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Operator assignment problem in aircraft assembly lines: a new planning approach taking into account economic and ergonomic constraints

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Abstract

The assembly process is extremely complex for aircraft and its management requires to address numerous optimization problems related to the assignment of tasks to workstations, staffing problem for each workstation and finally the assignment of tasks to operators at each workstation. This paper treats the latter problem dealing with the assignment of tasks to operators under ergonomic constraints. The problem of optimal tasks scheduling in aircraft assembly line is modelled as Resource-Constrained Project Scheduling Problem (RCPSP). The objective of this research is to assign tasks to operators and to find an optimal schedule of task processing under economic and ergonomic constraints. Two different models to solve this problem are presented and evaluated on an industrial case study.

Keywords: scheduling; ergonomics; human factors; constrained programming; project scheduling; assignment problem

1. Introduction

This research addresses the problem of work assignment for operators in final aircraft assembly lines (FAL). These lines are mainly manual and paced. Since the failure to deliver on time may result in significant penalties for the manufacturer, it is crucial to meet the schedule at each workstation.

We consider that the tasks to be performed at any workstation have been already defined and the set of operators with required skills is already assigned to each workstation. The scope of the optimization problem is one workstation with all its tasks and operators. The goal of the considered optimization problem is to assign all tasks to available operators while respecting economic (takt time) and ergonomic constraints. This problem can be considered as a special case of Resource Constrained Project Scheduling Problem (RCPSP). RCPSP is an NP-hard in a strong sense which means that there are no algorithm available to find an optimal solution for large-scaled industrial instances in reasonable time. In this research we develop new optimization approaches based on constraint programming and integer programming models to solve this problem. In order to benefit from a time buffer to manage possible delays in working process, the objective is to find a schedule with the minimal makespan.

RCPSP is a well-studied classical combinatorial optimisation problem. It was proved that the decision variant of the RCPSP is NP-complete in the strong sense even without precedence constraints and only one resource, by reduction from the 3-partition problem [1]. A comprehensive survey on project scheduling problems formulations and solution methods was presented in [2,3]. Various problem formulations have been proposed in the literature, however, none addressed the ergonomic constraints existing in aircraft assembly lines. The problem of aircraft assembly line optimization was also rarely considered in the literature. A heuristic approach to optimize aircraft assembly process was presented in [4]. Other optimization models for aircraft assembly lines management can be found in [5,6]. Workforce management in manual assembly lines of large products was considered in our previous work [7]. This model can be also used for aircraft assembly lines for deciding on the operators assigned to each workstation. An efficient application of constrained programming method for RCPSP with labour skills was presented in [8].

During the aircraft assembly process operators performing tasks manually in postures related to high ergonomic risks. To improve the performance of aircraft assembly lines, both economically and socially, it is necessary to develop new planning methods taking into account both economic and ergonomic cri-

teria (health / safety) for operators. However, only recently, works of [9–11] presented the first planning methods explicitly integrating the ergonomic data in assembly line planning. All cited studies were realized in the context of automotive production where the task repetitivity is much higher than in aircraft assembly lines. A comprehensive survey on the integration of ergonomic criteria in planning methods for assembly lines was recently presented in [12].

In ergonomics, numerous studies were realized on occupational hazards, but their results are usually not integrated in planning approaches. Usually companies conduct occupational risk assessments for existing units of work. This assessment is designed to identify a broad set of risks. The objective of this study is to integrate the ergonomic models in appropriate planning methods in order to improve the working conditions for the operators of final aircraft assembly lines.

This paper is organized as follows. In section 2, we give an overview of the existing ergonomic methods. In section 3, we provide a mathematical model for the considered problem. In section 4, we present a Constraint Programming (CP) model to solve it and in section 5, the CP model enhanced with Integer Linear Programming (ILP) step. In section 6, we describe the industrial case and provide the results of the numerical experiments. Concluding remarks are given in section 7.

2. Ergonomic methods overview

This section presents a brief overview of the most frequently used ergonomic methods which can be applied in aircraft assembly lines. Table 1 depicts the risk types used by ergonomic methods described here below.

- NIOSH-Eq – National Institute for Occupational Safety and Health lifting equation [13]. The National Institute for Occupational Safety and Health (NIOSH) developed the Work Practices Guide for Manual Lifting in 1981 in order to help safety and health practitioners to assess the risks related to lifting and lowering jobs. The main goal was to prevent and reduce the low back pain for manual operations. This Manual was revised and extended in 1991 and it is currently a part of ISO 11228 standard.
- LI – Lifting Index [14]. The lifting index is calculated as the ratio between the handled load and a recommended load. The recommended load is determined taking into account the weight of the handled object, horizontal and vertical locations, distance, angle of symmetry, frequency of lift, duration and the coupling between hands and the object.
- RULA – Rapid Upper Limb Assessment [15]. The RULA tool employs special worksheets to rapidly assess the ergonomic risks for upper limbs, neck and trunk. Seven steps are required in order to compute the final score which is determined taking into account such parameters as the applied forces, awkward and static postures and the frequency of repetition.
- REBA – Rapid Entire Body Assessment [16]. REBA is a method specially designed to be sensitive to the type of unpredictable working postures found in health care and other service industries. It was developed by a team of physiotherapists, occupational therapists and nurses col-

Table 1. Ergonomic methods comparison.

method	focus	neck	trunk	hands	legs	whole body	noise
NIOSH-Eq						+	
LI	+					+	
RULA		+	+	+			
REBA		+	+	+	+		
OCRA				+			
JSI				+			
DND							+
EAWS	+	+	+	+	+	+	
EnerExp	+					+	

lected and individually coded over 600 postural examples.

- OCRA – Occupational Repetitive Action tool [17]. The OCRA index is used to evaluate repetitive handling at high frequency performed by upper limbs. The final OCRA index is calculated as the ratio between the actual and the recommended frequency of actions which is calculated taking into account such parameters as the applied forces, postures and additional risk factors, such as vibration.
- JSI – Job Strain Index [18]. The JSI applies a methodology similar to that of OCRA where two additional parameters are integrated: speed of work and duration of strain.
- DND – Daily Noise Dosage [19]. DND provides a recommended exposure limit for occupational noise taking into account such parameters as the time of affection, sound volume and frequency.
- EAWS – Ergonomic Assessment Work Sheet [20]. The EAWS tool is used to assess postures, action forces, manual material handling as well as other whole-body risk factors and repetitive loads of the upper limbs. As a result, two aggregate risk values are estimated: risk points for the whole body and risk points for upper limbs. Higher risk points indicate higher risks for musculoskeletal disorders.
- EnerExp – Energy Expenditure Method [21]. Energy Expenditure Method is based on the evaluation of the amount of energy spent by a worker during activity execution.

Table 1 shows that different ergonomic methods consider different risks. Therefore, in order to improve the working conditions of workers and decrease the impact on their health it is reasonable to use several methods at the same time. We follow this idea in our problem statement.

3. Problem statement

The following statement of the problem is considered. There is a set of operators O each of which has only one speciality $s \in S$, where S – set of specialities. There is a set of resources R , such that for each $x \in R$ the capacity c_x is defined. There is a set of n tasks N to be done. For each task $j \in N$, the following attributes are defined:

- r_j – release time;
- p_j – processing time;
- a_{jx} – amount of resource $x \in R$ required to process task j ;
- b_{js} – number of operators with speciality $s \in S$ required to process task j .

For the set of tasks, 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: $S_j(\pi) + l_{ji} \leq S_i(\pi)$, where $S_j(\pi)$ – start time of processing task $j \in N$ under schedule π . Note that values l_{ji} can be negative and both edges e_{ji}, e_{ij} may exist if $l_{ji} + l_{ij} \leq 0$.

Ergonomic impact is measured by a set of methods M . For each triplet $(m \in M, j \in N, s \in S)$, the ergonomic impact of task j on operator with speciality s evaluated by method m is defined by erg_{mjs} . A critical level of the total ergonomic impact evaluated by method m for all tasks processed by the same operator o is defined by U_{mo} , which should not be violated. Note that this critical level can depend on individual capacities of the operator.

The objective is to find a schedule π^* with the minimal makespan i.e.

$$\min_{\pi} \max_{j \in N} (S_j(\pi) + p_j). \quad (1)$$

To address this problem in this study, we use exact solution methods based on constraint Programming (CP) and Integer Linear Programming (ILP) - they are well-known solution methods of intelligence search for exact solutions of mathematical optimization problems. For small problem instances, both methods should be able to provide an optimal solution for the considered problem. However, since RCPS is NP-complete, the complexity of performance of CP and ILP depends on the developed model and properties of particular problem instances. Our objective is to choose the method and create mathematical model which will be able to provide an optimal solution in reasonable time for realistic in industry problem instances.

4. Constraint programming model

Firstly, the following constraint programming (CP) model is developed to solve the considered optimization problem.

We consider two sets of decision variables.

- $interval_j$ – interval variable associated to the execution of task $j \in N$, i.e. $interval_j = [S_j, C_j]$;
- $assign_{oj}$ – binary variable equals to 1 if operator $o \in O$ assigned on task $j \in N$, otherwise $assign_{oj} = 0$.

The objective is to minimize the makespan as defined by equation (1). A solution of the problem must satisfy the following constraints.

The task interval size has to be equal to the task processing time, i.e.

$$\forall j \in N : |interval_j| = p_j. \quad (2)$$

For each task $j \in N$, the number of operators with speciality $s \in S$ has to be equal to b_{js}

$$\forall j \in N, s \in S : \sum_{o \in O: s_o = s} assign_{oj} = b_{js}. \quad (3)$$

Task processing intervals must satisfy the precedence relations with time lags, i.e.

$$\forall e_{ji} \in E : S_j(\pi) + l_{ji} \leq S_i(\pi). \quad (4)$$

The tasks assigned to the same operator cannot overlap, i.e.

$$\forall i, j \in N, o \in O : assign_{oi} \cdot assign_{oj} \cdot |interval_i \cap interval_j| = 0. \quad (5)$$

The total ergonomic impact of the tasks assigned to the same operator $o \in O$ measured by method $m \in M$ has to be less than the defined critical level U_{mo} , i.e.

$$\forall m \in M, o \in O : U_{mo} \geq \sum_{j \in N} erg_{mjs_o} \cdot assign_{oj}. \quad (6)$$

Resource capacity constraint is modelled through a cumulative function which represents the usage of resource $x \in R$ by processing tasks for each time t :

$$F(x, t) = \sum_{j \in N} a_{jx} \cdot f(interval_j, t), \quad (7)$$

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

$$\forall x \in R, t : c_x \geq F(x, t). \quad (8)$$

5. Joint CP and ILP model

The second optimization model consists of two parts. The first part uses CP to solve the scheduling problem with the aggregated demand. The objective is to find the schedule with the minimal makespan subject to resource constraints and precedence relations. The second part assigns the operators to the scheduled tasks under the ergonomic constraints. The second part is solved with Integer Linear Programming (ILP) approach.

5.1. Scheduling problem with the aggregated demand

This problem is a relaxation of the initial one because there is no need to assign operators to tasks and specialities are considered as resources. For each speciality, its capacity equals to the number of operators possessing this speciality.

There is one set of decision interval variables.

- $interval_j$ – interval variables associated with the execution of task $j \in N$, i.e. $interval_j = [S_j, C_j]$.

The solution of problem must satisfy the following constraints introduced by equations (2), (4), (7), (8) in section 4. The objective is to find a schedule π^* with minimal makespan as introduced by equation (1). The solution of this model provides the task processing intervals $[S_j, C_j]$ which will be used as input data for the following operator assignment problem.

5.2. Operator assignment problem

To solve this problem we have to assign the operators to tasks, which processing intervals $[S_j, C_j]$ are given as a solution of the volume-scheduling problem. Each task $j \in N$ assigned to operator $o \in O$ makes a contribution into total ergonomic impacts erg_{mjs_o} evaluated by method $m \in M$. The objective is to find an assignment with the minimal highest ergonomic impact.

There is one set of binary decision variables.

- $assign_{oj}$ – binary variable equals to 1 if operator $o \in O$ is assigned to task $j \in N$, otherwise $assign_{oj} = 0$.

The problem constraints include equations (3) and (6). Since the schedule of the tasks is known, the incompatible sets of tasks can be defined, i.e. the sets of the tasks e that cannot be performed by the same operator. Let E be the family of such incompatible sets, then the constraint on the non intersection of the tasks to be performed by the same operator can be modelled in the following way:

$$\forall e \in E, o \in O : \sum_{j \in e} assign_{oj} \leq 1. \quad (9)$$

The objective function is to minimize the highest ergonomic impact calculated for each pair ($m \in M, o \in O$).

$$\min_{m \in M, o \in O} \max_{j \in N} \sum assign_{oj} \cdot erg_{mjs_o} \quad (10)$$

The solution of this two-part model represents a schedule for tasks with operator assignment.

6. Numerical experiments

Presented models were implemented on the package IBM ILOG CPLEX. Experimental data was provided by our industrial partner and characterised by 289 tasks with 340 precedence relations, 12 resources, 7 operators with 3 skills and 1 ergonomic evaluation method. Experiments were realized with the use of processor Intel(R) Core(TM) i5-4670 3.40GHz and 16 GB of RAM.

The first version of CP model performed well only for a low number of tasks and even for 30 tasks it could not obtain any solution in 1 hour. Joint CP and ILP model showed better results. CP solved volume-scheduling problem for 289 tasks less than in 15 minutes, the second part was solved with ILP in less than 1 second. This approach can be considered as viable for industrial problem instances.

7. Conclusion

The objective of this study was to develop new optimization models taking into account both economic and ergonomic criteria for task scheduling and operator assignment in final aircraft assembly lines. The considered optimization problem was modelled as a Resource-Constrained Project Scheduling Problem with labour skills and additional ergonomic constraints. For this model, two optimization approaches were developed and applied to an industrial case study. The numerical experiments show that a joint utilization of CP and ILP approaches can be used to solve industrial problem instances. This approach outperformed the pure CP resolution.

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