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Skills management in the optimization of aircraft maintenance processes

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Abstract: The aircraft maintenance processes play an important role in a safe operation of an aircraft. Maintenance services organizations take responsibility for the maintenance process and approve the airworthiness of an aircraft after undertaking the maintenance activities. International law determines the quality of aircraft maintenance processes by setting requirements concerning, among other, a quality management system, a safety management system and operators' competences. As a consequence of the rising number of aircraft in operation, the volume of maintenance activities grows. However, the customers increasingly pose requirements concerning the minimization of the maintenance service lead time. In order to remain competitive, the maintenance service organizations have to reduce the lead time of their services. However, this objective in not easy to attain, since the complexity of aircraft maintenance operations require specific skills and pose a number of organisational and technical constraints to be respected during the maintenance process. In the paper, a mathematical programming model is developed in order to help decision makers in managing the operators' skills during the operators assignment to the activities to be performed. In particular, the Hall's marriage theorem is used to formalise complex restrictions of operators assignment to maintenance activities. The objective of the optimization problem is to minimize total makespan time. The model is applied to a case study.

Keywords: Maintenance processes, skills management, scheduling, optimization

1. INTRODUCTION

The aircraft industry needs to deal with different kinds of optimization problems in planning of the operations (Baohui et al. (2013)). The optimization of aircraft maintenance process plays a significant role as it directly affects the costs and income of an airline. For instance, sub-optimal maintenance and replacement programs result in increasing maintenance costs and operations disruptions (GENPACT (2015)).

Aircraft maintenance process is unavoidable during the overall life cycle of an aircraft, regardless of their operating environment, configuration or utilization rate (Broderick (2013)). Hence, it is vital for operators, manufacturers and maintenance providers to devise strategies in order to optimize the total downtime during a service life (Muchiri and Smit (2009)). The most common approach is to stretch out the maintenance intervals during the life cycle i.e. over 20-25 years (Ackert (2010)). However, the maintenance services have to be scheduled in according with the aircraft specification and utilization rate in different operating environments in order to minimize the risk of disruptions (Subramanian et al. (1994); Sun et al. (2007); Yang & Yang (2012)). In parallel, it is important to develop optimization approaches capable to minimize the total completion time of scheduled maintenance activities or the maintenance lead time which is defined as the "job processing time since the service was requested by a customer up to completely fulfilling that requirement" (Langford (2006), Yang et al. (2011), Pleumpirom and Amornsawadwatana (2012)).

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The content of the maintenance activities and the required specifications in terms of equipment and operators' skills are imposed by the international law. This law ensures the high level of a service process to prevent air accidents. The aircraft manufacturers are responsible for delivering manuals indicating the activities to be performed in order to ensure the continuing airworthiness of the aircraft. As a consequence of the rising number of aircraft in operation, the volume of maintenance activities grows. Since no compromise on quality could be allowed, the key performance indicators of the maintenance service companies are related to the service time. Different tools and methods (from organizational to technological) can be used in order to decrease the lead time.

This paper focuses on the planning and scheduling of maintenance activities. The optimization problem in this context involves the assignment of the limited resources to the maintenance tasks to be performed while respecting quality and safety constraints. The objective is to make the effective use of the maintenance equipment and aviation material as well as to employ the personnel with a relevant expertise. An improper maintenance plan leads to the waste of resources e.g. unnecessary material/personnel flows causing a significant time waste or/and duplication of investment.

In the literature, the optimization of scheduling maintenance activities taking into account a large number of constraints has been comparatively rarely discussed. Chen (2010) demonstrated the minimization of the maintenance completion time and proposed an integer linear programming model focusing on the jobs performed in a series. However, in practice, the aircraft maintenance activities are performed in both a parallel and serial manner (Pleumpirom and Amornsawadwatana (2012)).

In this way, the optimization problem falls in the class of Resource Constrained Project Scheduling Problem (RCPSP) and more particularly can be formulated as a Multi-Skill Resource Constrained Project Scheduling Problem (MSRCPSP) (Hartmann and Briskorn (2010)). This formulation has been firstly proposed by Néron and Baptista (2002) and is known to be NP-Hard in the strong sense (Artigues et al. (2008)). Further, the formulations with the objective to reduce the costs associated with the operators involved (Li and Womer (2008)) or to minimize the makespan (Bellenguez-Morineau and Néron (2007, 2014); Montoya et al. (2014); Almeida et al. (2016)) were studied. In particular, Bellenguez-Morineau and Néron (2007) and Montoya et al. (2014) proposed respectively a Branch-and-Bound and a Branch-and-Price methods to solve the problem. A Tabu search procedure was developed by Bellenguez-Morineau and Néron (2014). Almeida et al. (2016) proposed priority-based heuristics for solving large instances of the problem.

It should be noted that the integration of worker skills in the management problem is currently a topic of increasing interest in operational research literature, for a recent survey in the field, the reader is referred to De Bruecker et al. (2015).

The optimization problem that is proposed in this paper is motivated by a case study in an aircraft maintenance service company. As MSRCPSP, it deals with the assignment of a limited number of "single-skilled" resources as maintenance equipment and "multi-skilled" resources as operators having different competences or skills.

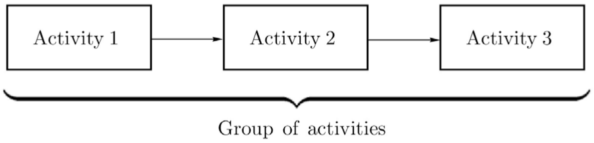

Fig. 1. Group of activities.

The optimization objective is to minimize the maintenance lead time or makespan. However, additionally to the previously considered constraints, the organization of activities in groups of activities associated with particular parts of aircraft should be taken into account. Such an organisation is illustrated in Figure 1.

The paper is organized in the following way. Section 2 introduces the mathematical formulation of the problem and presents the mathematical model developed to minimize the lead time of maintenance activities taking into account the requirements on operators' skills. Section 3 describes the case study and discusses the obtained results. Section 4 provides concluding remarks and perspectives for future research.

2. PROBLEM FORMULATION

The optimization problem is described as follows. In an aircraft maintenance service process a set of operators O is involved. They have different skills. The set of skills is denoted by C. One operator can have one or more skills. There is a set of activities N which have to be realized for an aircraft maintenance service. Each activity belongs to a group from set S of the groups of activities. Each group is a sequence of activities which is associated with a particular part of the aircraft and performed by the same operators (Fig. 1).

One operator can realize different activities depending on his/her competences, but can't realize more than one activity at any moment of time. For each activity, it is indicated how many operators it requires and what kind of skills should have operators to perform the activity. Processing times are given for all activities. In practice, the processing time may depend on the number of operators performing the activity, but in this study we simplify the model by defining the number of operators required for each activity and their skills.

The aircraft under the maintenance process is divided into several areas. Each activity has to be processed in one aircraft area. The walking time for operators from one aircraft area to another can be taken into account, but in the presented study the walking times were significantly low comparing to the activities processing times, for this reason they are neglected in the mathematical model.

Aircraft areas, special equipment and aircraft installations which operators have to use for performing the activities constitute the set of resources R. Groups of activities can be realized in parallel, subject to direct acyclic precedence relations graph of activities $G(N, I)$, operator assignment and resource capacity (Fig. 2).

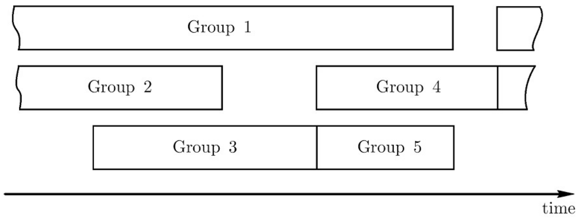

Fig. 2. Parallel performing of activity groups.

The objective is to minimize makespan of the whole maintenance process.

2.1 Mathematical Model

The described problem can be modeled as a mixed integer programming problem in the following way.

Input data.

- Timeslots $T = \{1, \dots, H\}$.
- Set of resources (pieces of equipment, installations, aircraft areas) R.
- Set of skills C.
- Set of operators O.
- Set of activities N, $|N| = n$.
- Precedence relations are modelled with a direct acyclic graph $G = (N, I)$.
- Set of groups of activities S.
- Each group $j \in S$ consists of an ordered set of activities $j = \{s_1, \dots, s_{L_j}\} \subseteq N$ which satisfies
  $$s_1 \to s_2 \dots \to s_{L_j},$$
  where $s_i \to s_j$ means that there is a direct edge from s_i to s_j in graph G. There are no incoming edges for vertices $s_2, \dots, s_{L_j}$ and outgoing edges for vertices $s_1, \dots, s_{L_j - 1}$ in graph G except edges $s_h \to s_{h+1}$, where $h = 1, \dots, L_j - 1$. Any pair of groups $S_i, S_j \in S$ holds $S_i \cap S_j = \emptyset$.

The capacity of resource $k \in R$ is defined as c_k.

For any activity $i \in N$ the following parameters are defined:

- Processing time $p_i \in Z_+$ – number of timeslots required to perform i.
- $r_{ik} \in Z_+$ – amount of resource $k \in R$ required to perform i.

For any operator $o \in O$ and any skill $i \in C$ parameter l_{oi}, equals 1 if operator o has skill i, and equals 0 otherwise.

For any group of activities $j \in S$ the demanded number of operators a_{ji} with competence $i \in C$ is given.

Variables.

- $x_{it} \in \{0, 1\}$. If activity $i \in N$ is performed in timeslot t, then $x_{it} = 1$ and $x_{it} = 0$ otherwise.
- $y_{it} \in \{0, 1\}$. If activity i is finished at the end of timeslot t, then $y_{it} = 1$ and $y_{it} = 0$ otherwise.
- $z_t \in \{0, 1\}$, $z_t = 1$ if all activities are finished at the end of timeslot t, and equals 0 otherwise.
- $v_{jo} \in \{0, 1\}$. If operator $o \in O$ assigned to the group of activities $j \in S$, then $v_{jo} = 1$, otherwise $v_{jo} = 0$;

Objective function.
The objective is to assign all activities respecting the requirement in competent operators in order to minimize maximum completion time:

$$\max \sum_{t=1}^{H} z_t.$$

Basic constraints.

- $z_t n \leq \sum_{j \in N} y_{jt}$ – the flag z equals 1 only when all activities are finished.
- For all $i \in N, j \in S_i, t \in 2, \dots, H : y_{i(t-1)} \leq y_{it}$, $z_{t-1} \leq z_t$ – flags are non-decreasing.
- $p_i y_{it} \leq \sum_{t' \in 1, \dots, t} x_{it'}$ – activity $i \in N$ is finally performed when p_i timeslots of it are performed.
- Any activity $i \in N$ has to be performed exactly in p_i timeslots: $\sum_{t \in T} x_{it} = p_i$.
- $x_{s_{i+1}t} \leq u_{s_i(t-1)} - u_{s_{i+1}(t-1)}$ – for any group $j \in S$ activity s_{i+1} can start only after activity s_i is finished.
- Preemptions are not allowed: $u_{i(t-1)} + x_{i(t-1)} \leq u_{it} + x_{it}$ for any $i \in N$ and $t \in \{2, \dots, H\}$.
- Resource capacity cannot be violated, i.e. $\sum_{i \in N} r_{ij} x_{it} \leq c_k$ for any resource $k \in R$ and timeslot t.
- Each operator $o \in O$ can't be assigned to more than one group of activities $j \in S$ in each timeslot t: $\sum_{j \in G} \sum_{i \in j} x_{it} v_{jo} \leq 1$.
- Number of operators for any group of activities $j \in S$ equals to the sum of demanded skills $\sum_{o \in O} v_{jo} = \sum_{i \in C} a_{ji}$

Hall's marriage theorem application.
There is an additional constraint formulated as follows. We have to assign operators to the group of activities respecting required skills. We also have to be sure that it is possible to distribute all the required skills among the operators assigned to this group. This means that for any group $j \in S$, set of demanded skills $C_j = \{i \mid i \in C,\ a_{ji} > 0\}$ and set of assigned operators $O_j = \{o \mid o \in O,\ v_{jo} = 1$ must satisfy the following constraint.

There is a surjective function $f : O_j \to C_j$ such that for any skill $i \in C_j$ the number of operators $o \in O_j$ which holds $f(o) = i$ equals a_{ji}.

Note that in case when for any demanded skill the number of required operators equals 1 function f is a bijection. To formalize this constraint we can use Hall's marriage theorem. In the terms of our problem it can be formulated as follows.

Hall's theorem.
There is a surjective function $f : O_j \to C_j$ for the activity j such that for any skill $i \in C_j$ the number of operators $o \in O_j$ which holds $f(o) = i$ equals a_{ji} if and only if for any subset of skills $C'_j \subseteq C_j$ the number of operators which has at least one skill belongs to C'_j is not lower than the sum of demanded number of operators for skills of set C'_j, i.e.

$$\sum_{i \in C'_j} a_{ji} \leq \sum_{o \in O_j} l_{oi}.$$

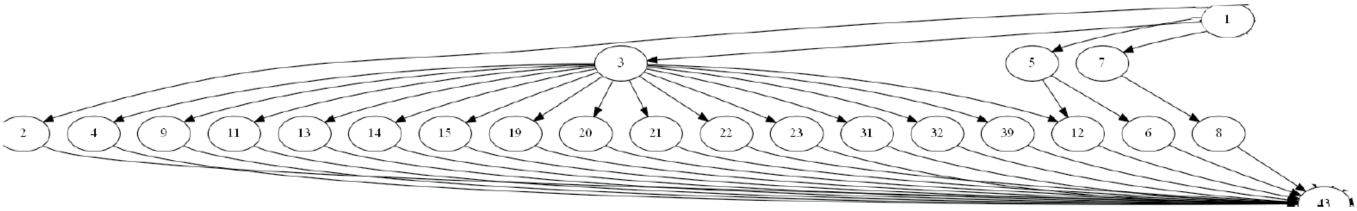

Fig. 3. Precedence graph for the groups of activities from 1 to 43 - Part 1

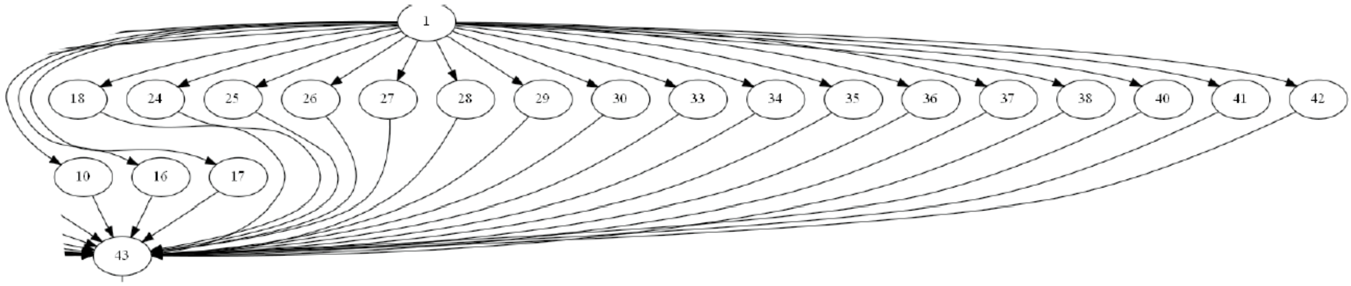

Fig. 4. Precedence graph for the groups of activities from 1 to 43 - Part 2

3. CASE STUDY

Two instances of the problem with 54 groups of activities have to be performed in an aircraft maintenance service process. Each group of activities includes between one and 7 activities. The process was previously analysed with the use of Value Stream Mapping (VSM) method to identify and eliminate wastes (Stadnicka and Ratnayake (2016)). The precedence graph is presented in Figures 3, 4 and . It can be noticed that some groups of activities shown in Figure 5 can be aggregated in pre-processing phase in order to decrease the number of decision variables.

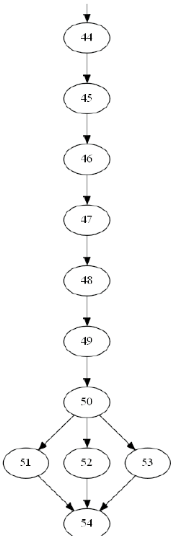

Fig. 5. Precedence graph for the groups of activities from 44 to 54

There are 7 possible levels of personnel skills of the personnel engaged in the process (Table 1). There are 12 operators avaialble. One person can have more than one skill.

There are 18 different types of equipment available in various quantity and required by activities (Table 2).

Table 1. Correspondence between operators and skills

	1	2	3	4	5	6	7	8	9	10	11	12
1	X											
2		X	X	X	X	X					X	
3					X	X					X	
4							X	X	X	X	X	
5									X	X	X	
6											X	
7											X	X

There are 12 different types of installation available in one piece. The aircraft is divided in 8 different areas to perform the activities. Table 3 presents the requirements in operators and skills per group of activity. It should be noted that some of them are expressed with a relation "OR".

Table 2. Number of available equipment per type

Equipment	Number of available equipment
E1	5
E2	4
E3	1
E4	1
E5	1
E6	1
E7	1
E8	1
E9	1
E10	1
E11	1
E12	1
E13	1
E14	1
E15	1
E16	1
E17	1
E18	1

The problem was solved by IBM ILOG CPLEX 12.6.2 using quad-core processor Intel(R) Core(TM) i5-4670 3.40GHz and 8 GB of RAM. The solution time to reach the

Table 3. Skills and number of operators assigned to complete the groups of activities

Group of activities	Skills Skills	Number of operators
A1	C-KH,C-ML,C-AL	3
A2	C-MZ	2
A3	C-MZ	4
A4	C-MZ, C-ML	2
A5	C-ML, C-AL	3
A6	C-MZ, C-AZ	2
A7	C-ML, C-AL	1
A8	C-MZ, C-AZ	2
A9	C-MZ or C-AZ, C-ML or C-AL	2
A10	C-MZ, C-ML	2
A11	C-MZ, C-ML	2
A12	C-MZ, C-ML	3
A13	C-ML	2
A14	C-AZ, C-AL	2
A15	C-MZ, C-ML	2
A16	C-MZ, C-ML	2
A17	C-MZ, C-ML	2
A18	C-AZ, C-AL	2
A19	C-MZ, C-ML	2
A20	C-MZ, C-ML	2
A21	C-AZ, C-AL	2
A22	C-MZ, C-ML	2
A23	C-ML	2
A24	C-AZ, C-AL	2
A25	C-MZ, C-ML	2
A26	C-AZ, C-AL	2
A27	C-AZ, C-AL	2
A28	C-MZ, C-ML	2
A29	C-MZ	2
A30	C-MZ	1
A31	C-MZ, C-ML	2
A32	C-MZ, C-ML, C-AL	3
A33	C-MZ	1-4
A34	C-MZ	2
A35	C-AZ, C-AL	2
A36	C-MZ	4
A37	C-AZ, C-AL	2
A38	C-MZ	3
A39	C-MZ, C-ML	2
A40	C-MZ, C-ML	2
A41	C-MZ, C-ML	4
A42	C-MZ	4
A43	C-MZ	4
A44	C-ML	3
A45	C-AZ, C-AL	4
A46	C-MZ	4
A47	C-ML, C-AL	4
A48	C-MZ	4
A49	C-ML	2
A50	C-PL	1
A51	C-MZ	2
A52	C-MZ	4
A53	C-ML, C-AL, C-PP	3
A54	C-KH	1

solution was about 300 seconds which can be considered as acceptable solution time. Gantt chart of the obtained solution is presented on the Figure 6.

4. CONCLUSION

The paper presents a mathematical model for optimizing aircraft maintenance lead time taking into account the assignment of multi-skilled operators. In particular, the Hall's marriage theorem is used to formalise complex restrictions of operators assignment to maintenance activities. Even if the number of inequalities generated by this theorem exponentially depends on the number of competences, this approach can be used in practice for the cases when the number of competences is not extremely high.

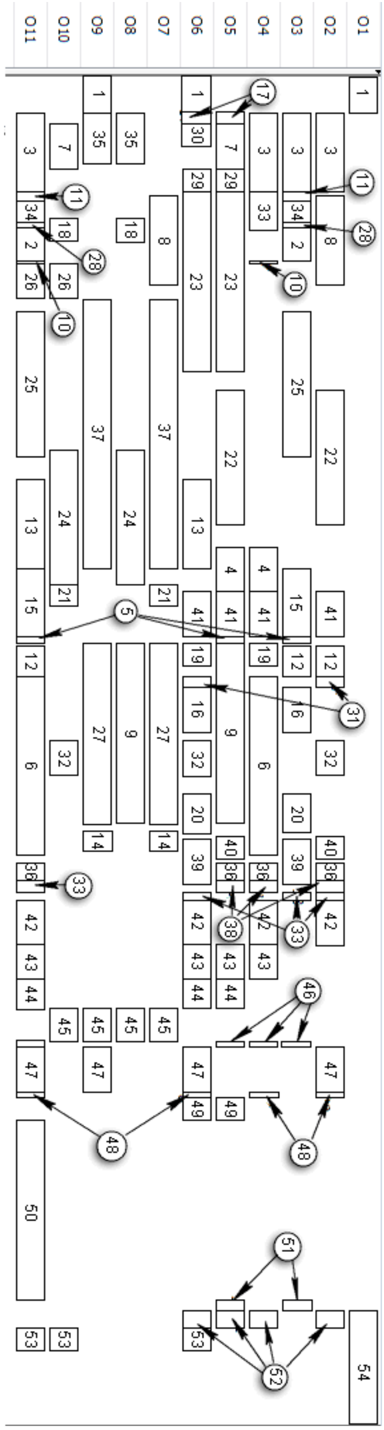

Fig. 6. Gantt chart of the obtained solution.

This first study shows a potential for including more technical constraints existing in practice such as the management of aircraft documents, the restriction on the number of workers located in the same aircraft's area and walking times for operators moving from one area to another.

This will be integrated in the consequent model of the optimization problem. Moreover, the model will be tested on a larger set of industrial cases provided by the industrial company participated in this study.

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