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Competence-oriented project team planning – university case study

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ABSTRACT

Selection of competent employees is one of the numerous factors that determine the success of a project. The literature describes many approaches that help decision makers to recruit candidates with the required skills. Only a few of them consider the disruptions that can occur during the implementation of a project, such as employee absenteeism and fluctuations in the duration of activities, etc. Collectively, what these approaches amount to is proactive planning of employee teams with redundant competences. Searching for competence frameworks robust to disruptions involves time-consuming calculations, which do not guarantee that an admissible solution will be found. In view of this, in the present study, we propose sufficient conditions, the fulfilment of which guarantees the existence of such a solution. By testing these conditions, one can determine whether there exists an admissible solution, i.e. whether it is at all worth searching for a robust competence framework. The possibilities of practical application of the proposed method are illustrated with an example.

Introduction

People (a project team) are the key resource that determines successful achievement of a goal (implementation of a project). That is why the right selection of members of a project team is such an important issue already at the stage of defining project resources. It is worth noting that team recruitment boils down to looking for variants of allocation of employees to project tasks/activities (Carter & Laporte, 1998; Fapohunda, 2013). The goal is to determine when to employ how many contractors with what competences at what cost.

In most cases, staffing decisions regarding the appointment of project teams are subject to uncertainty related to temporary unavailability of resources (e.g. employees) during the implementation of a project, delays in task start times, changes in task duration,

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etc. Moreover, decision-makers are unable to predict the probable, let alone the exact, moment of the occurrence of those disruptions (e.g. which employee will be absent when, which materials will be delivered with what delay, etc.). The effectiveness of reactive approaches (Vieira et al., 2003), which involve modification of the already implemented project schedule (so-called re-scheduling) in the event of a disruption, depends on many factors, including the competencies of available employees (Patalas-Maliszewska & Kłos, 2017).

Employee competencies are represented collectively as a personnel competence structure or framework (hereinafter referred to as competence framework) (Whiddett & Hollyforde, 2000). In simplified terms, a personnel competence framework can be identified with the competence matrix (Antosz, 2018; Smith & Smarkusky, 2005) commonly used in the construction, production and other industries, which defines current qualifications of staff members and their allocation to specific tasks (hereinafter referred to as task assignment).

An alternative to reactive management of disruptions, in cases such as employee absenteeism, is a proactive approach that generates frameworks robust to selected anticipated types of disruptions (Dück et al., 2012; Ionescu & Kliewer, 2011; Nielsen et al., 2014; Sobaszek et al., 2017). The proactive strategy consists in recruiting a team with a competence framework that allows to make changes to the existing project schedule. Competence frameworks that guarantee the possibility of re-scheduling a project are hereinafter referred to as robust to a specific set of disruptions. Put another way, a robust competence framework is one that guarantees the implementation of the assumed plan despite the occurrence of a specific type of disruption. The planning of competence frameworks that can guarantee the execution of the planned tasks is tantamount to seeking (synthesizing) alternative competence frameworks that are robust to the given set of disruptions.

Studies (Szwarc, Bocewicz, Banaszak, et al. 2019) show that due to the high computational complexity of this type of problems ($f(n, m) = O(2^{m \times n})$), where: m – number of employees, n – number of tasks), in special cases, they can only be solved by checking all variants of competence frameworks. This excludes the use of exact methods (e.g. the branch and bound algorithm). This is particularly important from the point of view of the scale of the problems encountered in practice and the fact that there is no guarantee that an admissible solution will be found. An interesting line of inquiry is the search for the so-called sufficient conditions, the satisfaction of which guarantees the existence of an admissible solution. By testing such conditions, as a preliminary step, one can determine whether it is at all worth searching for robust competence frameworks.

For this reason, this study's methodology used declarative programming (specifically constraint programming). Proposed model can be easily modified and extended to take into account the specific nature of the considered problems formulated by triples (data, constraints, questions), e.g. by determining redundant constraints (treated as sufficient conditions) which allow to run dedicated, and therefore quick and effective, searches of the space of potential solutions. This paper presents the development of such a sufficient condition (redundant constraint). Moreover, compared to the previous research, the proposed approach has been verified for the first time on the real, historical data from a technical university (Faculty of Electronics and Computer Science of Koszalin University of Technology).

Section 2 presents a literature review of assignment planning under uncertainty. In Section 3, a reference model is proposed which can be used to search for competence frameworks that allow development of competence allocation plans robust to a set of anticipated types of disruption, such as absences of individual employees. Based on this model, sufficient condition is proposed. Section 4 reports computational experiments which illustrate the possibilities of applying the proposed sufficient condition. The conclusions are drawn in Section 5.

Literature review

Planning of human teams under conditions of uncertainty is a well-researched problem. Many techniques based on a proactive (robust) scheduling approach, e.g. redundancy-based approaches have been published in the field of machine scheduling, project scheduling etc.

This approach uses and adheres to information about the particular variability characteristics (e.g. probability for operation durations) and/or information about the reactive scheduling approach during project realization (mostly very simple repair operations). The special case where the baseline objective is to minimize a function of the deviation between the baseline and the final schedule, focuses on stability. A popular approach is the dynamic resource allocation model (Elmaghraby, 2000; Jørgenson, 1999). It assumes certainty equivalents given by expected values. Deterministic static time/cost trade-off models underestimate the total expected project costs and neglect the value of flexibility. Updating the plans as new information becomes available by adjusting the amount of resources to be allocated can lead to superior results (Herroelen & Leus, 2005).

The solutions proposed in the literature are largely limited to the introduction of time buffers or capacity (resource) buffers. The buffer insertion is based on Goldratt's critical chain methodology (Goldratt, 1997). Time buffers (most often understood as additional time windows allowing for the completion of delayed tasks) are used in project management (Hazir et al., 2010), personnel assignment (Dück et al., 2012; Ehrgott & Ryan, 2002; Tam et al., 2011) and task planning problems (Davenport et al., 2001). In turn, the so-called capacity buffers (understood as surplus resources), also called reserve personnel (reserve crew/resources), ensure that surplus employees are present in specific time intervals in case there is a greater than anticipated demand for workers or there is a shortage of personnel. Several authors (Dück et al., 2012; Moudani & Mora-Camino, 2010; Tam et al., 2011) have studied the use of capacity buffers (reserve crew planning) in the aviation industry. They believe that sufficient back-up staff should be introduced to prevent disruptions, but the number of reserve crew members should not be too high to ensure crew availability for other duties. The size of a capacity buffer is usually determined in advance in a deterministic way. For example, Ingels and Maenhout (2015) define capacity buffers by setting a percentage above the expected staffing requirements that accounts for specific time constraints. Another type of buffer is overtime, which increases efficiency in specific time intervals (Ingels & Maenhout, 2018). Ionescu and Kliewer (2011) and Shebalov and Klabjan (2006) have focused on maximizing the number of crew swapping options for aircraft crew planning (Dück et al., 2012). Another solution to disruptions is the exchange of duties between employees, referred to as resource substitution (Ingels & Maenhout, 2017; Ionescu & Kliewer, 2011; Shebalov & Klabjan, 2006).

Reactive strategies can also be improved by extending daily work hours and total work hours in the entire planning horizon (Easton & Rossin, 1997; Ingels & Maenhout, 2018).

These research studies do not consider competency as capacity buffers (redundant competences). The previous works (Szwarc, Bocewicz, & Bach-Dąbrowska 2019, Szwarc, Bocewicz, Bach-Dąbrowska, et al. 2019, Szwarc, Bocewicz, Banaszak, et al. 2019) presented models and methods that allowed the search for the redundant competency frameworks. Other studies (Bocewicz et al., 2020; Szwarc, Bocewicz, Banaszak, et al. 2019) indicated that searching for a solution is time-consuming, without a guarantee of obtaining a non-empty space of feasible solutions. In this context, the considered model should be supplemented with sufficient conditions, the fulfilment of which ensures the existence of admissible solutions.

## Declarative modelling

Illustrative example

Disruptions that can occur during the project realization, caused by employee absenteeism, are illustrated by the following simplified example. Let's consider the project that consists of 10 operations: $\mathcal{Z} = \{Z_1, \ldots, Z_{10}\}$. Each operation consists of one task with a duration of one unit of time (t.u.). Figure 1(a) shows the structure of the project.

The tasks of operations have been assigned to a team of four employees $\mathcal{P} = \{P_1, P_2, P_3, P_4\}$. Their competences make up framework G presented in Table 1, where the values of the cells determine whether employee P_k has the competence (value '1') to perform operation Z_i. For instance, employee P_1 has competences B and D, indispensable for performing operations Z_5, Z_6, Z_7 and Z_{10}.

The following operations completion rules (constraints) have been adopted:

- an operations can only be completed by a competent employee
- P_1 and P_4 can perform no more than 3 operations, and P_2 and P_3 can execute no more than 4 operations
- all operations must be assigned to employees

Competence framework G allows for all planned operations to be completed, as shown in the schedule in Figure 1(b). Let us assume, however, that the project is jeopardized by
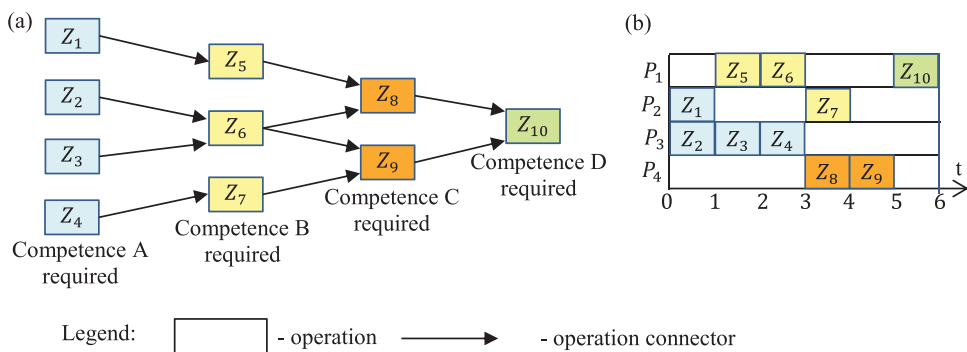
**Figure 1.** Project structure (a) and project schedule (b).

Table 1. Competence framework G.

Employee	Z_1	Z_2	Z_3	Z_4	Z_5	Z_6	Z_7	Z_8	Z_9	Z_{10}
						Operation				
P_1 (B, D)	0	0	0	0	1	1	1	0	0	1
P_2 (A, B)	1	1	1	1	1	1	1	0	0	0
P_3 (A, B, C)	1	1	1	1	1	1	1	1	1	0
P_4 (A, C, D)	1	1	1	1	0	0	0	1	1	1

the absence of one employee. *In such a situation, is framework G still sufficient to complete the planned operations? And if not, does there exist a version of that framework that can guarantee robustness in the event of an absence of one of the employees?*

For further considerations, let us assume that the competency framework is robust for a given disruption (e.g. absence of the employees) if it ensures that all tasks of operations are completed on time despite the disruption.

In that context, to answer this question, it is necessary to analyse each of the four cases of absence (it is assumed that a team member is absent from the very beginning of the project). As shown in Figure 2 (a, b, and c), in three cases of an absence of a single employee (P_1, P_2, P_3), the competencies of the remaining employees and the constraints on the number of operations they can perform allow for modification of the already implemented schedule. A modification is understood here as delegating the operations of an absent employee to the available personnel (a replacement), without changing the operation start/completion dates. In the event of an absence of P_4, the remaining
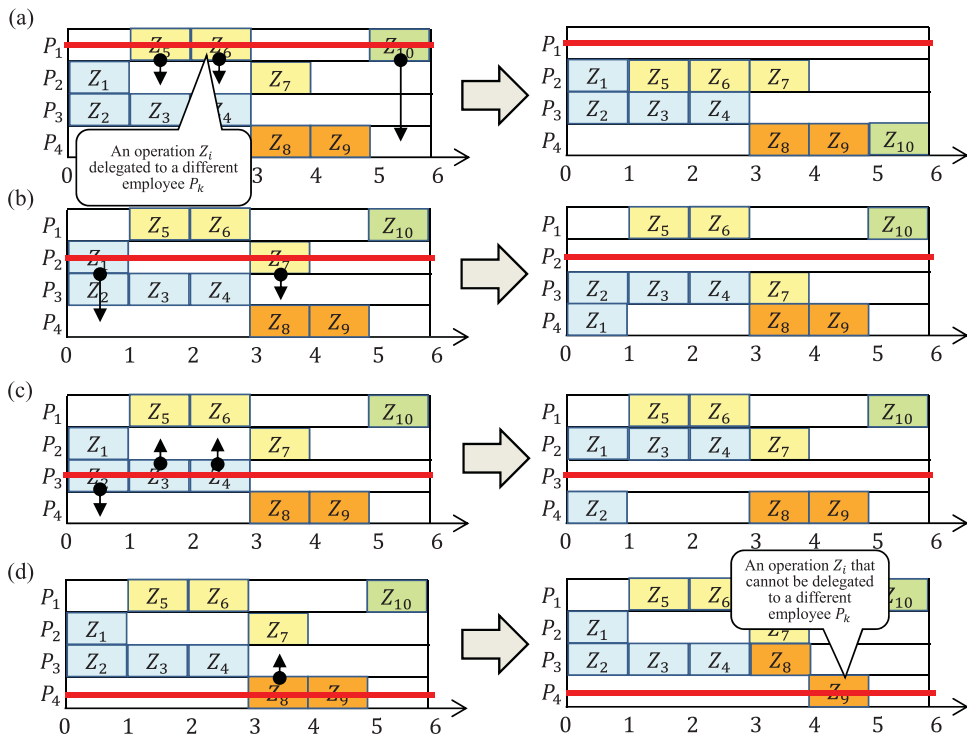
Figure 2. Replacement scenarios for the individual employees: P_1 (a), P_2 (b), P_3 (c) and P_4 (d).

Table 2. A competence framework G robust to the absence of one employee.

Employee	Operations									
	Z_1	Z_2	Z_3	Z_4	Z_5	Z_6	Z_7	Z_8	Z_9	Z_{10}
P_1 (B, D)	0	0	0	0	1	1	1	0	0	1
P_2 (A, B)	1	1	1	1	1	1	1	1	1	0
P_3 (A, B, C)	1	1	1	1	1	1	1	1	1	0
P_4 (A, C, D)	1	1	1	1	0	0	0	1	1	1

employees are not able to take over his/her duties (Figure 2(d)) either because they lack the required competencies or because they have already reached their limit on the number of operations they can perform.

It is easy to note that if employee P_2 acquires competence C, he/she will be able to take over the duties of employee P_4. This means that framework G (Table 2), which takes account of this fact, is robust to the absence of any one of the members of the project team. Usually, the given competency framework will secure only certain variants of employee absence.

The number of scenarios for a given disturbance for which a given competency framework guarantees an acceptable allocation of employees $\mathcal{P}$ to tasks from the operations set Z is determined by what is known as the robustness of a competency framework function $R_{\mathcal{P}}^{\mathcal{Z}}(\omega)$ (where: ω – is a number of simultaneously absent employees).

For problems of a similar scale (4 employees and 10 operations), the number of potential competence frameworks that should be considered to find a robust variant is 2^{40}. In the general case, the computational complexity is $f(m, n) = 2^{m \times n}$, which limits the use of these types of approaches to small-scale problems only. To avoid time-consuming calculations when solving large scale problems normally encountered in everyday practice (e.g. 50 employees, 100 operations), a sufficient condition has been proposed, the fulfilment of which will guarantee the existence of admissible solutions.

Problem statement

As part of preliminary research (Szwarc, Bocewicz, Bach-Dąbrowska, et al. 2019, Szwarc, Bocewicz, Banaszak, et al. 2019), a model for synthesizing competence frameworks robust to disruptions was developed. The model is limited to situations in which the disruptions are cases of a priori known (at the stage of planning the allocation of operations, e.g. at the beginning of the day's shift) absences of single members of a staff assigned to the execution of a given set of operations (a production order).

Sets:

$\mathcal{Z}$: the set of operations: $\mathcal{Z} = \{Z_1, \ldots, Z_i, \ldots, Z_n\}$

$\mathcal{P}$: the set of employees: $\mathcal{P} = \{P_1, \ldots, P_k, \ldots, P_m\}$

U_ω: the family of scenarios parametrized by $\omega-$ the number of simultaneous employees absences: $U_\omega = \left\{ u_i | u_i \subseteq \mathcal{P}; |u_i| = \omega; i = 1 \ldots \binom{|\mathcal{P}|}{\omega} \right\}$.

Θ: the single scenario of simultaneous of employees ω, $\Theta \in U_\omega$

LP_ω: the subset U_ω ($LP_\omega \subseteq U_\omega$) which contains absence scenarios for which competency framework G guarantees a permissible employees allocation X to tasks of operations in the event of absences of employees.

Parameters

n: the number of operations ($n \in \mathbb{N}$)

q_i: the number of tasks from operation Z_i

m: the number of employees ($m \in \mathbb{N}$)

ω: the number of absent employees $\mathcal{P}$ ($\omega \in \mathbb{N}$), $\omega < m$

l_i: the duration of the task execution belonging to the operation Z_i (in hours)

s_k: the minimum working hours of the employee P_k ($s_k \in \mathbb{N}$)

z_k: the maximum working hours of the employee P_k ($z_k \in \mathbb{N}$)

$^*R_\mathcal{P}^\mathcal{Z}$: the expected robustness of the competency framework ($^*R_\mathcal{P}^\mathcal{Z} \in [0, 1]$)

Decision variables:

G: the competency framework given by matrix $G = [g_{k,i}]_{k=1\ldots m;i=1\ldots n}$ where: $g_{k,i} \in \{0, 1\}$:

$$g_{k,i} = \begin{cases} 1 & \text{when employee } P_k \text{ has competences to execute the task from operation } Z_i \\ 0 & \text{in remaining cases} \end{cases}$$

$R_\mathcal{P}^\mathcal{Z}(\omega)$: the robustness of competency framework G of the given staff $\mathcal{P}$, performing tasks from operations Z in a situation corresponding to the simultaneous absence of ω employees

G^Θ: the competency framework which takes into account simultaneous absence of employees defined in the set Θ: $G^\Theta = [g_{k,i}^\Theta]_{k=1\ldots m;i=1\ldots n}$ where:

$$g_{k,i}^\Theta = \begin{cases} 1 & \text{when } k \notin \Theta \text{ and } P_k \text{ has the competence to execute the task of } Z_i \\ 0 & \text{in remaining cases} \end{cases}$$

X: the employee allocation, $X = [x_{k,i}]_{k=1\ldots m;i=1\ldots n}$ where: $x_{k,i} \in \{0, 1, \ldots, q_i\}$ means the number of tasks from operation Z_i executed by the employee P_k

X^Θ: the allocation in situation when employees defined in set Θ are absent from work: $X^\Theta = [x_{k,i}^\Theta]_{k=1\ldots m;i=1\ldots n}$ where: $x_{k,i}^\Theta \in \{0, 1, \ldots, q_i\}$ represents the number of tasks from operation Z_i executed by the employee P_k.

c^Θ: the variable that specifies whether there exists allocation X^Θ ensuring execution of tasks from operation Z. The value of variable $c^\Theta \in \{0, 1\}$ depends on ancillary sub-variables: $c_{1,i}^\Theta$, $c_{2,k}^\Theta$, $c_{3,k}^\Theta$ which specify whether constraints (1) – (5) hold.

Constraints:

(1) The element $g_{k,i}^\Theta$ of matrix G^Θ that characterises the absence of employee $P_k(P_k \in \Theta)$ takes the value 0:

$$g_{k,i}^\Theta = \begin{cases} g_{k,i} & \text{when } P_k \notin \Theta \\ 0 & \text{when } P_k \in \Theta \end{cases}$$

(2) Tasks are performed only by employees with appropriate competences:

$$x_{k,i}^\Theta \leq q_i \times g_{k,i}^\Theta, \text{ for } k = 1 \ldots m; i = 1 \ldots n; \Theta \in U_\omega \tag{2}$$

(3) All tasks q_i from operation Z_i should be executed:

$$\left(\sum_{k=1}^m x_{k,i}^\Theta = q_i \right) \Leftrightarrow (c_{1,i}^\Theta = 1), \text{ for } i = 1 \ldots n; \Theta \in U_\omega \tag{3}$$

(4) Workload of employee P_k is equal to or greater than the minimum number of working hours s_k:

$$\left(\sum_{i=1}^n x_{k,i}^\Theta \times l_i \geq s_k \right) \Leftrightarrow (c_{2,k}^\Theta = 1), \text{ for } P_k \in \mathcal{P} \backslash \Theta; \Theta \in U_\omega \tag{4}$$

(5) Workload of employee P_k is not greater than the maximum number of working hours z_k:

$$\left(\sum_{i=1}^n x_{k,i}^\Theta \times l_i \leq z_k \right) \Leftrightarrow (c_{3,k}^\Theta = 1), \text{ for } P_k \in \mathcal{P} \backslash \Theta; \Theta \in U_\omega \tag{5}$$

(6) Robustness $R_\mathcal{P}^\mathcal{Z}(\omega)$ is calculated as a ratio of the number of absence scenarios $|LP_\omega|$ for which the competency framework is robust to the simultaneous absence of ω employees to all possible disruption scenarios ($|U_\omega|$).

$$R_\mathcal{P}^\mathcal{Z}(\omega) = \frac{|LP_\omega|}{|U_\omega|} \geq {}^*R_\mathcal{P}^\mathcal{Z}(\omega) \tag{6}$$

$R_\mathcal{P}^\mathcal{Z}(\omega) \in [0, 1] \subset \mathbb{R}$, where:

$R_\mathcal{P}^\mathcal{Z}(\omega) = 0$ – stands for lifelessness (robustlessness), i.e. there is no suitable replacement enabling the execution of all tasks from set Z for any of the possible cases of absence (-ω-number of simultaneous employee absences).

$R_\mathcal{P}^\mathcal{Z}(\omega) = 1$ – stands for co called full robustness, corresponding to cases where scenarios of absence (ω-number of simultaneous employee absences) there is at least one replacement guaranteeing the execution of all the tasks from the set Z.

$$|LP_\omega| = \sum_{\Theta \in U_\omega} c^\Theta \tag{7}$$

$$c^\Theta = \prod_{i=1}^n c_{1,i}^\Theta \prod_{k=1}^m c_{2,k}^\Theta \prod_{k=1}^m c_{3,k}^\Theta \tag{8}$$

The competence framework and the task assignment are represented in the model by decision variables G, G^Θ and X^Θ, respectively. Employees allocation X^Θ which satisfies constraints (1) – (8) is referred to as an admissible allocation in the situation of simultaneous absence of employees Θ. In this context, the question to be considered is the following: *Does there exist a competence framework G that can guarantee robustness $R_\mathcal{P}^\mathcal{Z}(\omega) \geq {}^*R_\mathcal{P}^\mathcal{Z}(\omega)$ in the event of simultaneous absence of ω employees?*

The structure of the proposed model, which includes a set of decision variables and a set of constraints that relate those variables to one another in a natural way, allows to formulate the problem in hand as a *CS* and implement it in a constraint programming environment:

$$CS(\omega) = ((\mathcal{V}(\omega), \mathcal{D}(\omega)), \mathcal{C}(\omega)) , \qquad (9)$$

where:

$\mathcal{V}(\omega) = \{R_{\mathcal{P}}^{\mathcal{Z}}(\omega), G, G^{\Theta}, X^{\Theta} \,|\, \Theta \in U_{\omega}\}$ – the set of decision variables which includes: robustness of competency framework $R_{\mathcal{P}}^{\mathcal{Z}}(\omega)$, competency framework G, competency frameworks G^{Θ} for cases when the employees from set Θ are absent, corresponding allocations X^{Θ}.

$\mathcal{D}(\omega)$ – the finite set of decision variable domains $\{R_{\mathcal{P}}^{\mathcal{Z}}(\omega), G, G^{\Theta}, X^{\Theta} \,|\, \Theta \in U_{\omega}\}$,

$\mathcal{C}(\omega)$ – the set of constraints specifying the relationships between the competency framework and its robustness constraints (1–8).

In previous studies (Bocewicz et al., 2020; Szwarc, Bocewicz, Banaszak, et al. 2019), the above model and method were used to search for competence frameworks robust to disruptions caused by an absence of one to three employees. The results of those investigations indicated that the search for competence frameworks is effective (competence frameworks were obtained in less than 1500 s) for problems regarding projects with up to 50 operations and employing up to 10 employees. It is therefore worth identifying sufficient conditions which, when tested, provide an answer to the question of whether there exists an admissible solution.

Sufficient condition

The proposed recursive sufficient condition, which allows to determine, for a given project structure, whether there exists admissible competence frameworks robust to the absence of a single employee, in the following statement:

$$\forall z \in Z^*$$
$$\Theta(z, P)$$

$$\left|
\begin{array}{l}
\qquad\qquad \text{if } P \text{ is empty then} \\
\qquad\qquad\quad \text{return no solution;} \\
\text{if } \varphi(z) \in \Phi(P_1) \text{ and } C(\Psi(P_1) \cup \{z\}) = 1 \text{ then} \\
\qquad\qquad \Psi(P_1) \leftarrow \Psi(P_1) \cup \{z\}; \\
\qquad\qquad\quad \text{return } \Psi(P_1); \\
\text{if } \varphi(z) \notin \Phi(P_1) \text{ and } C(\Psi(P_1) \cup \{z\}) = 1 \text{ then} \\
\qquad\quad \Phi(P_1) \leftarrow \Phi(P_1) \cup \{\varphi(z)\}; \\
\qquad\quad \Psi(P_1) \leftarrow \Psi(P_1) \cup \{z\}; \\
\qquad\quad \text{return } \Phi(P_1),\ \Psi(P_1); \\
\qquad\quad \text{if}\{C(\Psi(P_1) \cup \{z\}) = 0\} \text{ then} \\
\qquad\qquad \Theta(z, (P_2, \ldots, P_q));
\end{array}
\right.$$

where:

$P = (P_1, P_2, \ldots, P_q)$ – the sequence of available employees (when employee P^* is absent),

Z^* – the set of tasks normally performed by employee P^* which need to be delegated to employees P,

$\Phi(P_k)$ – the set of competences of employee P_k,

$\Psi(P_k)$ – the set of tasks performed by the employee P_k,

$C(A)$ – the function that defines whether tasks from the set A can be completed in the given organization (if the function satisfies the organization's constraints, it returns 1; if the function does not satisfy the constraints, it returns 0),

$\varphi(z)$ – the competence necessary to complete task z.

The above condition is met if the available employees have the competencies to take over the tasks of the absent employee or if the acquisition of such competences will allow them to do so. By testing this condition, one can quickly (greedily) determine (computational complexity: $f(n, m) = O(m \times n)$) the existence (or non-existence) of an admissible solution (i.e. a framework robust to the absence of one employee). In the next section, the effectiveness of the proposed condition is shown using a computational experiment.

Experiment – university case study

Object description

The effectiveness of the proposed approach has been verified on the real data collected in the process of teaching at the Koszalin University of Technology in the academic year 2019/2020. The university is a public institution of higher education in Poland and carries out the educational activities and scientific research in disciplines related primarily to the directions of development of the Middle Pomerania region. Out of six faculties of this university, the Faculty of Electronics and Computer Science (FECS) was selected for furthered consideration.

FECS curriculum: In the academic year 2019/2020 the faculty conducted two fields of study including $n = 214$ courses (operations): $\mathcal{Z} = \{Z_1, Z_2, \ldots, Z_{214}\}$ (including full-time and part-time mode on bachelor's and master's degrees as well as doctoral studies) with a total of 14100 h. The number of q_i and duration l_i of tasks of the course Z_i following faculty syllabi were collected and shown in Table 3.

FECS employing staff: The classes are given by a team of $m = 49$ employees (academic teachers): $\mathcal{P} = \{P_1, P_2, \ldots, P_{49}\}$. The competency framework G was determined as a result of surveys which shows which employee what classes:

Table 3. FECS syllabus (file 'Syllabus.xlsx' at https://github.com/erykszw/JIT).

Z_i	q_i	l_i
Z_1: History of technics 1	16	5
Z_2: History of technics 2	5	5
Z_3: Inventics	12	5
Z_4: Economics	9	5
Z_5: Foundations of mathematical analysis	20	5
…	…	…
Z_{74}: Programming in.NET environment	21	5
…	…	…
Z_{213}: Distributed information processing	6	5
Z_{214}: Artificial Intelligence Methods	6	5

- may conduct: $g_{k,i} = 1$,
- may conduct if it gains the missing competences: $g_{k,i} \in \{0, 1\}$,
- may not conduct and can't get the missing competences: $g_{k,i} = 0$.

Part of considered competency framework G is illustrated in Table 4. Due to the requirements imposed by General Data Protection Regulation data pseudonymisation has been introduced.

In addition, a lower (s_k) and upper (z_k) limit of hours to be implemented for each employee is assumed (Table 5). For example, P_1: Mills has $s_k = 180$ h and $z_k = 360$ h, P_2: Garner has $s_k = 360$ h and $z_k = 600$ h, and so on. These limits are unchangeable for each employee.

FECS employees' allocation: Employees allocation X valid in the academic year 2019/2020 is presented in Table 6. Considered employees allocation X follows requirements assuming that:

- tasks of the course Z_i can only be executed by the competent employee
- employee working time limits (s_k and z_k) may not be exceeded

In other words, accepted employee allocation X is sufficient for the given FECS set of courses. The given data was used to verify the developed method and at a later stage to determine the G competency frameworks protecting FECS against selected types of disruptions, with the specific components listed below:

(a) Method verification based on historical data. The verification includes an assessment of whether the use of the developed method would allow the determination of the G, competency framework that would secure the FECS (robustness $R_P^Z(\omega) = 1$) against the effects implied by employee absence in the academic year 2019/2020, e.g. the need to hire an additional employee. And in the case of successful assessment:
(b) Use of the developed method aimed at synthesis of competency frameworks robust to selected kinds of disruptions including:
(c) simultaneous absence of $\omega = 1, \ldots, 3$ employees
(d) absence of employees from the age group of pre-retirement and retirement employees

Method verification based on historical data

During the 2019/2020 academic year, the employee P_{18} was absent: Roach was in the hospital and consequently quit his job. In order to maintain the continuity of the classes, a decision was taken about hiring a new employee having competences in teaching courses Z_{47}, Z_{48}, Z_{74}, Z_{106}, Z_{121}, Z_{125}, Z_{211} conducted so far by the employee P_{18}. Organisational changes introduced were associated with additional costs implied by reorganizing the class schedule, training a new employee and so on.

The question naturally arises: could this type of situation be avoided? Or, alternatively speaking, could it have been previously possible to supplement the competences of the selected employee (or employees) so that he (they) could replace a absent colleague?

Table 4. Competency framework G of FECS employees (file 'G_base.xlsx' at https://github.com/erykszw/JIT).

G	Z_1: History of technics 1	Z_2: History of technics 2	Z_3: Inventics	Z_4: Economics	Z_5: Foundations of mathematical analysis	Z_6: Mathematical analysis and linear algebra	...	...	Z_{74}: Programming in.NET environment	...	...	Z_{212}: Selected branches of physics	Z_{213}: Distributed information processing systems	Z_{214}: Artificial Intelligence Methods
P_1: Mills	1	1	0	0	0	0	...	...	0	...	...	1	0	0
P_2: Garner	0	0	0	0	0	0	...	...	0	...	...	0	0	0
P_3: Ray	0	0	0	0	0	0	...	...	0	...	...	0	0	0
P_4: MacPherson	0	0	0	0	0	0	...	...	{0,1}	...	...	0	0	0
P_5: Burnham	0	0	0	0	0	0	...	...	{0,1}	...	...	0	0	0
P_6: Davis	0	0	0	0	0	0	...	...	0	...	...	0	0	{0,1}
P_7: Crockett	{0,1}	{0,1}	{0,1}	0	0	0	...	...	{0,1}	...	...	0	0	{0,1}
P_8: Hudson	{0,1}	{0,1}	{0,1}	0	0	0	...	...	0	...	...	0	0	0
...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
P_{18}: Roach	0	0	0	0	0	0	...	...	1	...	...	0	0	{0,1}
...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
P_{47}: Fox	0	0	0	1	0	0	...	...	0	...	...	0	0	0
P_{48}: Porterfield	0	0	0	0	0	0	...	...	0	...	...	0	0	0
P_{49}: Johnson	0	0	0	0	0	0	...	...	0	...	...	0	0	0

Table 5. Limits on the hours of the members of the staff employed by FECS.

	s_k	z_k		s_k	z_k		s_k	z_k		s_k	z_k
P_1: Mills	180	360	P_{14}: Buckley	240	480	P_{27}: Slaughter	240	500	P_{40}: Hansen	240	480
P_2: Garner	360	600	P_{15}: Johnston	360	600	P_{28}: Gardner	360	600	P_{41}: Thorpe	180	360
P_3: Ray	180	360	P_{16}: Bullock	180	360	P_{29}: Richardson	190	480	P_{42}: Rice	340	600
P_4: MacPherson	180	360	P_{17}: Dowling	360	600	P_{30}: Byrne	240	480	P_{43}: Whitehead	240	480
P_5: Burnham	360	600	P_{18}: Roach	180	360	P_{31}: Curran	240	480	P_{44}: Lacroix	20	120
P_6: Davis	120	240	P_{19}: Schneider	240	480	P_{32}: Owens	180	400	P_{45}: Nichols	50	120
P_7: Crockett	128	360	P_{20}: Reyes	240	480	P_{33}: Hoover	345	600	P_{46}: Cooley	20	120
P_8: Hudson	240	480	P_{21}: Barnes	120	240	P_{34}: Reynolds	240	480	P_{47}: Fox	30	120
P_9: Whittaker	240	480	P_{22}: Meyer	360	600	P_{35}: Morrow	180	360	P_{48}: Porterfield	150	300
P_{10}: Middleton	360	600	P_{23}: Sharpe	120	240	P_{36}: Fitch	240	480	P_{49}: Johnson	50	100
P_{11}: Sloan	330	600	P_{24}: Sinclair	160	360	P_{37}: Clay	240	480			
P_{12}: Flynn	360	600	P_{25}: Mahoney	180	360	P_{38}: Manning	240	480			
P_{13}: Pope	240	480	P_{26}: Kirkland	240	480	P_{39}: Ramsey	180	360			

Table 6. Employees allocation X of staff employed by FECS (file 'X_base.xlsx' at https://github.com/erykszw/JIT).

X	Z_1: History of technics 1	Z_2: History of technics 2	Z_3: Inventics	Z_4: Economics	Z_5: Foundations of mathematical analysis	Z_6: Mathematical analysis and linear algebra	...	...	Z_{74}: Programming in .NET environment	...	...	Z_{212}: Selected branches of physics	Z_{213}: Distributed information processing systems	Z_{214}: Artificial Intelligence Methods
P_1: Mills	0	0	0	0	0	0	...	...	0	...	...	15	0	0
P_2: Garner	0	0	0	0	0	0	...	...	0	...	...	0	0	0
P_3: Ray	0	0	0	0	0	0	...	...	0	...	...	0	0	0
P_4: MacPherson	0	0	0	0	0	0	...	...	0	...	...	0	0	0
P_5: Burnham	0	0	0	0	0	0	...	...	0	...	...	0	0	0
P_6: Davis	0	0	0	0	0	0	...	...	0	...	...	0	0	0
P_7: Crockett	0	0	0	0	0	0	...	...	0	...	...	0	0	0
...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
P_{18}: Roach	0	0	0	0	0	0	...	...	80	...	...	0	0	0
...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
P_{47}: Fox	0	0	0	0	0	0	...	...	0	...	...	0	0	0
P_{48}: Porterfield	0	0	0	0	0	0	...	...	0	...	...	0	0	0
P_{49}: Johnson	0	0	0	0	0	0	...	...	0	...	...	0	0	0

To such kind of questions, the method presented addresses these issues. In order to illustrate the possibility of its use, let's consider a data set collected in Tables 4, 5, 6 for which a competency framework G_{OPT} robustness ($R_P^{\mathcal{Z}}(\omega) = 1$) to employee's P_{18}: *Roach* absence is sought. In other words, the following question is being sought:

Does there exist minimal competency framework G_{OPT} of FECS, which, guarantees robustness value $R_P^{\mathcal{Z}}(\omega) = 1$ in the situation when employee P_{18}: Roach is absent?

The overviewed problem $CS(\omega)$ (updated by proposed sufficient conditions) has been implemented in the LINGO environment (Intel i7-4770, 8GB RAM). Among many other commercially available software tools such as GUROBI, CPLEX, etc., the LINGO software was chosen because of its ability to express the considered problem in a natural manner (which is very similar to standard mathematical notation) and calculating speed is very fast. Its choice ensures that the issues of continuous variables, integer variables, and discrete variables in optimization design can be addressed effectively. In the future, we plan to use the ECL^{i}PS^e-CLP language software system, as it enables faster problem solving than in LINGO (Wikarek et al., 2019).

The optimal solution G_{OPT} (file 'G_opt_P18 absence.xlsx' at https://github.com/erykszw/JIT) was obtained in less than 1 s. In the case of obtained competency framework G_{OPT} there is an acceptable employees allocation X allowing to conduct courses Z_{47}, Z_{48}, Z_{74}, Z_{106}, Z_{121}, Z_{211}, Z_{125} assigned to the absent employee P_{18} by some of the other employees P_{29}, P_{41}, P_{44}, P_7:

- the employee P_{29}: Richardson can take over the substitution by conducting classes in:
  – the course Z_{47} (50 h, 10 tasks),
  – the course Z_{48} (75 h, 15 tasks)
  – the course Z_{74} (80 h, 16 tasks),
- the employee P_{41}: Thorpe can take over the substitution by conducting classes in:
  – the course Z_{106} (15 h, 3 tasks),
  – the course Z_{211} (20 h, 4 tasks),
- the employee P_{44}: Lacroix can take over the substitution by conducting classes in:
  – the course Z_{121}. (30 h, 6 tasks),
- the employee P_7: Crockett can take over the substitution by conducting classes in:
  – the course Z_{125} (75 h, 15 tasks).

The newly designated competency framework G_{OPT} assumes supplementing only one competence in conductg classes in the course Z_{125} by the employee P_7. The G_{OPT} competency framework determined in this way allows for continuity of classes in the event of employee's P_{18}: Roach, absence without having to hire an additional tutor.

The illustrated option of supplementing competences in the scope of conducting classes in the course Z_{125} by the employee P_7 is one of several solutions obtained. Examples of other solutions are frameworks in which:

- the employee P_{22}: Meyer complements the competence of the course Z_{125},
- the employee P_{43}: Whitehead complements the competence of the course Z_{125}, and so on.

The solutions presented above includes cases involving the need to complete competences in only one course. In practice, this means that a sufficiently early supplementation of competences by one employee would protect the FECS against the effects of resignation from the employee's P_{18}: Roach work.

In general, employee absences are usually unexpected (unplanned). This means that it is difficult to predict which employees will be absent and in what number. This necessitates considering the case of simultaneous absences of several employees.

In the next stage, attempts were made to syntheszse the G_{OPT} competency framework that guarantees $R_{\mathcal{P}}^Z(\omega) = 1$ robustness to absenteeism:

(a) any single employee ($\omega = 1$),
(b) any two employees ($\omega = 2$),
(c) any three employees ($\omega = 3$).

In experiments, FECS data were adopted in accordance with Tables 4, 5, 6. For such data, the answer to the following question is sought:

Does there exist (minimal) competency framework G_{OPT}, which, guarantees robustness value $R_{\mathcal{P}}^Z(\omega) = 1$ in the situation when ω employees are absent ($\omega = 1, 2, 3$)?

As in the previous case, the problem $CS(\omega)$ has been implemented in the LINGO environment (Intel i7-4770, 8GB RAM) and the solutions obtained with it were obtained in 3.5 s (option of $\omega = 1$), 12.9 s (option of $\omega = 2$), 291 s (option of $\omega = 3$). The answer to this question is negative, i.e. there is no such form among the permissible competency framework that guarantees the maximum robustness level $R_{\mathcal{P}}^Z(\omega) = 1$, however for disruptions following $\omega = 1, 2, 3$, cases the corresponding levels are:

(a) $R_{\mathcal{P}}^Z(1) = 0.77$,
(b) $R_{\mathcal{P}}^Z(2) = 0.58$,
(c) $R_{\mathcal{P}}^Z(3) = 0.43$.

Competency frameworks G_{OPT}^1, G_{OPT}^2, G_{OPT}^3 (where the superscript refers to variants $\omega = 1, 2, 3$ respectively), guaranteeing the above values of robustness $R_{\mathcal{P}}^Z(\omega)$ are presented in the file 'Gopt1_Gopt2_Gopt3.xlsx' at https://github.com/erykszw/JIT

The results presented above describe the capability of assumed staff members. This means that the development of employee competences in accordance with the designated framework G_{OPT}^1 ($R_{\mathcal{P}}^Z(1) = 0.77$) will allow the faculty to be protected against the effects of 77% possible scenarios of absence of a single employee. Further development of competences will not, however, improve the robustness of the competency framework with a maximum value equal to 0.77. In other words, there are no such changes in the current competency framework G (see Table 4) that will guarantee robustness to the absence of any single employee at the level $R_{\mathcal{P}}^Z(1) > 0.77$.

Due to the method proposed for the absence of a solution to the synthesis problem, the possibility of increasing of employees' competences amount should be taken into account. Therefore, the answer to the question is sought:

Employees with what competences should be employed to obtain G competency framework whose robustness level $R_{\mathcal{P}}^Z(\omega) = 1$ corresponds to situations when ω employees are absent ($\omega = 1, 2, 3$)?

The discussed method allowed to determine acceptable solutions in 3.9 s (option of $\omega = 1$), 14.2 s (option of $\omega = 2$), 297 s (option of $\omega = 3$). The calculations showed that in order to obtain the competency framework G guaranteeing robustness level $R_{\mathcal{P}}^{Z}(\omega) = 1$ respectively for $\omega = 1, 2, 3$, some additional employees with competences allowing them to conduct the following courses should be employed. The results of the calculations (G_{OPT}^{1}, G_{OPT}^{2}, G_{OPT}^{3} – in the file 'Gopt1_Gopt2_Gopt3_R=1.xlsx' at https://github.com/erykszw/JIT) showed that in order to obtain full robustness ($R_{\mathcal{P}}^{Z}(\omega) = 1$ for $\omega = 1, 2, 3$) one should employ a team of employees with competences in:

(a) conducting 21 courses: Z_4, Z_7, Z_{23}, Z_{24}, Z_{25}, Z_{45}, Z_{93}, Z_{103}, Z_{114}, Z_{131}, Z_{132}, Z_{134}, Z_{135}, Z_{157}, Z_{158}, Z_{159}, Z_{160}, Z_{166}, Z_{168}, Z_{169}, Z_{170} (option of $\omega = 1$),

(b) conducting 71 courses: Z_4, Z_5, Z_6, Z_7, Z_9, Z_{10}, Z_{19}, Z_{21}, Z_{22}, Z_{23}, Z_{24}, Z_{25}, Z_{26}, Z_{27}, Z_{28}, Z_{29}, Z_{30}, Z_{34}, Z_{45}, Z_{51}, Z_{55}, Z_{56}, Z_{58}, Z_{77}, Z_{78}, Z_{79}, Z_{84}, Z_{86}, Z_{93}, Z_{99}, Z_{101}, Z_{102}, Z_{103}, Z_{104}, Z_{107}, Z_{111}, Z_{114}, Z_{115}, Z_{117}, $Z_{120, 130}$, Z_{131}, Z_{132}, Z_{133}, Z_{134}, Z_{135}, Z_{136}, Z_{137}, Z_{149}, Z_{153}, Z_{156}, Z_{157}, Z_{158}, Z_{159}, Z_{160}, Z_{161}, Z_{162}, Z_{164}, Z_{165}, Z_{166}, Z_{168}, Z_{169}, Z_{170}, Z_{179}, Z_{191}, Z_{196}, Z_{201}, Z_{203}, Z_{204}, Z_{208}, Z_{212} (option of $\omega = 2$),

(c) conducting 129 courses (option of $\omega = 3$) – see G_{OPT}^{3}.

The obtained results determine the competences that newly recruited employees should have in order for the G_{OPT} competency framework to be fully robust ($R_{\mathcal{P}}^{Z}(\omega) = 1$) to the disruptions discussed in this subsection. However, they do not provide the number of employees that should be employed. How many employees should be hired depends on available candidates and their competences. Selection of a team of employees having a specific set of competences is the next stage of research extending the developed model with elements related to the framework of the newly employed staff.

As part of a series of experiments, another one is envisaged regarding the synthesis of the FECS competency framework robust to the absence of a selected group of employees, for instance pre-retirement aged employees, who because of age may retire at any time. There are 9 such employees in FECS:

$$EM = \{P_1: \text{Mills}, \quad P_3: \text{Ray}, \quad P_7: \text{Crockett}, \quad P_{16}: \text{Bullock}, P_{18}: \text{Roach},$$

$$P_{21}: \text{Barnes}, P_{24}: \text{Sinclair}, \quad P_{39}: \text{Ramsey}, \quad P_{41}: \text{Thorpe}\}$$

For such a set EM, the answer to the following question is sought:

Does there exist (minimal) competency framework G_{OPT} of FECS, which, guarantees robustness value $R_{\mathcal{P}}^{Z}(\omega) = 1$ in the situation when ω employees of set EM are absent ($\omega = 1, \ldots, 9$)?

A positive answer was obtained (calculation time 1.1 s) only for the variant of absence of a single employee ($\omega = 1$). The resulting G_{OPT}^{1} competency framework has been placed in the file 'Gopt9.xlsx' at https://github.com/erykszw/JIT Due to the obtained framework there exists set of employees $\{P_3, P_8, P_{22}, P_{31}, P_{33}, P_{36}, P_{38}, P_{41}, P_{42}, P_{43}, P_{46}\}$ being able to broaden their competences enabling their allocation X that will ensure continuity of classes without having to hire a new employee.

For the other variants of the disruption under consideration ($\omega = 2, \ldots, 9$), it is not possible to obtain a G_{OPT} competency framework that guarantees full robustness level $R_{\mathcal{P}}^{\mathcal{Z}}(\omega) = 1$. In other words, the available employees are not able to secure the FECS education process in the absence of more than one EM employee. The calculations carried out showed that the maximum level of robustness for $\omega = 2, \ldots, 9$, is respectively: $R_{\mathcal{P}}^{\mathcal{Z}}(2) = 0.92$; $R_{\mathcal{P}}^{\mathcal{Z}}(3) = 0.76$; $R_{\mathcal{P}}^{\mathcal{Z}}(4) = 0.55$; $R_{\mathcal{P}}^{\mathcal{Z}}(5) = 0.31$; $R_{\mathcal{P}}^{\mathcal{Z}}(6) = 0.11$; ; $R_{\mathcal{P}}^{\mathcal{Z}}(7) = 0$; $R_{\mathcal{P}}^{\mathcal{Z}}(8) = 0$; $R_{\mathcal{P}}^{\mathcal{Z}}(9) = 0$.

Note that the maximum robustness value for $\omega = 7, \ldots, 9$ is equal to 0. This means that in extreme situations such as leaving 7 (or more) pre-retirement aged employees it is not possible to maintain the continuity of classes without employing additional employees. Consequently, assuming an increase in the number of newly employed employees an attempt to synthesis a proper competency framework was made. In this context, it means seeking the answer to the following question:

Employees with what competences should be employed to obtain G competency framework whose robustness level $R_{\mathcal{P}}^{\mathcal{Z}}(\omega) = 1$ corresponds to situations when ω employees of set EM are absent ($\omega = 2, \ldots, 9$)?

The results of the calculations (obtained in 8.7 s) showed that achieving full robustness level $R_{\mathcal{P}}^{\mathcal{Z}}(\omega) = 1$ for $\omega = 2$, is conditioned by employing employees with competences in 7 courses: Z_9, Z_{10}, Z_{136}, Z_{137}, Z_{179}, Z_{208}, Z_{212}, as well as for $\omega = 3, \ldots, 9$ is conditioned by employing employees with competences in 9 courses:Z_9, Z_{10}, Z_{130}, Z_{136}, Z_{137}, Z_{146}, Z_{179}, Z_{208}, Z_{212}.

Quantitative experiments

In addition to the above-mentioned computer experiments dedicated to illustrations of selected applications of the developed method were also carried out, the approach proposed in this paper has been verified in several quantitative experiments devoted to its scalability testing. With this in mind, the effectiveness of the method in solving of competency framework analysis and synthesis problems subject to occurrence of disruptions of various scale was assessed. Using data collected in Tables 4, 5, 6, solutions were sought to guarantee levels of robustness $R_{\mathcal{P}}^{\mathcal{Z}}(\omega) \geq 0.2 \ldots 1$ in the absence of $\omega = 1, \ldots, 7$ employees. The experiments were carried out in the LINGO software environment. The results are presented in Tables 7–9.

It is easy to notice that in the case of the competency framework analysis problem (Table 7) the answer can be obtained in online mode (1500 s) even when $\omega = 7$. In turn, in the cases of the competency framework synthesis problems (Tables 8 and 9) the online decision support is limited to $\omega = 3$ (i.e. synthesis of a robust competency framework for 3 employees absence) – computation times exceeded assumed value: 1500 s.

Table 7. Analysis of robustness $R_{\mathcal{P}}^{\mathcal{Z}}(\omega)$ of FECS competency framework (Tab. 4).

Number of absent employees ω	Robustness level $R_{\mathcal{P}}^{\mathcal{Z}}(\omega)$	Calculation time [s]
1	0.35	0.9
2	0.1	1.1
3	0.03	1.4
4	0.01	2.2
5	0	4.5
6	0	6.8
7	0	9.2

Table 8. Synthesis of competency framework G_{OPT} following robustness level condition $R_{\mathcal{P}}^{\mathcal{Z}}(\omega) \geq {}^{*}R_{\mathcal{P}}^{\mathcal{Z}}(\omega)$ assumed on ω employees absenteeism.

Number of absent employees ω	Expected robustness level ${}^{*}R_{\mathcal{P}}^{\mathcal{Z}}(\omega)$	Obtained robustness level $R_{\mathcal{P}}^{\mathcal{Z}}(\omega)$	Number of changes introduced to the competency framework G	Calculation time [s]
1	0.2	0.23	9	2.8
	0.4	0.49	62	3.2
	0.6	0.77	138	3.5
	0.8	[1)]×	×	3.9
	1	×	×	4.4
2	0.2	0.29	121	11.2
	0.4	0.58	415	12.9
	0.6	×	×	14.1
	0.8	×	×	15.9
	1	×	×	18.3
3	0.2	0.27	170	236
	0.4	0.43	660	291
	0.6	×	×	361
	0.8	×	×	428
	1	×	×	515
4	0.2	0.31	752	1197
	0.4	×	×	1346
	0.6	×	×	>1500
	0.8	×	×	>1500
	1	×	×	>1500

[1)] × - no acceptable solution, i.e. there is no the competency framework G which guarantee expected value of robustness: $R_{\mathcal{P}}^{\mathcal{Z}}(\omega) \geq {}^{*}R_{\mathcal{P}}^{\mathcal{Z}}(\omega)$.

Table 9. Synthesis of competency framework G_{OPT} following robustness level condition $R_{\mathcal{P}}^{\mathcal{Z}}(\omega) = 1$ assumed on ω employees absenteeism, while taking into account the employment of additional staff.

Number of absent employees ω	Obtained robustness level $R_{\mathcal{P}}^{\mathcal{Z}}(\omega)$	Number of competences in the team of newly employed employees	Calculation time [s]
1	1	21	3.9
2	1	71	14.2
3	1	129	297
4	1	155	1168
5	1	184	>1500
6	1	197	>1500
7	1	204	>1500

Table 10. Synthesis of competency framework G_{OPT} guaranteeing full robustness ($R_{\mathcal{P}}^{\mathcal{Z}}(\omega) = 1$) for different number of employees and courses.

Number of employees m	Number of courses n	Number of absent employees ω	Calculation time [s]
50	300	1	7
50	300	2	15
50	300	3	267
100	400	1	39
100	400	2	92
100	400	3	1550
150	500	1	61
150	500	2	238
150	500	3	2860
200	600	1	390
200	600	2	1480
200	600	3	>5000

It is worth noting that the presented experiments determine the maximum capabilities of the available FECS staff. The results obtained show that in the case of simultaneous absence of 5 (or more) employees (specified by the competency framework G – see Table 4) the other employees are unable to ensure continuity of FECS classes, no matter what competence set is completed. Protection against these types of cases is possible provided that additional staff are employed to provide replacement for 184 courses.

Experiments carried out for a larger scale of objects (see Table 10: $m = 50 \ldots 200, n = 300 \ldots 600$) show that the proposed approach can be used to support decisions on the synthesis of robust competency frameworks for instances of no more than 200 employees and 600 courses.

Conclusions and future works

The search for competence frameworks that can guarantee the completion of the planned tasks is tantamount to seeking (synthesizing) alternative competence frameworks that are robust to the given (a priori known) set of disruptions.

Recruiting a project team robust to the selected type of disruptions boils down to seeking (synthesizing) alternative variants of competence frameworks for which it will be possible to complete the planned tasks despite the disruptions. The computational complexity of the problem considered in the present study means that determination of robust competence frameworks in specific cases can be time consuming. To guarantee that it is worth making the tedious calculations, a sufficient condition has been proposed. By testing this condition, one can check whether there exist admissible solutions.

The results of the experiments demonstrate that the proposed approach can be implemented for in example in Decision Support Systems (DSS), Enterprise Resource Planning (ERP) systems (Patalas-Maliszewska, 2012), used in online task assignment. In that context our future work will focus on developing the computational module which can be used as a software overlay for commercially available decision support systems used in human resources management. The functionalities discussed are solutions falling within the scope of human resource controlling (Dugelova & Strenitzerova, 2015) aimed at effective staff management while creating transparent rules and procedures for planning, monitoring, and control. It is easy to notice that from the controlling perspective, our method can be used in a broader sense of a digital twin concept (Lim et al., 2019). Due to this concept, a computer programme that takes real-world data about a physical object can duplicate it, the more likely that efficiencies and other benefits can be found.

In our future work, we plan to focus on the robustness of competence frameworks to other disruptions, such as changing task time durations, etc. It is also planned to use various hybrid approach variants for implementation of the proposed models (Sitek & Wikarek, 2018).

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References

Antosz, K. (2018). Maintenance – identification and analysis of the competency gap. *Maintenance and Reliability*, *20*(3), 484–494. https://doi.org/10.17531/ein.2018.3.19

Bocewicz, G., Wikarek, J., Sitek, P., & Banaszak, Z. (2020). Robust competence allocation for multi-project scheduling. In J. Świątek, L. Borzemski, & Z. Wilimowska (Eds.), *Information Systems Architecture and Technology: Proceedings of 40th Anniversary International Conference on Information Systems Architecture and Technology – ISAT 2019* (Vol. 1051, pp. 16–30). Springer.10.1007/978-3-030-30604-5_2.

Carter, M.W., & Laporte, G. (1998). Recent developments in practical course timetabling. In E. Burke & M. Carter (Eds.), *Practice and theory of automated timetabling II* (pp. 3–19). Springer. PATAT 1997. Lecture Notes in Computer Science.10.1007/BFb0055878.

Davenport, A., Gefflot, C., & Beck, C. (2001). Slack-based techniques for robust schedules. In A. Cesta & D. Borrajo (Eds.), *Proceedings of the Sixth European conference on planning* (pp. 43–49). Association for the Advancement of Artificial Intelligence.

Dück, V., Ionescu, L., Kliewer, N., & Suhl, L. (2012). Increasing stability of crew and aircraft schedules. *Transportation Research Part C: Emerging Technologies*, *20*(1), 47–61. https://doi.org/10.1016/j.trc.2011.02.009

Dugelova, M., & Strenitzerova, M. (2015). How to select appropriate human resource controlling indicators. *CBU International Conference On Innovation, Technology Transfer And Education*, Prague, Czech Republic.

Easton, F., & Rossin, D. (1997). Overtime schedules for full-time service workers. *Omega*, *25*(3), 285–299. https://doi.org/10.1016/S0305-0483(96)00063-1

Ehrgott, M., & Ryan, D.M. (2002). Constructing robust crew schedules with bicriteria optimization. *Journal of Multi-Criteria Decision Analysis*, *11*(3), 139–150. https://doi.org/10.1002/mcda.321

Elmaghraby, S. E. E. (2000). *Optimal resource allocation and budget estimation in multimodal activity networks*. North Carolina State University at Raleigh.

Fapohunda, T. M. (2013). Towards effective team Building in the workplace. *International Journal of Education and Research*, *1*(4).

Goldratt, E. (1997). *Critical chain*. The North River Press.

Hazir, O., Haouari, M., & Erel, E. (2010). Robust scheduling and robustness measures for the discrete time/cost trade-off problem. *European Journal of Operational Research*, *207*(2), 633–643. https://doi.org/10.1016/j.ejor.2010.05.046

Herroelen, W., & Leus, R. (2005). Project scheduling under uncertainty: Survey and research potentials. *European Journal of Operational Research*, *165*(2), 289–306. https://doi.org/10.1016/j.ejor.2004.04.002

Ingels, J., & Maenhout, B. (2015). The impact of reserve duties on the robustness of a personnel shift roster: An empirical investigation. *Computers & Operations Research*, *61*, 153–169. https://doi.org/10.1016/j.cor.2015.03.010

Ingels, J., & Maenhout, B. (2017). Employee substitutability as a tool to improve the robustness in personnel scheduling. *OR Spectrum*, *39*(3), 623–658. https://doi.org/10.1007/s00291-017-0476-0

Ingels, J., & Maenhout, B. (2018). The impact of overtime as a time-based proactive scheduling and reactive allocation strategy on the robustness of a personnel shift roster. *Journal of Scheduling*, *21*(2), 143–165. https://doi.org/10.1007/s10951-017-0512-6

Ionescu, L., & Kliewer, N. (2011). Increasing flexibility of airline crew schedules. *Procedia - Social and Behavioral Sciences*, *20*(3), 1019–1028. https://doi.org/10.1016/j.sbspro.2011.08.111

Jørgenson, T. (1999). *Project scheduling - a stochastic dynamic decision problem* [Doctoral Dissertation]. Norwegian University of Science and Technology.

Lim, K.Y.H., Zheng, P., & Chen, CH. (2019). A state-of-the-art survey of digital twin: Techniques, engineering product lifecycle management and business innovation perspective. *Journal of Intelligent Manufacturing*, *31*, 1313–1337. doi:10.1007/s10845-019-01512-w.

Moudani, W., & Mora-Camino, F. (2010). Solving crew reserve in airlines using dynamic programming approach. . *International Journal of optimization: Theory, Methods and Applications*, *2*(4), 302–329.

Nielsen, P., Jiang, L., Rytter, N.G.M., & Chen, G. (2014). An investigation of forecast horizon and observation fit's influence on an econometric rate forecast model in the liner shipping industry. *Maritime Policy and Management*, *41*(7), 667–682. https://doi.org/10.1080/03088839.2014.960499

Patalas-Maliszewska, J. (2012). Assessing the impact of ERP implementation in the small enterprises. *Foundations of Management*, *4*(2), 51–62. https://doi.org/10.2478/fman-2013-0010

Patalas-Maliszewska, J., & Kłos, S. (2017). A study on improving the effectiveness of a manufacturing company in the context of knowledge management – research results. *Foundations of Management*, *9*(1), 149–160. https://doi.org/10.1515/fman-2017-0012

Shebalov, J., & Klabjan, D. (2006). Robust airline crew pairing: Move-up crews. *Transportation Science*, *40*(3), 300–312. https://doi.org/10.1287/trsc.1050.0131

Sitek, P., & Wikarek, J. (2018). A multi-level approach to ubiquitous modeling and solving constraints in combinatorial optimization problems in production and distribution. *Applied Intelligence*, *48*, 1344–1367. doi:10.1007/s10489-017-1107-9.

Smith IIIH. H., & Smarkusky, D. (2005). Competency matrices for peer assessment of individuals in team projects. In *Proceedings of the 6th Conference on Information Technology Education, SIGITE 2005*, Newark, NJ, USA.

Sobaszek, Ł, Gola, A., & Kozłowski, E. (2017). Application of survival function in robust scheduling of production jobs. In M. Ganzha, M. Maciaszek, & M. Paprzycki (Eds.), *Proceedings of the 2017 Federated Conference on Computer Science and Information Systems (FEDCSIS)*, pp. 575–578.

Szwarc, E., Bocewicz, G., Bach-Dąbrowska, I., & Banaszak, Z. (2019). Declarative model of competences assessment robust to personnel absence. In R. Damaševičius, & G. Vasiljevienė (Eds.), *Information and software technologies. ICIST 2019. Communications in Computer and information Science* (vol. 1078, pp. 12–23). Springer.

Szwarc E., Bocewicz G., & Bach-Dąbrowska I. (2019). Planning of teacher staff competence structure robust to unexpected personnel absence. *IFAC-PaperOnLine*, *52*(13), 2740–2745. https://doi.org/10.1016/j.ifacol.2019.11.622

Szwarc, E., Bocewicz, G., Banaszak, Z., & Wikarek, J. (2019). Competence allocation planning robust to unexpected staff absenteeism. *Maintenance and Reliability*, *21*(3), 440–450. https://doi.org/10.17531/ein.2019.3.10

Tam, B., Ehrgott, M., Ryan, D.M., & Zakeri, G. (2011). A comparison of stochastic programming and bi-objective optimisation approaches to robust airline crew scheduling. *OR Spectrum*, *33*(1), 49–75. https://doi.org/10.1007/s00291-009-0164-9

Vieira, G.E., Herrmann, J.W., & Lin, E. (2003). Rescheduling manufacturing systems: A framework of strategies, policies and methods. *Journal of Scheduling*, *6*(1), 39–62. https://doi.org/10.1023/A:1022235519958

Whiddett, S., & Hollyforde, S. (2000). *The competency handbook*. Institute of Personnel and Development.

Wikarek, J., Sitek, P., & Jagodziński, M. (2019). A declarative approach to shop orders optimization. *Applied Computer Science*, *15*(4), 5–15. doi:10.23743/acs-2019-25.