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Work planning in low-volume assembly lines under ergonomic constraints

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Abstract

In order to implement the human-centric manufacturing and sustainability concepts in industry, an important effort should be done in order to model working conditions for human operators and improve them. Several studies have been conducted for mass production assembly lines where short cycle times make the work content highly repetitive. However, the case of low-volume production with long cycle times and different impacts on human operators has been rarely considered in the literature. In this paper, we develop a model to take into account the associated ergonomic risks in assembly lines with long cycle times. An optimization method is also developed in order to schedule tasks and assign the required tasks to a set of human operators taking into account the existing ergonomic risks.

Keywords:

assembly lines, scheduling, assignment problem, human factors, ergonomics

1. Introduction

This research addresses the task scheduling and operator assignment problem in manual aircraft assembly lines (FAL). In an aircraft assembly line, in contrast to the intensively studied automotive assembly lines, an important number of operators can be assigned to the same workstation. The objective of this study is to develop new planning tools which take into account the ergonomic constraints for the operators in order to improve their working conditions.

In the literature, this issue was firstly studied for mass assembly lines characterized by low cycle times. For example, 13 different parameters describing physical load for each assembly task were proposed in [1] including environmental parameters, physical load of awkward and static postures, physical load of other factors. It was shown in [2] by Otto and Scholl that several possible objective functions could be used in order to diminish the ergonomic impact on the operators: minimization of average ergonomic risks, minimization of the number of stations with high ergonomic risks and minimization of deviations from acceptable levels of station physical loads.

Lexicographically arranged economic and ergonomic objectives were firstly considered for planning assembly lines in [3]. Each task was characterized by its physical demand stating the

amount of energy required to perform this task. The total physical demand of the station was constrained by the value of the individual physical tolerance of the worker. The study of [4] also considered several lexicographically arranged objective functions. The first objective was to minimize cycle time for the given number of stations. Further objectives were to minimize average ergonomic risks, to minimize average deviation of ergonomic risks among stations and to minimize the number of stations with high risks.

However, most articles consider a weighted sum of two groups of objective functions: ergonomic and economic e.g. [5–9]. A detailed study on the trade-offs between economic and ergonomic objectives was performed in [10] where were considered two time-oriented and two ergonomic objective functions: minimization of the variance of station times, minimization of the cycle time, minimization of the variance of the energy expenditures at stations and minimization of the maximal energy expenditure at a station.

The most cited studies considered the assumption of a single worker per workstation. However, in aircraft assembly lines there could be several dozens of operators working at the same workstation. This fact changes profoundly the mathematical structure of the problem. In addition to this, the cycle time is much longer and can take several days, this modifies the calcu-

lation of the ergonomic impact on the operators, which should be measured for each operator separately and not in total for the workstation. The longer cycles offer more possibilities to change of activity and to have breaks.

From the mathematical point of view, the assignment of tasks to operators in aircraft assembly lines can be modelled as a special case of Resource Constrained Project Scheduling Problem (RCPSP). Even a classical statement of RCPSP is NP-hard in a strong sense [11]. The need to include the ergonomic constraints in the model further increases the complexity of the optimization problem to solve. In order to be able to tackle this complex problem, its resolution is realized in two phases: first an aggregated resource demand problem is solved (the "master schedule"), then the assignment of work to operators is solved under operator's speciality constraints, physical ergonomic constraints and cognitive-oriented objective function. The latter expresses the will to assign each operator preferably to a sequence of tasks belonging to a same group. The optimization problem addressed in this paper therefore concerns task scheduling and assignment of scheduled tasks among operators trying to minimize the number of changes between different groups of tasks for the workers. Each task belongs to exactly one group.

RCPSP problem is a well-studied combinatorial optimisation problem. For solving methods of classical statement of RCPSP we recommend to read surveys [12,13]. However, aircraft assembly line scheduling and assignment problem is rarely addressed in the literature. In [14], a heuristic approach to optimize aircraft assembly process was presented. The mixed model assembly alternatives for the aerospace industry were considered by [15]. Constrained programming method for solving RCPSP with labour skills is presented in [16]. Workforce management in manual assembly lines of large products was considered in work [17].

This paper is organized as follows. In section 2 we formulate the problem and decompose it in two parts. In sections 3 and 4 we suggest mathematical models to find optimal solutions of task scheduling and operator assignment problems. In section 5 we present the results of numerical experiments and in section 6 we conclude.

2. Problem statement

We can state the aircraft assembly scheduling problem in terms of Resource-Constrained Scheduling Problem (RCPSP). There is a set of operators O each of which has only one speciality $s_o \in S$, where S – set of specialities. There is a set of resources (equipment, aircraft parts) R , such that for each $x \in R$ the capacity c_x is defined. There is a set of tasks N divided into set of groups G . All tasks should be processed in planning horizon H , which is equal to takt time. For each task $j \in N$ the following attributes are defined:

- g_j – group of task;
- r_j – release time;
- p_j – processing time;
- a_{jx} – amount of resource $x \in R$ required during the processing of j ;
- b_j – number of operators required to process task j .
- s_j – speciality of operators.

Precedence relations with time lags are defined by a direct weighted graph $G(N, E)$. The existence of edge e_{ji} with weight l_{ji} means that for processing of tasks $j, i \in N$ the following inequality should be satisfied $S_j + l_{ji} \leq S_i$, where S_j – start time of processing task $j \in N$. Note that values l_{ji} can be negative and both edges e_{ji}, e_{ij} may exist if $l_{ji} + l_{ij} \leq 0$.

The set of ergonomic impact evaluation methods is defined by M . Such methods are used to evaluate the present ergonomic risks such that environmental risks (such as inappropriate temperature, light, noise, vibration, and exposure to chemicals), physical load of awkward and static postures (such as bending, or twisting), physical load of other factors (such as weight of the handled load, or frequency of actions for gripping tasks). Ergonomic score erg_{mj} evaluated by method $m \in M$ of one unit of worktime of operator $o \in O$ on task $j \in N$. We consider two types of physical ergonomic constraints for each method $m \in M$. U_{mo}^h – an upper bound on the total ergonomic impact evaluated by method m for all tasks processed by operator o during planning horizon H . $U_{mo}^i(t_1, t_2)$ – an upper bound on the total ergonomic impact evaluated by method m for all tasks processed by operator o during time interval $[t_1, t_2)$, where $t_1, t_2 \in [0, H)$ and $t_1 < t_2$.

To decrease number of mistakes and improve operators' involvement, the objective is to minimize the number of switches between the groups of tasks. This means that we have to minimize number of triplets $(o \in O, i \in N, j \in N)$ such that $g_i \neq g_j$ and both tasks are consequently processed by the same operator o .

To solve this problem for large-scale instances, we decompose it into two parts and develop two following models.

1. Constraint programming (CP) model is used to find the start times of tasks, with respect to resource, precedence and time horizon constraints.
2. Integer linear programming model (ILP) is used to assign operators to scheduled tasks.

We also suggest some techniques for data pre-processing to decrease the solution time.

3. Task scheduling problem

First of all we solve task scheduling problem using CP model. In the pre-processing part, we create a new resource for each speciality with capacity $c_s = \sum_{j \in N: s_j = s} 1$. If this resource capacity is not violated then under a feasible schedule, all tasks being processed at moment of time $t \in [0, H)$ require no more than c_s operators with speciality $s \in S$. The model to solve this volume-panning problem is as follows.

There is one set of decision interval variables.

- $interval_j$ – interval variable associated with the execution of task $j \in N$, i.e. $interval_j = [S_j, S_j + p_j)$.

The solution of the problem must satisfy the following constraints.

- All tasks are to be processed in the planning horizon $H \geq \max_{j \in N} (S_j + p_j)$.
- Interval size should be equal to processing time, i.e. $\forall j \in N$

$N : |interval_j| = p_j$.

- Task processing interval must satisfy precedence relations with time lags, i.e. $\forall e_{ij} \in E : S_i + l_{ij} \leq S_j$.
- Resource capacity constraint is modelled through a cumulative function which represents the usage of resource $x \in R$ while processing tasks at each time t :

$$F(x, t) = \sum_{j \in N} a_{jx} \cdot f(interval_j, t),$$

where $f(interval_j, t) = 1$ if $t \in interval_j$ and $f(interval_j, t) = 0$ otherwise. Then resource capacity constraint can be formulated as $\forall x \in R, t : c_x \geq F(x, t)$.

The solution of this model provides task processing intervals $[S_j, S_j + p_j)$ which will be used as an input for the following operator assignment problem.

4. Operator assignment problem

Here, the objective is to assign operators to tasks already scheduled to time intervals $[S_j, S_j + p_j)$.

It is impossible to process two different tasks by the same operator. To make this constraint linear, we create a set of pairs of tasks P consisting of ordered pairs of tasks which require the same specialities and have intersected processing intervals, i.e. for each $(i, j) \in P, i < j$ such that $s_i = s_j$ and $[S_i, S_i + p_i) \cap [S_j, S_j + p_j) \neq \emptyset$.

The objective function is related to the pairs of tasks consequently processed by the same operator. If two tasks are executed by the same operator and belong to different groups, then the contribution to the objective function of this triplet of one operator and two tasks equals to 1, otherwise 0. To increase the speed of search we create a set of all possible ordered pairs which belong to the same group and can be theoretically processed consequently by the same operator, i.e. for any $(i, j) \in V$ holds

- $g_i = g_j$ – tasks belong to the same group;
- $s_i = s_j$ – tasks require the same speciality;
- $S_i + p_i \leq S_j$ – task i ends before the start of task j .

The IP model developed for this problem is as follows.

There are two sets of decision variables.

- $assign_{oj}$ – binary variable equals to 1 if operator $o \in O$ assigned to task $j \in N$, otherwise $assign_{oj} = 0$.
- seq_{ov} – binary variable equals to 0 if operator $o \in O$ process tasks of pair $v \in V$ in a sequence, otherwise $seq_{ov} = 1$.

The constraints are formulated as follows.

- An operator can be assigned only to a task which requires his/her speciality
 $\forall j \in N, o \in O, s_j \neq s_o : assign_{oj} = 0$.
- For each $(i, j) \in P$ operator cannot be assigned to 2 different tasks simultaneously
 $\forall (i, j) \in P, o \in O : assign_{oi} + assign_{oj} \leq 1$.
- To each task $j \in N$ should be assigned exact number of required operators
 $\forall j \in N : \sum_{o \in O} assign_{oj} = b_j$.
- Correctness of seq variables. For any $o \in O$ and $v = (i, j) \in$

$V, seq_{ov} = 1$ if operator o is not assigned to i or j

$\forall v = (i, j) \in V, o \in O : seq_{ov} \geq 1 - assign_{oi}$,

$\forall v = (i, j) \in V, o \in O : seq_{ov} \geq 1 - assign_{oj}$.

- Correctness of seq variables. For any $o \in O$ and $v = (i, j) \in V, seq_{ov} = 0$ if operator o does not process any task during time interval $[S_i + p_i, S_j]$
 $\forall v = (i, j) \in V, o \in O :$

$$seq_{ov} \leq 2 - assign_{oi} - assign_{oj} + \sum_{k \in N: S_i < S_k < S_j} assign_{ok}.$$

- Correctness of seq variables. For any $o \in O$ and $v = (i, j)$, $seq_{ov} = 0$ there are no tasks processed by operator o between i and j
 $\forall v = (i, j) \in V, o \in O, k \in N | s_i < s_k < s_j : assign_{ok} \leq seq_{ov}$
- For each task $i \in N$ and operator $o \in O$ there can be no more than one pair $(i, j) \in V$ such that i is processed by o just before j
 $\forall i \in N : 1 + \sum_{v \in V: v=(i,j)} (seq_{ov} - 1) \geq 0$.
- For each task $i \in N$ and operator $o \in O$ there can be no more than one pair $(j, i) \in V$ such that j is processed by o just before i
 $\forall i \in N : 1 + \sum_{v \in V: v=(j,i)} (seq_{ov} - 1) \geq 0$.
- The total ergonomic score evaluated by method $m \in M$ for operator $o \in O$ should not be more than U_{mo}^h :
 $\forall o \in O, m \in M : \sum_{j \in N} erg_{mj} \cdot p_j \cdot assign_{oj} \leq U_{mo}^h$.

There is an additional constraint related to the ergonomic impact on operator o during time interval $[t_1, t_2)$. In the considered industrial case, it is defined by a constant interval length T and a set of upper bounds U_m^i on ergonomic impact evaluated by method $m \in M$ in each interval $[t_1, t_2)$ such as $t_2 - t_1 = T$. This type of constraints should be satisfied for any operator $o \in O$, method $m \in M$ and time interval $[t_1, t_1 + T)$ where $0 \leq t_1 \leq H - T$. This means that a feasible assignment of operators to tasks should satisfy $|O||M||H - T + 1|$ interval ergonomic constraints. Since time horizon length H can be very large we need some techniques to decrease this number. Let us prove the following lemma.

Lemma 1. *Let $N^s \subseteq N$ – the set of tasks which require speciality s . Then if for any method m , operator o , task $j \in N^{s_o}$ and $t = \{S_j, \max\{0, S_j + p_j - T\}\}$ ergonomic impact on operator o evaluated by method m during time interval $[t, t + T)$ is no more than U_m^i , then all interval ergonomic constraints are not violated.*

Proof. Let for one feasible assignment operator $o \in O$ to be assigned to the set of tasks $N^o \subseteq N^{s_o} \subseteq N$. Then ergonomic impact on operator o evaluated by method $m \in M$ during time interval $[t, t + T)$ is defined by function

$$Erg_{mo}(t) = \sum_{j \in N^o} erg_{mj} \cdot (\min\{t + T, S_j + p_j\} - \max\{t, S_j\}) \cdot assign_{oj}.$$

Local extremes of this function can only be found when $t + T = S_j + p_j$ or $t = S_j$, i.e. we only need to check that inequality $Erg_{mo}(t) \leq U_m^i$ is correct for $t = S_j + p_j - T$ and $t = S_j$ for each $j \in N^o$. Since $N^o \subseteq N^{s_o}$ the lemma is proved. ■

Lemma 1 decreases the number of interval ergonomic constraints from $|O||M||H - T + 1|$ to $|M| \cdot \sum_{o \in O} 2|N^{s_o}| = 2|N||M||O|$. These constraints can be modelled as follows:

$\forall m \in M, o \in O, j \in N :$

$$\sum_{i \in N^{so}} erg_{mi} \cdot (\min\{S_j + T, S_i + p_i\} - \max\{S_j, S_i\}) assign_{oj} \leq U_m^i,$$

$$\sum_{i \in N^{so}} erg_{mi} \cdot (\min\{S_j + p_j, S_i + p_i\} - \max\{S_j + p_j - T, S_i\}) assign_{oj} \leq U_m^i.$$

The objective is to minimize total number of group switches for operators. For each feasible assignment of operators to tasks, total number of triplets ($o \in O, i \in N, j \in N$) where operator o processes task i just before j is equal to $|N| - |O|$. Number of pairs of tasks, which belong to different groups consequently processed by the same operator can be calculated as: *number of pairs of tasks belonging to different groups and consequently processed by the same operator = total number of tasks processed by operator – number of pairs of tasks belonging to the same group and consequently processed by operator – 1*. Then the objective function can be modelled as follows:

$$\min \sum_{j \in N} b_j - \sum_{o \in O, v \in V} (1 - seq_{ov}) - |O|.$$

5. Numerical experiments

Presented model was tested on two industrial data instances. Experiments were done on the IBM ILOG CPLEX software using processor Intel(R) Core(TM) i5-4670 3.40GHz and 16 GB of RAM.

The first instance was characterized by 289 tasks with 340 precedences divided into 79 groups, 12 resources, 7 operators with 3 specialities and 1 ergonomic evaluation method. For this instance optimal solution of task scheduling problem was found in 15 seconds. Optimal solution of operator assignment problem was found in 18 seconds.

For the second instance task processing schedule was given and only the solution of operator assignment problem was required. This instance is characterized by 447 tasks divided into 79 groups, 5 operators with 2 specialities and 1 ergonomic evaluation method. For this instance optimal solution was found in 36 seconds.

6. Conclusion

Aircraft assembly line planning problem was studied. The considered problem was formulated as a special case of Resource-Constrained Project Scheduling Problem with labour skills, two types of physical ergonomic constraints and a cognitive-oriented objective function. The problem was decomposed into two parts and CP and ILP models were developed to find optimal solutions for industrial cases. Numerical experiments showed that suggested models can solve real industrial instances efficiently even for a high number of tasks. The further research will be concentrated on the improvement of the CP model where some additional constraints will be added in order to obtain a solution in the first phase with the best potential for the second phase.

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