28	1.0000	1.83	100.00	0.19	1.0000
SAWYER30	2.00	100.00	1.95	1.0000	1.00	100.00	1.14	1.0000
WARNECKE	1.00	100.00	3.37	1.0000	1.00	100.00	2.65	1.0000
WEE-MAG	1.00	100.00	3.24	1.0000	1.00	100.00	3.01	1.0000
Avg ; WAvg	1.90	94.18	212.06	1.0067	1.86	97.12	282.21	1.0037

Table A.2. Experiment 2 : Highest takt time

	Uniform Distribution				Beta Distribution			
	Avg Nb of sol	Pareto Opt sol (%)	Avg time per inst (s)	Hyperarea ratio	Avg Nb of sol	Pareto Opt sol (%)	Avg time per inst (s)	Hyperarea ratio
ARC83	15.4	44.16	9703.17	1.0008	11.17	66.67	4780.70	1.0003
ARC111	11.2	31.58	7763.28	1.0002	10.83	18.18	8525.50	1.0002
BARTHOLD	8	45.00	4376.88	1.0004	9.00	39.58	5832.16	1.0009
BOWMAN8	2	100.00	0.04	1.0000	1.67	100.00	0.02	1.0000
BUXEY	4.6	100.00	1.37	1.0000	5.00	100.00	2.17	1.0000
GUNTHER	4.6	100.00	0.96	1.0000	3.00	100.00	0.30	1.0000
HAHN	4.4	100.00	0.57	1.0000	5.50	92.59	0.99	1.0023
HESKIA	4.8	100.00	0.89	1.0000	5.83	100.00	2.26	1.0000
JACKSON	4	100.00	0.10	1.0000	3.83	100.00	0.11	1.0000
JAECHKE	3.8	100.00	0.16	1.0000	3.33	100.00	0.07	1.0000
KILBRID	9.4	97.87	583.59	1.0000	10.00	89.58	1612.68	1.0002
LUTZ1	6.4	100.00	1.66	1.0000	7.83	100.00	2.95	1.0000
LUTZ2	7.4	40.54	4821.53	1.0558	5.00	45.45	2425.42	1.0111
LUTZ3	9	100.00	51.06	1.0000	9.17	100.00	88.10	1.0000
MANSOOR	3	100.00	0.10	1.0000	3.33	100.00	0.09	1.0000
MERTENS	3.6	100.00	0.12	1.0000	3.67	100.00	0.09	1.0000
MITCHELL	7.2	100.00	0.48	1.0000	6.17	100.00	0.36	1.0000
MUKHERJE	5.6	47.22	4521.44	1.0002	5.50	31.58	3096.31	1.0000
ROSZEIG	7.2	97.22	1.25	1.0001	6.50	100.00	0.88	1.0000
SAWYER30	5.2	100.00	1.55	1.0000	4.50	100.00	1.16	1.0000
TONGUE70	11.2	89.29	2562.27	1.0001	10.17	81.63	2206.13	1.0002
WARNECKE	4.8	75.00	1746.94	1.0167	4.83	68.00	3608.30	1.0004
WEE-MAG	5	16.67	3651.52	1.0513	3.33	66.67	1219.38	1.0238
Avg ; WAvg	6.42	76.03	1730.04	1.0055	6.05	78.48	1452.44	1.0017