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A method for planning competency frameworks robust to disruptions – a case study of a manufacturing company

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Abstract: **Competent personnel is one of the many factors that define the success of a project. The literature describes numerous approaches to supporting decision-makers in planning competency frameworks (CF) that permit to deliver project portfolios. Only some of them, however, take into account the disruptions that may occur during the realization of a project, caused by employee absenteeism or staffing fluctuations, etc. There is still a lack of solutions in this area (methods and IT environments implementing them) that could be used to support decision-makers in planning CF robust to disruptions, which can guarantee the completion of planned project portfolios in dynamically changing conditions. The practicability of the proposed method is demonstrated using an example of a manufacturing company.**

Keywords: **project portfolios, competency framework, disruptions, robustness, decision support.**

1. INTRODUCTION

To achieve its business goals, an organization which is running a portfolio of projects must take stock of the resources it already has and those it needs to complete its projects (Relich 2016). A trend observed in the recent years indicates that attention should be focused on human resources (Becker and Huselid 2006; Gangani et al. 2006; Kupczyk 2014), especially on project team competency framework (CF), which determine whether or not a project can be successfully completed. There are numerous studies on methods of supporting decision-makers in assessing employee competencies, identifying competency gaps, prototyping competency changes, planning the allocation of employees to operations, etc. (Antosz 2018; Wikarek and Sitek 2020). The main assumption of these solutions is that the structures of the project portfolio (e.g. a fixed number of operations executed in a fixed order) and the personnel (e.g. a fixed number of employees) are invariant. Meanwhile, the execution of projects in an organization's dynamically changing environment (Bombiak 2017) necessitates the prediction of disruptions, such as employee absences (sick leaves, maternity leaves, etc.), loss of qualifications (electrician license, driving license), changes in the number of tasks (new orders), loss of employees (employee walkouts), etc. (Hashemi-Petroodi et al. 2020). Failure to consider such events when planning a project portfolio may result in stalling or, at the very least, delaying the implementation of the baseline project plan (Bocewicz et al. 2016; Ingels and Maenhout 2019).

In actual practice, decision makers and planners usually cannot predict the exact moment of occurrence of this type of disruptions (e.g. which employee will be absent in what period of time or when a new task will have to be performed and what task it will be, etc.). An overview of existing studies shows that problems related to protecting organizations against the effects of such events are rarely considered in the literature. The techniques proposed so far in this area assume that an organization should have redundant human resources, including redundant employee competencies (Dück et al. 2012; Ionescu and Kliewer 2011). The redundancy-based approach permits to increase an organization's efficiency understood as its ability to execute operations despite the occurrence of disruptions. Unfortunately, there is still a lack of decision support solutions for planning CF robust to disruptions, i.e. CF that can guarantee the completion of planned project portfolios in dynamically changing conditions. In this paper, we present an original approach to synthesizing CF robust to disruptions. Comparison with similar works was made in previous papers like as (Szwarc et al. 2019; Szwarc and Wikarek 2020) therefore the section of related works is omitted here. A new problem of planning CF robust to a selected set of disruptions in an organization executing a project portfolio was formulated. A reference model was built for the problem of planning a CF robust to two types of disruptions: employee absenteeism and arrival of new orders (addition of new operations). Based on the model developed in the study, a method for planning CF robust to disruptions was presented and possible applications of this method as a software add-on in human resource management systems were discussed. The effectiveness of the method was assessed in a series of experiments.

Section 2, below, presents a model that allows to search for CF robust to a set of anticipated types of disruptions: employee absenteeism and addition of unplanned tasks. Based on this model, a procedure for the assessment and synthesis of CF robust to these types of disruption is presented in Section 3. The results of computational experiments are reported in Section 4. Section 5 discusses the conclusions and directions for future research.

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2. MODEL

The problem of decision-support in planning CF in an organization that runs projects revolves around issues related to balancing the company's existing competencies (its capabilities) with the competencies it needs to execute projects (requirements related to order completion). An organization's capability and the requirements posed by the orders it receives (projects) can be represented by a model which includes a portfolio of projects delivered by the organization and the organization's personnel characterized by a CF, and a task assignment.

Project portfolio. Given is a set of projects Q, hereinafter referred to as the project portfolio. The portfolio is assumed to include projects executed at a customer's order or projects that are the organization's own undertakings. A formula is adopted in which $Q = \{Q_1, \dots, Q_j, \dots, Q_{lq}\}$ stands for the project portfolio, Q_j is the j-th project that involves a set of operations $\mathbb{Z}_j \subseteq Z = \{Z_1, \dots, Z_i, \dots, Z_n\}$, where Z is the set of operations Z_i to be executed by the organization. Operation Z_i is defined as follows:

$$Z_i = (q_i, y_i, l_i, w_i, \varphi_i), \tag{1}$$

where:

q_i: number of tasks of operation Z_i (value q_i specifies the number of references to operation Z_i related to the performance of the tasks it comprises),

y_i: sequence of starting times of the tasks of operation Z_i: $y_i = (y_{i,1}, \dots, y_{i,q_i})$, where: $y_{i,j}$ describes the starting time of the$j$-th task of operation Z_i,

l_i: duration of each task of operation Z_i,

w_i: a set of operations the execution of which excludes the execution of operations Z_i and $w_i \subseteq Z$. Operation Z_i and operation $Z_a \in w_i$ are said to be mutually exclusive when they cannot be executed by the same employee,

φ_i: number of employees needed to perform each task of operation Z_i.

The operation network is modelled as digraph DG_j, in which two nodes are connected by an arc when the corresponding operations are tied together by a precedence relationship. This means that every project can be represented as $DG_j = (\mathbb{Z}_j, E_j)$, where: $\mathbb{Z}_j$ – set of operations of project Q_j, $E_j \subseteq \mathbb{Z}_j \times \mathbb{Z}_j$ – set of arcs.

Moreover, it is assumed that project portfolio Q is delivered in a known time horizon: $H = \{0,1, \dots, h\}$, and that operations are indivisible in time, i.e. once started, an operation cannot be interrupted until it has been completed.

Staff of employees. An organization's staff of employees $\mathcal{P}$ is allocated to the completion of the planned operations. Set $\mathcal{P} = \{P_1, \dots, P_k, \dots, P_m\}$ defines a staff of employees where each employee P_k is assigned a pair Γ_k, which specifies the maximum working time limit:

$$\Gamma_k = (s_k, z_k), \tag{2}$$

where: s_k stands for the minimum working time of employee P_k, and z_k is the maximum working time of employee P_k .

The staff of employees $\mathcal{P}$ corresponds to a CF defined as matrix G:

$$G = [g_{k,i}]_{k=1\dots m; i=1\dots n} \ , \tag{3}$$

where: $g_{k,i} \in \{0,1\}$,

$$g_{k,i} = \begin{cases} 1 & \text{has the competencies required to perform } Z_i \\ 0 & \text{otherwise} \end{cases} .$$

If employee P_k has the competencies required to perform operation Z_i ($g_{k,i} = 1$), by the same token, they have the competencies required to perform all the tasks this operation involves. As a consequence, a task assignment X is created, which specifies what tasks of operation Z are assigned to each member of staff $\mathcal{P}$ during the delivery of the project portfolio Q. This assignment is defined as matrix X, whose elements $x_{k,i}$ take on values $\{0,1, \dots, q_i\}$:

$$X = [x_{k,i}]_{k=1\dots m; i=1\dots n} \ , \tag{4}$$

where: $x_{k,i} \in \{0,1, \dots, q_i\}$ specifies the number of tasks of operation Z_i performed during the execution of this operation by P_k. For example, an operation which involves three tasks ($q_i = 3$) that take $l_i = 1$ u.t. to complete can be performed by one employee ($x_{k,i} = 3$ – the tasks of the operation are performed in sequence, and the operation lasts 3 u.t.) or by three employees (for each of the employees $x_{k,i} = 1$, the tasks of the operation are performed concurrently and the operation lasts 1 u.t.).

It is further assumed that:

- the tasks of operation Z can only be executed by competent employees,
- at any time point, employee P_k can perform a maximum of one task of a given operation;
- the resources are non-preemptive, i.e. the employee who is performing a given task cannot discontinue it in order to undertake another task;
- employee working time limits may not be exceeded.

Disruptions and the measure of CF robustness There are two types of disruptions that may occur as project portfolio Q is being delivered by staff $\mathcal{P}$:

- employee absences, which reduce the organization's capability (expressed as CF) and
- new operations added to the existing schedule which require a change of the project portfolio (expressed as a change in the operations network).

The disruption caused by employee absenteeism is characterized by a set of ω-element combinations from set $\{1, \dots, m\}$: $U_\omega = \{\{u_1, \dots, u_i, \dots, u_\omega\} | \ u_i \in \{1, \dots, m\}\}$. U_ω, then, defines ω-element employee absence scenarios. For example, when 2 employees ($\omega = 2$) of staff $\mathcal{P} = \{P_1, P_2, P_3, P_4\}$ are absent, set U_2 has the following form: $U_2 = \{\{1,2\}, \{1,3\}, \{1,4\}, \{2,3\}, \{2,4\}, \{3,4\}\}$.

The disruption related to the addition of new operations is characterized by set $Z^\lambda = \{Z_{n+1}, \dots, Z_{n+\lambda}\}$ containing λ unforeseen operations. It is assumed that each operation $Z_i \in Z^\lambda$ has a known duration l_i and that it can be added at any point in time horizon H ($y_i \in H$). The additional operation $Z_i \in Z^\lambda$

may be required for the execution of the already planned projects or may be part of a new project. The occurrence of this type of disruptions spurs the search for an assignment X that allows the project portfolio Q to be delivered without interruptions and/or delays. An assignment like this should, for example, allow the company to transfer the responsibilities of an absent employee to another, currently available employee. If an additional operation is ordered, the company should have the possibility of assigning it to an employee who does not perform any other task while the operation is being executed. It is not always possible to implement such an assignment X, though. To assess the chances of implementing an assignment, we use the concept of robustness (Nielsen et al. 2014) of CF G to the disruptions given by U_ω and Z^λ. The measure of robustness of CF G to the absence of ω employees and the addition of λ new operations is defined by function $R(U_\omega, Z^\lambda) = R_\omega^\lambda \in [0,1]$, where:

- $R_\omega^\lambda = 0$ – stands for no robustness, i.e. for each case of absenteeism and each newly placed order that requires the execution of additional operations, there does not exist an assignment X that guarantees the timely delivery of portfolio Q;
- $R_\omega^\lambda = 1$ – stands for full robustness, i.e. for each case of absenteeism and each newly placed order that requires the execution of additional operations, there exists an assignment X that guarantees the timely delivery of portfolio Q.

In general, robustness can be defined in many ways. In the present model, it is assumed that the value of function R_ω^λ is determined as a ratio of the number of disruption scenarios the CF is robust to, to all possible disruption scenarios.

The problem of planning CF robust to the select disruptions (defined by sets U_ω and Z^λ) can be reduced to the following problems of analysis and synthesis of CF:

Problem of analysis of CF: *Given is a project portfolio Q, a staff of employees $\mathcal{P}$, a competency framework G, and disruptions defined by sets U_ω and Z^λ. Question: What level of robustness R_ω^λ to the given disruptions does the competency framework G of the staff of employees $\mathcal{P}$ delivering the project portfolio Q have?*

Problem of synthesis of CF: *Given is a project portfolio Q, a staff of employees $\mathcal{P}$, and disruptions defined by sets U_ω and Z^λ. Question: Does there exist a competency framework G (and if so, what is its minimum form) of the staff of employees $\mathcal{P}$ delivering the portfolio Q which guarantees the given level of robustness R_ω^λ ($R_\omega^\lambda \geq R^*$) to the occurrence of the given disruptions?*

These problems correspond, respectively, to the decision-making and optimization problems associated with:

- the assessment of robustness R_ω^λ of the competency framework G of the staff of employees $\mathcal{P}$ delivering the given project portfolio Q to disruptions caused by U_ω and Z^λ.
- the determination of a (minimum) competency framework G of the staff of employees $\mathcal{P}$ who are delivering the project portfolio Q which guarantees the given level of robustness R_ω^λ ($R_\omega^\lambda \geq R^*$) to disruptions caused by U_ω and Z^λ.

A reference model

Because the decision variables used in this study are discrete and the relations between them (related to the assumptions of mutual exclusion and non-preemptiveness of operations, etc.) are non-linear, we assumed that the problems under consideration could be described using the declarative modelling paradigm.

Sets:

Z: set of operations executed as part of the project portfolio Q: $Z = \{Z_1, \dots, Z_n\}$,
Z^λ: set of additional operations: $Z^\lambda = \{Z_{n+1}, \dots, Z_{n+\lambda}\}$,
$\mathcal{P}$: set of employees, $\mathcal{P} = \{P_1, \dots, P_m\}$,
U_ω: set of ω-element employee absence scenarios: $U_\omega = \{\{u_1, .., u_\omega\} | \, u_i \in \{1, \dots, m\}\}$,
LP_ω: subset of setU_ω ($LP_\omega \subseteq U_\omega$) defining the cases of absenteeism for which the CF is robust to the absence of ω employees and the addition of λ new tasks).
Θ: an individual scenario of the absence of ω employees, $\Theta \in U_\omega$.

Parameters:

n: number of operations executed as part of the project portfolio Q,
q_i: number of tasks of operation Z_i,
m: number of employees of staff $\mathcal{P}$,
ω: number of absent employees of staff $\mathcal{P}$, $\omega < m$,
λ: number of additional operations specified in set Z^λ,
l_i: duration of a tasks_of operation Z_i,
y_i: starting time of a tasks of operation Z_i,
φ_i: number of employees needed to execute Z_i,
s_k: minimum working time of the k-th employee,
z_k: maximum working time of the k-th employee,
w_i: set of operations that exclude the execution of operation Z_i,
R^*: expected robustness level of CF, $R^* \in [0,1]$.

Decision variables:

G: CF given by $G = [g_{k,i}]_{k=1\dots m; i=1\dots n+\lambda}$, where: $g_{k,i} \in \{0,1\}$:

$$g_{k,i} = \begin{cases} 1 & \text{gdy } P_k \text{ posiada kompetencje do operacji } Z_i \\ 0 & \text{w pozostałych przypadkach} \end{cases},$$

R_ω^λ: measure of robustness of CF G to the disruptions specified by U_ω and Z^λ.

G^Θ: CF which takes into account absences of the employees specified in set Θ: $G^\Theta = [g_{k,i}^\Theta]_{k=1\dots m; i=1\dots n+\lambda}$, where: $g_{k,i}^\Theta \in \{0,1\}$,

$$g_{k,i}^\Theta = \begin{cases} 1 & \text{gdy } k \notin \Theta \text{ i } P_k \text{ posiada kompetencje do } Z_i \\ 0 & \text{w pozostałych przypadkach} \end{cases},$$

X: assignment of tasks of operation Z of project portfolio Q to the employees of staff $\mathcal{P}$, $X = [x_{k,i}]_{k=1\dots m; i=1\dots n+\lambda}$, where: $x_{k,i} \in \{0,1, \dots, q_i\}$ defines the number of tasks of operation Z_i, which is performed by employee P_k
X^Θ: assignment in situations when employees defined in set Θ are absent from work: $X^\Theta = [x_{k,i}^\Theta]_{k=1\dots m; i=1\dots n+\lambda}$,

where: $x_{k,i}^{\Theta} \in \{0,1,\dots,q_i\}$ defines the number of tasks of operation Z_i performed by employee P_k in the situation of absence of employees specified in set Θ.

c^{Θ}: a variable that specifies whether there exists an assignment X^{Θ} that guarantees timely completion of operations in set $Z \cup Z^{\lambda}$.

Constraints:

Elements $g_{k,i}^{\Theta}$ of matrix G^{Θ}, which characterize the absence of employees P_k ($k \in \Theta$) take the value 0:

$$\mathrm{g}_{\mathrm{k,i}}^{\Theta} = \begin{cases} \mathrm{g}_{\mathrm{k,i}} & when\ \mathrm{k} \notin \Theta \\ 0 & when\ \mathrm{k} \in \Theta \end{cases}. \tag{5}$$

Tasks of operation Z are only executed by employees who have the appropriate competencies:

$$x_{k,i}^{\Theta} \le q_i \cdot g_{k,i}^{\Theta},\ k = 1 \dots m; i = 1 \dots n + \lambda; \forall \Theta \in U_{\omega}. \tag{6}$$

$$\neg\Big(\big(y_{\alpha,a} + l_{\alpha} \le y_{\beta,b}\big) \vee \big(y_{\beta,b} + l_{\beta} \le y_{\alpha,a}\big)\Big) \Rightarrow \big(x_{k,\alpha}^{\Theta} \cdot x_{k,\beta}^{\Theta} = 0\big),$$
$$\alpha,\beta = 1 \dots n; a = 1 \dots q_{\alpha}; b = 1 \dots q_b\ \forall \Theta \in U_{\omega} \tag{7}$$

Operations Z are performed by staffs φ_i of competent employees:

$$\left(\textstyle\sum_{k=1}^{m} x_{k,i}^{\Theta} = q_i \cdot \varphi_i\right) \Leftrightarrow \left(c_{1,i}^{\Theta} = 1\right), i = 1 \dots n; \forall \Theta \in U_{\omega}, \tag{8}$$

$$\left(\textstyle\sum_{k=1}^{m} x_{k,i}^{\Theta} \ge q_i \cdot \varphi_i\right) \Leftrightarrow \left(c_{1,i}^{\Theta} = 1\right), i = n \dots n + \lambda; \forall \Theta \in U_{\omega}, \tag{9}$$

$$\forall_{\alpha \in H}\ \exists_{k \in \{1 \dots m\}}^{!\varphi_i} \left(x_{k,i}^{\Theta} = q_i\right) \wedge \Big[\neg\Big(\big(\alpha + l_i \le y_{\beta,b}\big) \vee \big(y_{\beta,b} + l_{\beta} \le \alpha\big)\Big) \Rightarrow \big(x_{k,\beta}^{\Theta} = 0\big)\Big]$$
$$\text{for } \beta = 1 \dots n;\ i = n \dots n + \lambda; b = 1 \dots q_b; \forall \Theta \in U_{\omega}, \tag{10}$$

where: $\exists^{!a}$ – quantifier: "there exist exactly a elements".

Workload of employee P_k does not exceed the maximum working time limit $[s_k\ , z_k]$:

$$\left(\textstyle\sum_{\mathrm{i}=1}^{n+\lambda} x_{k,i}^{\Theta} \cdot l_i \ge s_k\right) \Leftrightarrow (c_{2,k}^{\Theta} = 1), k = \{1 \dots m\} \backslash \Theta; \forall \Theta \in U_{\omega}. \tag{11}$$

$$\left(\textstyle\sum_{\mathrm{i}=1}^{n+\lambda} x_{k,i}^{\Theta} \cdot l_i \le z_k\right) \Leftrightarrow \left(c_{3,k}^{\Theta} = 1\right), k = \{1 \dots m\} \backslash \Theta; \forall \Theta \in U_{\omega}. \tag{12}$$

Execution of mutually exclusive activities:

$$(Z_b \in w_i) \Rightarrow \left(x_{k,i}^{\Theta} \cdot x_{k,b}^{\Theta} = 1\right), i = 1 \dots n + \lambda; \forall \Theta \in U_{\omega}. \tag{13}$$

Robustness R_{ω}^{λ}, calculated as a ratio of the number of absence scenarios $|LP_{\omega}|$ for which the competency framework is robust to the absence of ω employees and the addition of λ new tasks, to all possible disruption scenarios ($|U_{\omega}|$).

$$R_{\omega}^{\lambda} = \frac{|LP_{\omega}|}{|U_{\omega}|} \ge R^{*}, \tag{14}$$

$$LP = \textstyle\sum_{\Theta \in U_{\omega}} c^{\Theta}, \tag{15}$$

$$c^{\Theta} = \textstyle\prod_{i=1}^{n+\lambda} c_{1,i}^{\Theta} \prod_{k=1}^{m} c_{2,k}^{\Theta} \prod_{k=1}^{m} c_{3,k}^{\Theta}. \tag{16}$$

Variants of the CF of staff $\mathcal{P}$ and assignment X are represented in the proposed model using the decision variables G, G^{Θ}, and X^{Θ}. Assignment X^{Θ}, in situations of employee absences defined in set Θ and addition of new operations Z^{λ} which satisfy constraints (5)–(16).

Given the way in which the model is specified, which is limited to defining the decision variables, domains of variables, and the constraints on subsets of variables, the problems of analysis and synthesis under consideration belong to the class of Constraint Satisfaction Problems (CSP).

Problem of analysis of CF The problem of analysis formulated as a CSP takes the following form:

$$PS_A = \Big((\mathcal{V}_A, \mathcal{D}_A), \mathcal{C}_A\Big), \tag{17}$$

where: $\mathcal{V}_A = \{X^{\Theta \in U_{\omega}}, R_{\omega}^{\lambda}\}$ – a set of decision variables which includes assignments $X^{\Theta \in U_{\omega}}$ for a situation when ω employees are absent simultaneously and robustness R_{ω}^{λ} of the given CF G; $\mathcal{D}_A$ – a finite set of domains of decision variables $\{X^{\Theta \in U_{\omega}}, R_{\omega}^{\lambda}\}$: $x_{k,i}^{\Theta} \in \{0,1,\dots,q_i\}$, $R_{\omega}^{\lambda} \in [0,1]$; $\mathcal{C}_A$ – a set of constraints specifying the relationships of G with the set of operations $Z \cup Z^{\lambda}$ and robustness R_{ω}^{λ} (constraints (5)–(16)).

To solve problem PS_A (17), it is enough to find such values of decision variables X^{Θ} (assignment) and R_{ω}^{λ} (robustness to the absence of ω employees), for which all the constraints given in set $\mathcal{C}_A$ are satisfied. In other words, to solve PS_A is to determine the robustness R_{ω}^{λ} of the given CF G to the selected type of disruption.

Problem of synthesis of CF The problem of synthesis formulated as a CSP takes the following form:

$$PS_S = \Big((\mathcal{V}_S, \mathcal{D}_S), \mathcal{C}_S\Big), \tag{18}$$

where: $\mathcal{V}_S = \{G, G^{\Theta \in U_{\omega}}, X^{\Theta \in U_{\omega}}, R_{\omega}^{\lambda}\}$ – a set of decision variables that includes CF G, competency sub-frameworks $G^{\Theta \in U_{\omega}}$ corresponding to a situation of simultaneous absence of ω employees, assignments $X^{\Theta \in U_{\omega}}$ and robustness R_{ω}^{λ}; $\mathcal{D}_S$ – a finite set of domains of decision variables $\{G, G^{\Theta \in U_{\omega}}, X^{\Theta \in U_{\omega}}, R_{\omega}^{\lambda}\}$: $g_{k,i} \in \{0,1\}$, $g_{k,i}^{\Theta} \in \{0,1\}$, $x_{k,i}^{\Theta} \in \{0,1,\dots,q_i\}$, $R_{\omega}^{\lambda} \in [0,1]$; $\mathcal{C}_S$ – a set of constraints specifying the relationships of G with the set of operations $Z \cup Z^{\lambda}$ and robustness R_{ω}^{λ} (constraints (5)–(16)).

As in the case of the problem of analysis, solving problem PS_S (18) comes down to determining such values of the decision variables G, X^{Θ}, and R_{ω}^{λ} for which all constraints defined in set $\mathcal{C}_S$ (including $R_{\omega}^{\lambda} \ge R^{*}$) are satisfied. In other words, the solution to PS_S is a form of the CF which guarantees a given level R^{*} of robustness R_{ω}^{λ}.

In the general case, a PS_S defined in this way can be treated as an optimization problem whose goal is to determine the minimum CF G_{OPT} (e.g., one that requires the minimum number of adjustments to the baseline CF). The CSP can be transformed into a Constraint Optimization Problem (COP) [Sitek and Wikarek 2016; Bożejko et al. 2017] given by the following formula:

$$CO_S = \Big((\mathcal{V}_S, \mathcal{D}_S), \mathcal{C}_S, F_S\Big), \tag{19}$$

where: $\mathcal{V}_S, \mathcal{D}_S, \mathcal{C}_S$ defined as in (18), F_S – objective function:

$$F_S\,(G) = \textstyle\sum_{k=1 \dots m}^{i=1 \dots n+\lambda} g_{k,i} \tag{20}$$

To solve CO_S (19) it is enough to find such values of decision variables G_{OPT} for which all constraints given in set $\mathcal{C}$ are satisfied and for which function F_S has a minimum value. In general, CSP CO_S (19) allows to synthesize minimum CFs robust to the simultaneous absence of ω employees and the addition of λ new tasks.

The problems of analysis and synthesis PS_A (17) and CO_S (19) formulated in this way and implemented in CP environments, allow to develop a method for supporting the planning of robust CF.

3. METHOD FOR PLANNING COMPETENCY FRAMEWORKS ROBUST TO DISRUPTIONS

The CF planning method (Fig. 1) assumes that an organization has access to information about its employees (the staff of employees $\mathcal{P}$ and their competency framework G are known) and the project portfolio Q being delivered (including information on task assignment X), and that the constraints describing the relationships between these variables (5)–(16) are also known.

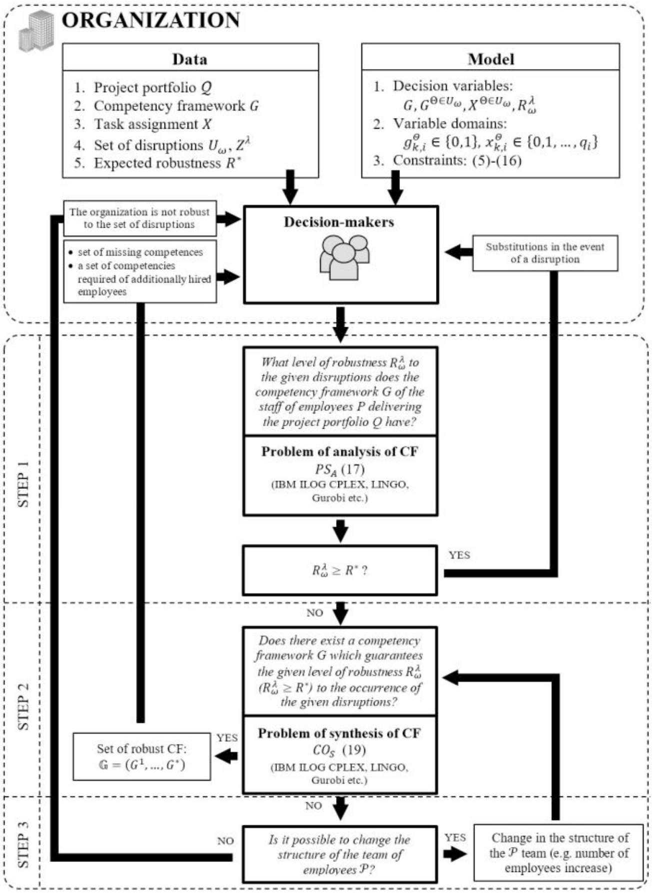

Fig. 1. CF planning method.

It is assumed that the decision-maker who uses this method is aware that a specific set of disruptions (employee absences U_ω and/or addition of new operations Z^λ) can occur while the portfolio is being delivered Q. The method consists of three steps (Fig. 1):

1. Assessment of the robustness R_ω^λ of the current staff of employees, which is made by solving the problem of analysis PS_A (17).
2. Synthesis of a minimum CF (problem CO_S (19)) that guarantees the expected level $R_\omega^\lambda \geq R^*$ of robustness R_ω^λ .
3. Modification of the structure of the staff of employees $\mathcal{P}$.

4. COMPUTATIONAL EXPERIMENTS

The CF planning method was tested in an experiment using data obtained from a manufacturing company (Rudnik 2018). In the experiment, we wanted to synthesize CF which would be robust to disruptions recorded in the company's history. We used data for a portfolio Q consisting of 7 projects (March/April 2020): $Q = \{Q_1, \dots, Q_7\}$. Set $\mathcal{Z}$ contains a total of 108 operations: $\mathcal{Z} = \{Z_1, Z_2, \dots, Z_{108}\}$. The operations were assigned to the projects in the following way: $\mathbb{Z}_1 = \{Z_1, \dots, Z_{13}\}$, $\mathbb{Z}_2 = \{Z_{14}, \dots, Z_{26}\}$, $\mathbb{Z}_3 = \{Z_{27}, \dots, Z_{38}\}$, $\mathbb{Z}_4 = \{Z_{39}, \dots, Z_{50}\}$, $\mathbb{Z}_5 = \{Z_{51}, \dots, Z_{67}\}$, $\mathbb{Z}_6 = \{Z_{68}, \dots, Z_{89}\}$, $\mathbb{Z}_7 = \{Z_{90}, \dots, Z_{108}\}$.

The following parameters were specified for each operation Z_i: number of tasks q_i required for completing operation Z_i, duration l_i of each task [in days], number of employees φ_i required for completing each task, starting times y_i, and exclusion sets w_i (Table 1). The operation networks $DG_1 - DG_7$ for project portfolio Q are shown in Fig. 2.

Table 1. Set of operations Z of project portfolio Q

Z_i	q_i	y_i	l_i [days]	w_i	φ_i
Z_1	1	0	4	$\emptyset$	2
Z_2	1	4	2	$\{Z_3, Z_{39}\}$	2
Z_3	1	4	2	$\{Z_2, Z_{39}\}$	2
Z_4	1	6	4	$\{Z_{39}, Z_{40}\}$	3
…	…	…	…	…	…
Z_{50}	1	21	2	$\{Z_{18}, Z_{19}, Z_{20}, \dots, Z_{52}\}$	1
…	…	…	…	…	…
Z_{107}	1	37	3	$Z_{29}, Z_{62}, \dots, Z_{106}\}$	2
Z_{108}	1	40	3	$\{Z_{30}, Z_{31}, \dots, Z_{85}\}$	1

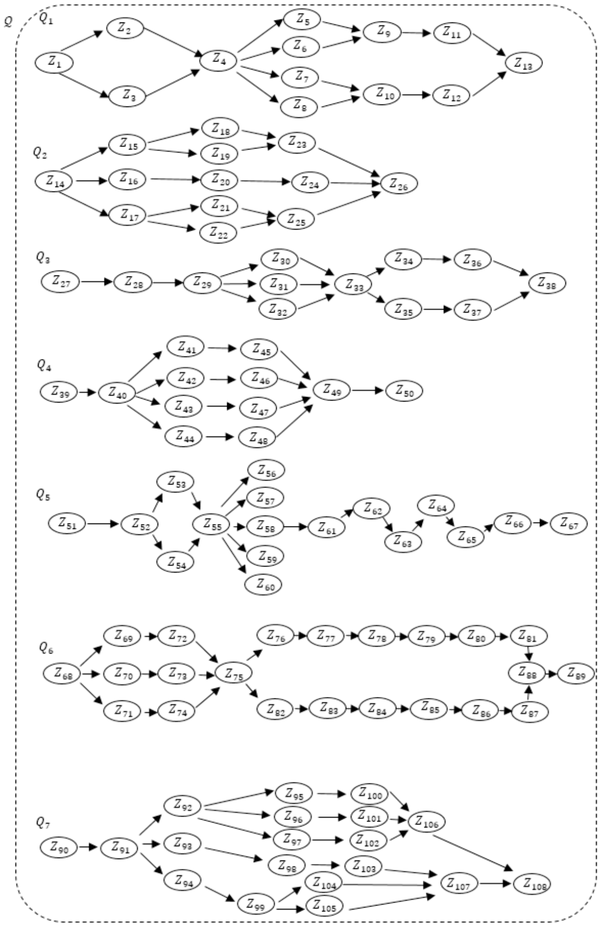

Fig. 2. The network of operations for the project portfolio $Q = \{Q_1, \dots, Q_7\}$.

A total of 36 employees were employed to deliver the project portfolio Q. In keeping with the notation, a team of employees is described by set $\mathcal{P} = \{P_1, P_2, \dots, P_{36}\}$. A fragment of the competency framework of this set is shown in Table 2. Due to personal data protection considerations, the data were pseudonymized. The cells in Table 2 contain the values of $g_{k,i}$, which mean the following:

1 – employee P_k has the competencies to execute operation Z_i ($g_{k,i} = 1$),

$\{0,1\}$ – employee P_k does not have the competencies to execute operation Z_i, but can acquire them ($g_{k,i} \in \{0,1\}$),

0 – employee P_k does not have the competencies to execute operation Z_i and cannot acquire them ($g_{k,i} = 0$).

Table 2. Employee competency framework G

G	Z_1	Z_2	Z_3	Z_4	…	Z_{50}	…	Z_{107}	Z_{108}
P_1: Smith	0	0	0	1	…	0	…	1	0
P_2: Jones	0	1	1	1	…	1	…	{0,1}	1
P_3: Wilson	1	1	1	0	…	{0,1}	…	0	{0,1}
…	…	…	…	…	…	…	…	…	…
P_{20}: Taylor	1	1	1	{0,1}	…	1	…	0	1
…	…	…	…	…	…	…	…	…	…
P_{35}: Brown	0	{0,1}	{0,1}	1	…	1	…	0	1
P_{36}: Cox	0	0	0	1	…	0	…	1	0

Moreover, for each employee of set $\mathcal{P}$, the lower (s_k) and upper (z_k) limits of the working time assigned to the projects being delivered is known (Table 3). For example, the working time of employee P_1 (Smith) ranges from 10 to 53 days. It is also assumed that the working times of the individual employees are invariant in time.

Table 3. Employee working time limits

P_k	s_k	z_k	P_k	s_k	z_k	P_k	s_k	z_k
P_1: Smith	10	53	P_{13}: Bailey	20	53	P_{25}: Moore	10	25
P_2: Jones	20	53	P_{14}: Morris	20	53	P_{26}: Hughes	20	53
P_3: Wilson	20	53	P_{15}: Lee	10	25	P_{27}: Clarke	10	25
P_4: Baker	20	53	P_{16}: Hill	20	53	P_{28}: Polinski	20	53
P_5: Cooper	20	53	P_{17}: Khan	20	53	P_{29}: Edwards	20	53
P_6: Hoffmann	20	53	P_{18}: Green	20	53	P_{30}: Phillips	20	53
P_7: Atkins	10	25	P_{19}: Collins	10	25	P_{31}: Young	20	53
P_8: Robinson	10	25	P_{20}: Taylor	20	53	P_{32}: Coates	20	53
P_9: Fox	20	53	P_{21}: Rowling	20	53	P_{33}: Potter	20	53
P_{10}: Foreman	10	25	P_{22}: Patel	20	53	P_{34}: Anderson	20	53
P_{11}: Campbell	10	25	P_{23}: Morgan	20	53	P_{35}: Brown	10	25
P_{12}: Savchuk	20	53	P_{24}: Scott	20	53	P_{36}: Cox	20	53

A fragment of the assignment X that corresponds to these assumptions is shown in Table 4.

Table 4. Task assignment X for project portfolio Q

G	Z_1	Z_2	…	Z_{39}	…	Z_{99}	…	Z_{107}	Z_{108}
P_1: Smith	0	0	…	0	…	0	…	0	0
P_2: Jones	0	0	…	0	…	0	…	0	0
…	…	…	...	…	…	…	…	…	…
P_{17}: Khan	0	0	…	0	…	4	…	3	0
…	…	…	…	…	…	…	…	…	…
P_{19}: Collins	4	0	…	3	…	0	…	0	0
…	…	…	…	…	…	…	…	…	…
P_{35}: Brown	0	0	…	0	…	0	…	0	0
P_{36}: Cox	0	0	…	0	…	0	…	0	0

The task assignment meets the following requirements:

- tasks of operation Z_i are executed only by competent employees,
- employee working time limits (s_k, z_k) may not be exceeded.
- at any time point, employee P_k can perform a maximum of one task of a given operation,
- and the resources used are non-preemptive.

Schedule for the project portfolio is shown in Fig. 3. The schedule shows that project portfolio Q should be delivered within 60 days. Projects $Q_1, \dots, Q_7$ are run concurrently during this period. The completion times for the individual projects are as follows: $Q_1{:}\,0-21$; $Q_2{:}\,13-30$; $Q_3{:}\,31-53$; $Q_4{:}\,5-23$; $Q_5{:}\,19-51$; $Q_6{:}\,23-60$; $Q_7{:}\,24-43$.

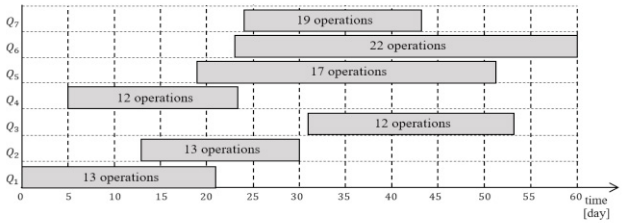

Fig. 3. Schedule of project portfolio Q.

The delivery of the project portfolio Q may be disrupted by events such as employee absenteeism and/or placement of an additional order that requires the execution of tasks unplanned for in the portfolio Q. In the experiments, an attempt was made at synthesizing a competency framework G that would safeguard the company (robustness $R_\omega^\lambda = 1$) against the consequences of simultaneous absence of any $\omega = 1, \dots, 3$ employees and newly placed orders $\lambda = 10$.

4.1. Synthesis of CF robust to simultaneous absence of ω employees

The aim of the experiments was to use the CF planning method to synthesize a competency framework G that would protect the company (robustness $R_\omega^\lambda = 1$) against the consequences of simultaneous absence of $\omega = 1, \dots, 3$ employees. To solve this problem, the following question has to be answered: *Does there exist a competency framework (and if so, what is its minimum form)* G_{OPT} *of a given staff of employees that guarantees robustness* $R_\omega^\lambda = 1$ *when* ω *employees* ($\omega = 1, 2, 3;\ \lambda = 0$ *) are absent from work?*

The answer obtained in the GUROBI environment (Intel i7-4770, 16 GB RAM) is positive only when $\omega = 1$. The results were generated in $t = 8.1$ s (case $\omega = 1$), $t = 29.4$ s ($\omega = 2$), $t = 658$ s ($\omega = 3$). When more employees ($\omega = 2, 3$) are absent, the answer to the question above is negative, i.e. robustness $R_\omega^\lambda = 1$ cannot be achieved. The maximum robustness values for the individual cases of disruptions $\omega = 2, 3$ are: $R_2^0 = 0.99$ and $R_3^0 = 0.76$.

Supplementing the CF with 17 new competencies (CF G_{OPT}^1) will allow the company to accommodate the effects of all possible scenarios of absence of one employee ($R_1^0 = 1$). The addition of 39 new competencies (CF G_{OPT}^2) will safeguard the company against the consequences of 99% of all possible scenarios of absence of two employees. This means that to achieve a robustness level $R_2^0 = 1$, the company would have to hire additional employees, answering the following question in the process: *Employees with what competencies should be hired for the competency framework* G *to guarantee robustness* $R_\omega^\lambda = 1$ *in the event of an absence of ω employees* ($\omega = 2, 3;\ \lambda = 0$)*?*

In the case under consideration, the answer to this question was obtained in $t = 33.8$ s ($\omega = 2$) and $t = 694$ s ($\omega = 3$). To achieve robustness $R_\omega^\lambda = 1$ ($\omega = 2, 3$), the company needs to hire employees who have:

a) 1 competence to execute operation: Z_{27} (case $\omega = 2$),
b) 17 competencies to execute operations: $Z_{27}, Z_{56}, Z_{57}, Z_{58}, Z_{59}, Z_{60}, Z_{76}, Z_{77}, Z_{78}, Z_{79}, Z_{80}, Z_{81}, Z_{95}, Z_{96}, Z_{97}, Z_{98}, Z_{99}$ (case $\omega = 3$).

By hiring employees with those competencies, the company can avoid the consequences of all possible scenarios of employee absenteeism ($\omega = 2, 3$).

4.2. Synthesis of CF robust to the absence of ω employees and the addition of λ new operations

In another experiment, we synthesized a CF robust to the placement of additional orders (the company experienced this type of disruption several times a year). The new project Q_8 starts on day 42 and consists of 10 operations $\mathbb{Z}_8 = \{Z_{109}, \dots, Z_{118}\}$. Data on the new project are summarized in Table 5.

Table 5. Set of λ additional operations Z

Z_i	q_i	y_i	l_i	w_i	φ_i
Z_{109}	1	46	3	$\{Z_{34}, Z_{35}, Z_{36}, Z_{37}, Z_{67}, Z_{80}, Z_{87}\}$	1
Z_{110}	1	49	2	$\{Z_{36}, Z_{37}, Z_{67}, Z_{80}\}$	1
Z_{111}	1	51	4	$\{Z_{38}, Z_{80}, Z_{81}, Z_{114}, Z_{115}\}$	2
Z_{112}	1	55	4	$\{Z_{81}, Z_{88}, Z_{89}, Z_{116}\}$	2
Z_{113}	1	59	4	$\{Z_{89}\}$	2
Z_{114}	1	51	2	$\{Z_{38}, Z_{80}, Z_{81}, Z_{111}\}$	2
Z_{115}	1	53	2	$\{Z_{81}, Z_{111}\}$	2
Z_{116}	1	55	2	$\{Z_{81}, Z_{88}, Z_{112}\}$	2
Z_{117}	1	63	3	$\emptyset$	1
Z_{118}	1	65	2	$\emptyset$	1

The operations network of project Q_8 is shown in Fig. 4. The schedule of project portfolio Q that takes into account the new (unplanned) project is shown in Fig. 5.

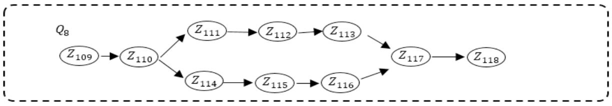

Fig. 4. Operations network of project Q_8.

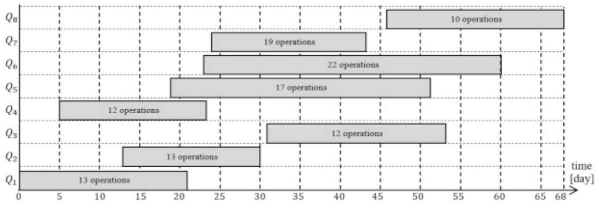

Fig. 5. Schedule of project portfolio Q with an additional project Q_8.

Using the CF planning method, we sought an answer to the following question: *Does there exist a competency framework (and if so, what is its minimum form)* G_{OPT} *of the company's staff of employees that guarantees robustness* $R_\omega^\lambda = 1$ *in the event of an absence of ω employees and placement of λ additional orders* ($\omega = 1, 2, 3;\ \lambda = 10$)*?*

A positive answer was obtained only when $\omega = 1$. It was computed in $t = 9.3$ s (case $\omega = 1$), $t = 32.1$ s (case $\omega = 2$), $t = 675$ s (case $\omega = 3$).

When more employees ($\omega = 2, 3$) were absent, the answer to the question above was negative, i.e. robustness $R_\omega^\lambda = 1$ could not be achieved. The maximum robustness for the particular cases of disruption $\omega = 2, 3$ is: $R_2^{10} = 0.95$ and $R_3^{10} = 0.70$.

Supplementing the CF with 19 new competencies (CF G_{OPT}^1) would allow the company to accommodate the effects of all possible scenarios of absence of one employee when an additional project Q_8 has to be completed. The addition of 43 new competencies (CF G_{OPT}^2) would safeguard the company against the negative effects of 95% of all possible scenarios of absence of any two employees. Further changes in the CF would not improve its robustness. To achieve a robustness level $R_2^0 = 1$, the company would have to hire additional employees, answering the following question in the process: *Employees with what competencies should be hired for the competency framework* G *to guarantee robustness* $R_\omega^\lambda = 1$ *in the event of an absence of ω employees and addition of λ new operations* ($\omega = 2, 3;\ \lambda = 10$)*?*

In the case under consideration, the answer was obtained in $t = 36.9$ s (case $\omega = 2;\ \lambda = 10$) and $t = 707$ s (case $\omega = 3;\ \lambda = 10$). To achieve robustness $R_\omega^{10} = 1$ ($\omega = 2, 3$), the company needs to hire employees who have:

a) 3 competencies to execute operation: Z_{27}, Z_{62}, Z_{90} (case $\omega = 2;\ \lambda = 10$),
b) 21 competencies to execute operations: $Z_{27}, Z_{56}, Z_{57}, Z_{58}, Z_{59}, Z_{60}, Z_{62}, Z_{68}, Z_{76}, Z_{77}, Z_{78}, Z_{79}, Z_{80}, Z_{81}, Z_{90}, Z_{95}, Z_{96}, Z_{97}, Z_{98}, Z_{99}, Z_{113}$ (case $\omega = 3;\ \lambda = 10$).

When the disruption caused by the unforeseen introduction of an additional project Q_8 is taken into account, robustness $R_\omega^{10} = 1$ ($\omega = 2, 3$) can be achieved by hiring employees with 2 more competencies (for $\omega = 2;\ \lambda = 10$) or 4 more competences (for $\omega = 2;\ \lambda = 10$), compared to the situation when absenteeism alone is considered.

The results of the experiment demonstrate that the CF planning method can be successfully used for planning the professional development of the existing staff and, especially, for personnel planning in constantly changing conditions, where unplanned events, such as employee absences, placement of additional orders, etc. must be considered. The present example of a manufacturing company may serve as a starting point for further research on the uses of the proposed method in other sectors and areas. In this context, our future work will focus on the development of a computational module that could be used as a software add-on for commercial Decision Support Systems (DSS) used in human resource management.

5. CONCLUSIONS AND FUTURE RESEARCH

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

The results of the present experiments show that the proposed approach can be implemented in task assignment decision support (TADS) systems. In this context, our future work will focus on the development of a computational module that can serve as a software add-on for commercially available DSS used in human resource management. The functionalities discussed in the present paper can be treated as human resource controlling tools (Dugelova and Strenitzerova 2015), which can be used to effectively manage personnel while creating transparent rules and planning, monitoring and control procedures. Implemented in HRMS/CMS systems, this type of functionalities enable early detection of needs and quick prototyping of alternative competency management decisions, allowing managers to make personnel-related decisions in response to employee absenteeism and/or staffing fluctuation, legislative changes, modifications of the volume of orders, changes in customer requirements, etc.

In our future work, we plan to investigate the problems of robustness of CF to other disruptions, such as changes in task duration, etc. We also plan to use different variants of the hybrid approach to implement the proposed models (Sitek and Wikarek 2018).

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