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A Mathematical Model for the Astronaut Training Scheduling Problem

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Abstract: We consider a problem of the astronaut training scheduling. Each astronaut has his own set of tasks which should be performed with respect to resource and time constraints. The problem is to determine start moments for all considered tasks. For this issue a mathematical model based on integer linear programming is proposed. Computational results of the implemented model and experiments on real data are presented.

Keywords: Operations Research, scheduling models, integer linear programming.

1. INTRODUCTION

There is a wide range of tough issues in modern astronautics. All these issues require careful planning of all activities in order to avoid organizational mistakes. What is more important, all activities have to be performed before the given deadlines. One of such issues is the problem of preparing astronaut crews for working on the International Space Station (ISS). The astronaut training is a very long, expensive and complex process. A spacecraft is one of the most complex peaces of equipment which has been ever built. Safety and security are the crucial points of any spaceflight. Therefore, all astronauts need to have strong background in many spheres. So, the main purpose of the astronauts training is to achieve necessary skills and knowledge.

Nowadays, in Russia, spaceflight training scheduling is performed manually and without using any mathematical approaches. Due to that, fast changes of a training plan will cause a huge workload. We hope that the considered approaches and models will lead to reducing these workloads.

Commonly, the astronaut training planning is divided into the two stages: the volume planning and the timetabling. In the former one, for each astronaut a set of tasks is formed depending on requirements of their qualifications and forthcoming on-board experiments complexity conditions. For details, see at Bronnikov et al. (2015a), Bronnikov et al. (2015b).

At the stage of timetabling, for each astronaut the schedule should be compiled: for each task the start time of its performance should be determined, see Bronnikov et al. (2015c). It is assumed that for each astronaut the set of tasks is founded at the previous stage.

From a mathematical point of view, the spaceflight training scheduling can be considered as a generalization of the resource-constrained project scheduling problem, see Artigues (2008). This problem is NP-hard. In practice, a planning horizon is about 3 years. Each astronaut has an individual, aperiodical learning plan. So, the problem has a very large dimension and is hard to solve. In this paper a mathematical model based on integer linear programming (see Wolsey et al. (1988)) is proposed. Computational results is the best evidence of the applied approach.

2. PROBLEM STATEMENT

There is a set of crews. Each crew consists of a number of astronauts. Each astronaut has his own set of training tasks. Dates of the training start and finish are given. The goal is to form a training schedule for each astronaut.

There are the following constraints:

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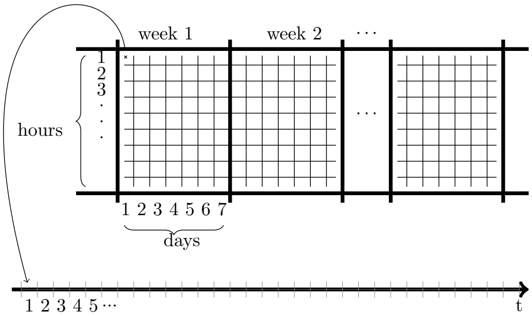

Fig. 1. Time intervals

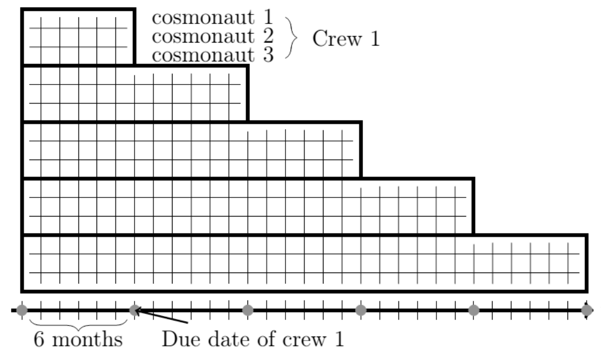

Fig. 2. Training schedule for all crews.

- each astronaut should perform all required tasks;
- physiological aspects of training should be properly taken into account;
- the partial order of tasks is given;
- training resources (teachers, simulators and etc) are restricted;
- some tasks have fixed start times.

2.1 Notations

The following time intervals are introduced:

- W — set of planning weeks, where $|W| = 156$ weeks (3 years);
- $D_w = \{1, 2, 3, 4, 5\}$ — set of work days per week, $w \in W$. The set may be decreased to meet real life requirements (e.g., holidays, day offs, etc.);
- $H_{wd} = \{1, \ldots, 18\}$ — set of half-hour intervals of day $d \in D_w$ of week $w \in W$.

It is assumed that the first interval begins at 9.00 a.m. and the latest one ends at 6.00 p.m. In some cases the duration of a work day may be increased if any feasible schedule with the current set of intervals cannot be formed. In this case, schedulers may extend a work day (for instance, for 1 hour) and re-form the schedule in order to provide a solution.

The set of time intervals is designed to work with constraints like "no more than 2 times a week", "in the morning", etc. However, in order to work with constraints linked with task durations let us arrange all triples (w, d, h) in the lexicographical order.

Let us associate each triple to its number: $(w, d, h) \to t(w, d, h)$ (see Fig. 1):

$$t(w, d, h) = \sum_{w'=1}^{w-1} \sum_{d' \in D_{w'}} |H_{w'd'}| + \sum_{d'=1}^{d-1} |H_{wd'}| + h. \qquad (1)$$

We denote the set of all triples (w, d, h) by Y:

$$Y = \{(w, d, h) | w \in W, d \in D_w, h \in H_{wd}\}.$$

The crews start their trainings at different moments (see. Fig. 5). Therefore, over the period of 2.5–3 years, some astronauts have already mastered a part of the operations and thus, each astronaut has his own set of current operations.

Next, the basic notations are introduced.

- C — set of crews.
- K_c — set of astronauts of crew $c \in C$. Usually, $|K_c| = 3$.
- K — set of all astronauts.
- J — set of all tasks.
- J^c — set of tasks of crew $c \in C$.
- J_k — set of tasks of astronaut k, which are required for the implementation of the training plan. We divide this set into the following subsets:
  - J_k^T — set of technical tasks of astronaut k.
  - J_k^F — set of physical training tasks of astronaut k (each task lasts 2 hours or 4 intervals).
  - J_k^A — set of tasks of astronaut k directed to solving administrative issues (self-study, work with documentation).
  - J_k^L — set of language lessons of astronaut k (each task lasts 2 hours or 4 intervals).
- p_j — execution time of task $j \in J$.
- R — set of resources. The set of all astronauts is a subset of R.
- rc_{jr} — amount of resource r needed to perform task j.
- ra_{rwdh} — amount of resource r accessible during time interval h of day d, of week w. Each astronaut is available in amount of 1 at any time.
- e_j, l_j — the earliest and the latest moments at which task $j \in J$ can be performed.
- J_k^{bound} — set of tasks for which time constraints are defined. Due dates can also be described using these boundaries.
- $G = (J, \Gamma)$ – the graph of precedence relations between the tasks. We have $(j, j') \in \Gamma$ if task j must be performed before task j'. With the help of this general graph G individual precedence graphs for each astronaut can be built: $G_k = (J_k, \Gamma_k), k \in K$.
- $H = (J, \mathcal{H})$ – the weighted graph of the strict precedence relations between the tasks. We have $(j, j') \in \mathcal{H}$ if task j' must be performed strictly after $h_{j,j'}$ intervals after the task j. With the help of the graph H individual graphs of the strict precedence relations can be built: $H_k = (J_k, \mathcal{H}_k)$, $k \in K$.

Some tasks are grouped into the butches by studied subjects. In practise, these butches are named on-board systems. Let m_k be the number of on-board systems studied by the astronaut k. So,

$$J_k^{B_1}, J_k^{B_2}, \ldots, J_k^{B_{m_k}}$$

are sets of on-board systems studied by the astronaut k.