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Competence-driven employee substitutability planning robust to unexpected staff absenteeism

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Abstract: In order to deal with unexpected events such as employee absenteeism and/or a demand for personnel that is higher or lower than expected, organizations need to adopt proactive and reactive scheduling strategies to protect the personnel roster and to respond to this operational variability, respectively. In this paper, we propose a preemptive programming approach to construct a personnel shift roster that maximizes the employee substitutability. A proactive approach builds in a certain degree of robustness in the original roster. This built-in robustness improves both the absorption and adjustment capability of the original roster during the operational allocation phase when unexpected events occur. With a view to developing a DSS-driven method dedicated to competence allocation planning robust to unexpected staff absenteeism, we present a methodology, based on constraints programming and robust employee competence structure concepts. Introduced approach allows to find an employee competence structure robust to a given set of disruptions while guaranteeing an admissible personnel allocation to the assumed set of tasks. Potential applications of the proposed solution are discussed using examples.

Keywords: Competence assignment, robust planning, employee competences, robust employee competence structure, employee absenteeism.

1. INTRODUCTION

The object of planning man-power needs, as part of employment planning, is to define the competence profiles of the personnel and other individuals employed in a company. In particular, this involves defining the requirements regarding employees' knowledge, skills, abilities and behavior, determining the number of workers needed for various positions, and the scope of work that employees in each position have to perform. The quality of employment plans obtained in this process depends on the robustness of the production process to disruptions caused by unexpected events such as employee absences, machine failures, accidents at work, etc. This variability leads to the occurrence of unexpected events such as employee absenteeism and/or a demand for personnel that is higher or lower than expected. In order to deal with these uncertainties, organizations need to adopt proactive and reactive scheduling strategies to protect the personnel roster and to respond to this operational variability, respectively. In this paper, we discuss a proactive approach that exploits the concept of employee substitutability to improve the flexibility of a personnel shift roster to respond to schedule disruptions. In other words, due to this approach an organization builds a staff of employees with specific competences, robust to a selected set of disruptions (Van den Bergh et al. 2013).

In the literature of the subject, competences are defined in various ways (Korytkowski 2017; Woodruffe 1992). Competences are defined as a set comprising theoretical knowledge, practical skills, behaviors and qualifications that enable successful task performance. It should be noted that planning decisions regarding the allocation of production tasks (which require specific employee competences) to resources (employees with given competences) are made in dynamically changing organizational settings, which involve frequent changes in the scope and structure of objectives, tasks and resources. Examples of such changes include employee absenteeism (sick leaves, accidents, maternity leaves, etc.), changes in the number of jobs, staff mobility (frequent employment changes), etc. Most of them are random and cannot be anticipated well in advance. Such events are henceforth referred to as disruptions (Ingels and Maenhout 2019). If a disruption caused by an employee's absence results in a so-called competence gap, it is usually too late to bridge the gap by introducing appropriate changes (training, employment, outsourcing, etc.). While the existing literature describes many methods for the assessment and determination of competence structures (Wikarek and Sitek 2019), there is still a scarcity of research addressing the issues of planning of the construction of robust personnel rosters is a topic that has received only limited attention in the literature.

The known methods offer no possibility of predicting disruptions and shaping competence structures robust to selected types of disruptions. It is worth noting that the problem of allocation of employees to the individual component activities of a job being performed belongs to the category of task assignment problems. Problems of this type are found in many areas of science and business, such as distribution of goods, production management, telecommunications, roster planning, etc. They all boil down to assigning a known set of tasks to a given set of agents (e.g. employees, vehicles, processors, warehouses). Different allocation problems can accentuate different objective functions that include, for example, minimizing total task

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completion time, minimizing costs, maximizing profit, minimizing the length of routes, etc. One commonly used approach to improving the robustness of task assignments is to introduce time buffers or capacity buffers. Time buffers (most often additional time windows for the completion of delayed tasks) are used in project management in situations involving uncertain job durations (Hazir et al. 2010) or unexpected delays in task completion (Ehrgott and Ryan 2002). In turn, so-called capacity buffers (surplus resources), also referred to as reserve personnel (reserve crew, reserve resources, etc.) are often used in services, e.g. passenger transport, school services, hospital services, etc. where common disruptions include events such as employee sickness (Moudani and Mora-Camino 2010) or technical failures (Ingels and Maenhout 2015; Rosenberger et al. 2002). One example of an approach which assumes that a system should necessarily have surplus resources (financial, material, human), is the solution presented in (Antosz 2018), which allows to determine a competence structure that minimizes the risk of non-performance of tasks (brought on by a specific type of disruption). Research that deals with the planning of competence structures robust to disruptions, similarly to research on robust scheduling (Wikarek and Sitek 2019), is still in its initial, conceptual phase. One of the reasons for this state of affairs is NP-hardness of this class of problems. Preliminary results of studies aimed at developing a method for synthesizing competence structures robust to a selected set of disruptions (Szwarc et al. 2019) confirm the attractiveness of approaches based on the declarative modeling paradigm. A declarative model of a task assignment and scheduling problem allows to develop interactive methods of planning competence allocation that can be directly implemented in declarative programming environments such as ECLiPSe, IBM CPLEX and OzMozart.

In Section 2, a reference model is proposed which can be used to search for competence structures that guarantees robust to the set of anticipated types of disruption. A procedure for the assessment and synthesis of competence structures robust to disruptions is presented in Section 3. Section 4 reports computational experiments performed in the IBM ILOG CPLEX, which illustrate the possibilities of applying the proposed method. The conclusions and directions for further research are discussed in Section 5.

2. MODELING OF COMPETENCE ALLOCATION

2.1. A motivational example

A company uses a cyclic multi-item batch flow production system to complete three orders a day: $\{J_1,J_2,J_3\}$ – Fig. 1. Each order is comprised of a set of tasks (jobs) Z_i: $J_1=\{Z_1,\dots,Z_5\}$, $J_2=\{Z_6,\dots,Z_{10}\}$, $J_3=\{Z_{11},\dots,Z_{14}\}$, executed in a given technological order, job durations l_i, and a job schedule determined by the critical path – Fig. 2a). For example, order placement tasks J_1 are executed along the route marked in blue, and their duration times are: 3h for Z_1, 2h for Z_2 5h for Z_3, 2h for Z_4, and 2h for Z_5. The order processing schedule assumes that the orders can be completed within 10 hours (10h for J_1,J_2 and 9h for J_3). Each day, a staff of 6 employees are assigned to process the given orders: $\{P_1,\dots,P_6\}$. The employees have different competences. The competence structure G adopted in the model is shown in Fig 1. Cell values (henceforth described by variable $g_{k,i}$) show whether a given employee P_k has the competence (value "1") to complete job Z_i. For instance, employee P_1 has competences necessary to perform jobs Z_7, Z_{10}, Z_{11} and Z_{12}. It is assumed that for the duration of job Z_i, exactly one employee, who has the competences required to perform it, is reserved for the job. For example, jobs Z_2, Z_9 and Z_{10} have been assigned to employee P_6. The workload in this case is from 3h (employee P_5) to 7h. The job cannot be interrupted while it is being processed and the employee is only released once the task has been completed. In addition, it is assumed that employees are engaged in the execution of given jobs for no less than 2 hours and no more than 8 hours. In a general case, the time limits during which an employee is assigned to a particular job may be established arbitrarily or on the basis of an analysis of the orders being processed. In the case under consideration, to assess the robustness of the earlier adopted competence structure (Fig. 1) one has to answer the following question: *Is competence structure G robust to the absence of one employee? Or, put differently, is it possible to create a job assignment such that jobs are executed in accordance with the schedule from Fig. 2a) and that working time limits are obeyed for all available employees?* As an illustration, a job assignment for the case of an absence of employee P_5 is shown in Fig 2b).The absence of this employee means that his/her duties (execution of job Z_7) have to be taken over by employee P_1 (only this employee has the competence to complete job Z_7). Part of the duties of P_1 (job Z_{11}) are taken over by employee P_6. Such an assignment of jobs does allow the staff to complete all orders but within a period exceeding 10 hours and with workload of employee P_6 exceeding the permissible 8h. A similar analysis of other cases of employee absence shows that the processing time limit (deadline) of 10h is exceeded in each case. If the deadline is exceeded for each case of employee absence, this means that the competence structure G is not robust to this type of disruption. It is worth noting that the adopted definition of robustness does not allow for changes to be made to the order processing schedule (Fig. 2a). In practice, sometimes a small change to a schedule may enable timely execution of orders even in the event of an absence of one employee. Cases which admit of changes in the adopted schedule as well as changes caused by other types of disruptions, are the subject of our other, parallel study. A generalized version of the question formulated earlier in this section takes the following form: What should a competence structure robust to a disruption caused by the absence of one of the employees be like? Or, put differently, which employee should acquire what competences for the competence structure to become robust to the given type of disruption? It is assumed that each employee can acquire competences needed for the completion of each job $Z_1,\dots,Z_{14}$. The problem of synthesis of competence structures robust to a selected set of disruptions formulated in this way is an NP-hard problem. The synthesis problem of competence structures robust to a selected set of disruptions can be formulated as follows: given is an organization/firm/production company with human capital represented by the competence structure of the personnel (employees).

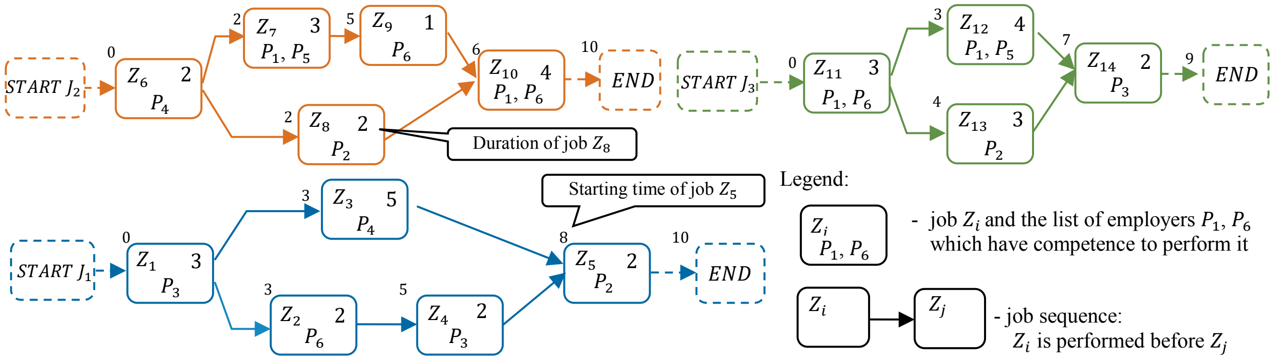

Fig. 1. Structure of production orders J_1, J_2, J_3

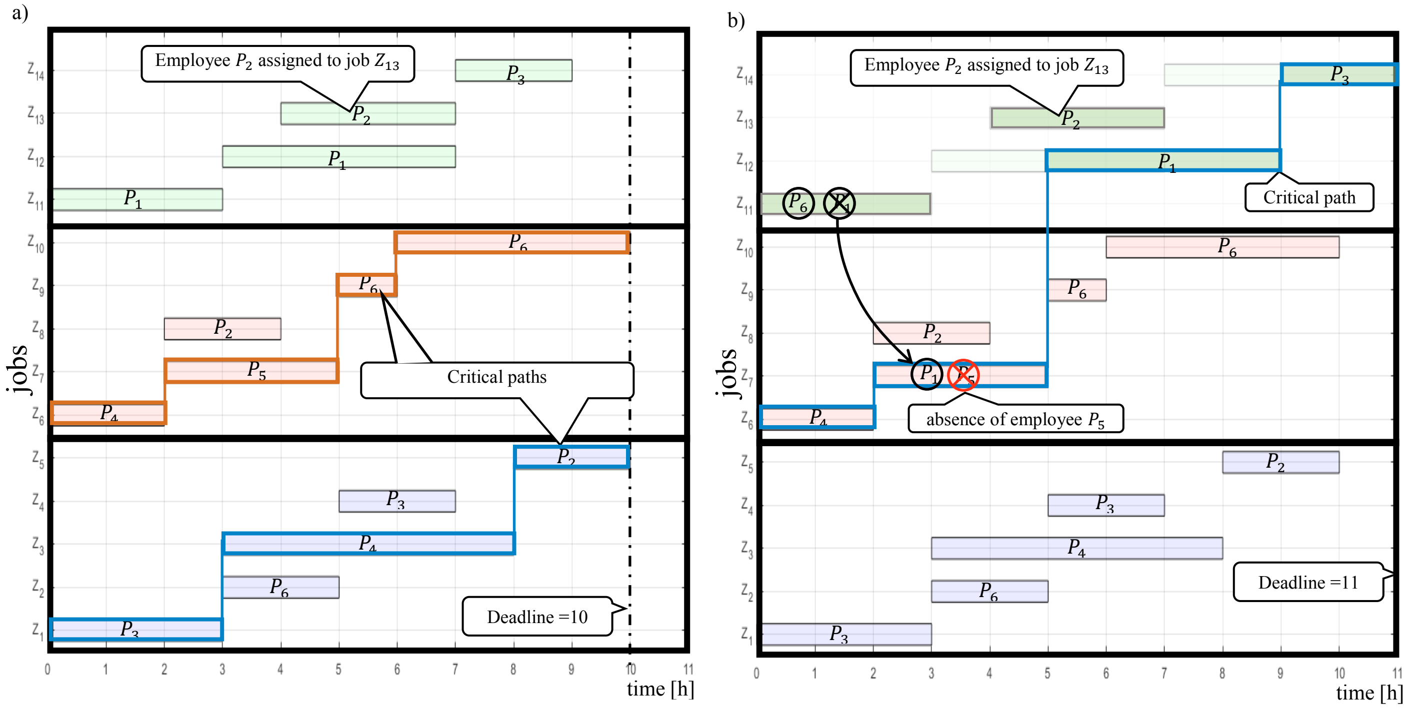

Fig. 2. a) Assignment of employee competences to jobs, b) Assignment when employee P_5 is absent

Known are the organization's objectives and the set of tasks it carries out. The goal is to find a set of personnel development decisions which should be taken to make the competence structure robust to the selected type of disruption. The problem can be solved by finding an answer to the question: Does there exist a model and a method of constructing competence structures robust to selected disruptions caused by employee absenteeism, loss of qualifications, etc.?

2.2. A reference model

Further deliberations, illustrating how competence structures robust to the absence of one employee can be synthesized, are based on the following model:

Sets:

Z_i: set of jobs indexed by $i = 1, \ldots, n$

P_k: set of employees indexed by $k = 1, \ldots, m$

Parameters

l_i: duration of the i-th job Z_i (in hours)

s_k^j: minimum number of working hours (lower working time limit) of the k-th employee ($s_k \in \mathbb{N}$) when the j-th employee is absent

z_k^j: maximum number of working hours (upper working time limit) of the k-th employee ($z_k \in \mathbb{N}$) when the j-th employee is absent

$w_{a,b}$: a parameter that specifies whether jobs Z_a and Z_b can be performed by the same employee (the jobs are mutually exclusive):

$$w_{a,b} = \begin{cases} 1 & \text{when jobs } Z_a \text{ and } Z_b \textit{ are mutually exclusive} \\ 0 & \textit{in the remaining cases} \end{cases}$$

R^* expected robustness of competence structure, $R^* \in [0,1]$

Decision variables

G: competence structure defined as $G = (g_{k,i} | k = 1 \ldots m; i = 1 \ldots n)$, where $g_{k,i}$ stands for employees' competences to perform jobs; $g_{k,i} \in \{0, 1\}$, $g_{k,i} = 0$ means that the k-th employee has no competences to perform the i-th job, and $g_{k,i} = 1$ means that the k-th employee has the competences to perform the i-th job.

R: measure of robustness of competence structure G to the absence of one employee $R \in [0,1]$. $R = 0$ – stands for **lack of robustness**, i.e. each absence results in unassigned jobs; $R = 1$ – stands for **full robustness**, i.e. regardless of which employee is absent, all jobs are assigned to available staff.

G^j: a competence structure obtained for a situation in which the j-th employee $G^j = \left(g^j_{k,i} \middle| k = 1 \dots (m-1); i = 1 \dots n\right)$ is absent from his/her scheduled duty

X^j: job assignment in the situation when the j-th employee is absent, defined as $X^j = \left(x^j_{k,i} \middle| k = 1 \dots (m-1); i = 1 \dots n\right)$,, where $x^j_{k,i} \in \{0,1\}$:

$$x^j_{k,i} = \begin{cases} 1 & \text{when job } Z_i \text{ has been assigned to employee } P_k \\ 0 & \text{in the remaining cases} \end{cases}$$

c^j: an auxiliary variable that specifies whether assignment X^j satisfies the given constraints. The value of variable $c^j \in \{0,1\}$ depends on variables: $c^j_{1,i}$, $c^j_{2,k}$, $c^j_{3,k}$ which specify whether constraints (3), (4), (5) are satisfied.

Constraints:

1. Construction of competence structures for situations when the j-th employee is absent from his scheduled duty:

$$g^j_{k,i} = \begin{cases} g_{k,i} & when\ k < j \\ g_{(k+1),i} & when\ k \geq j \end{cases}. \tag{1}$$

2. Jobs can only be performed by employees who have appropriate competences:

$$x^j_{k,i} = 0\ ,\ when\ g^j_{k,i} = 0,\ \text{for } k = 1 \dots (m-1); i = 1 \dots n\ ;\ j = 1 \dots m. \tag{2}$$

3. Job Z_i is assigned to exactly one employee:

$$\left(\sum_{k=1}^{m-1} x^j_{k,i} = 1\right) \Leftrightarrow \left(c^j_{1,i} = 1\right), \text{for } i = 1 \dots n \tag{3}$$

4. Workload of the *k*-th employee should be no less than the lower working time limit s^j_k:

$$\left(\sum_{\mathrm{i}=1}^{n} x^j_{k,i} \cdot l_i \geq s^j_k\right) \Leftrightarrow (c^j_{2,k} = 1)\ , \tag{4}$$

5. Workload of the *k*-th employee should not exceed the upper working time limit z^j_k:

$$\left(\sum_{\mathrm{i}=1}^{n} x^j_{k,i} \cdot l_i \geq z^j_k\right) \Leftrightarrow \left(c^j_{3,k} = 1\right)\ , \tag{5}$$

6. Performance of mutually exclusive jobs:

$$x^j_{k,a} + x^j_{k,b} \leq 1\ , \text{when } w_{a,b} = 0, \tag{6}$$

7. Robustness of the competence structure:

$$R = \frac{LP}{m}\ , \tag{7}$$

$$R \geq R^*\ , \tag{8}$$

$$LP = \sum_{j=1}^{m} c^j\ , \tag{9}$$

$$c^j = \prod_{i=1}^{n} c^j_{1,i} \prod_{k=1}^{m} c^j_{2,k} \prod_{k=1}^{m} c^j_{3,k}\ . \tag{10}$$

The concepts of competence structure and job assignment are represented in the model by decision variables G, G^j and X^j. Job assignment X^j which satisfies constraints (2)–(6) is referred to as an admissible assignment in the situation of an absence of the j-th employee. In this context, the questions considered previously can be narrowed down to: *Does there exist a competence structure G that can guarantee robustness $R \geq R^*$ in the event of an absence of one employee?*

2.3 Problem formulation

An answer to the question above can be searched for using brute force methods. The literature provides advanced declarative programming techniques which allow to reduce the calculation time compared to that required by exact methods. One such technique is constraint programming/constraint logic programming (CP/CLP) [31]. It is a set of techniques used to solve combinatorial problems, such as the assignment problem considered in the present work, and many others, e.g. the problems of vehicle routing, batching, and scheduling. The essence of constraint programming is to solve problems formulated as constraint satisfaction problems (CSP) (Banaszak and Bocewicz 2014; Nielsen et al. 2014).

The search for robust competence structures can be modeled using the CSP formalism, which allows to implement the proposed model directly in commercially available constraint programming environments, such as IBM ILOG CPLEX, Gurobi, ECL^{i}PS^e, Oz Mozart, and others, which are a subclass of declarative programming environments. In reference to the CSP formulated in this work, any change in the structure of orders, organization and staff will only require a correction/change in the set of constraints without affecting the implemented constraint propagation and variable distribution mechanisms. *The structure of the proposed model that 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 CSP and implement it in a constraint programming environment:*

$$CS = \left((\mathcal{V}, \mathcal{D}), \mathcal{C}\right), \tag{11}$$

where: $\mathcal{V} = \{G, G^1, \dots, G^m, X^1, \dots, X^m, R\}$ - a set of decision variables which includes: competence structure G, competence substructures G^j for cases when the j-th employee is absent, corresponding job assignments X^j, and robustness R. $\mathcal{D}$ – a finite set of decision variable domains $\{G, G^1, \dots, G^m, X^1, \dots, X^m, R\}$,$\mathcal{C}$ – a set of constraints specifying the relationships between the competence structure and its robustness (constraints 1–10).To solve CS (11), it is enough to find such values of decision variables G (personnel competence structure), X^j (job assignment) and R (robustness to absenteeism of one employee), determined by domains $\mathcal{D}$, for which all the constraints of set $\mathcal{C}$ are satisfied. In other words, what is sought is a solution that guarantees a given level R^* of robustness R. In general, a CSP defined in this way can be treated as an optimization problem. In such cases, the search focuses on determining the minimum competence structure G_{OPT} (e.g. one that meets the criterion of minimum number of competence changes). A specific level of robustness can be obtained due to the introduction of decision variables $G^1, \dots, G^m$ which represent the substructures of structure G for the particular cases of one-employee absence. Full robustness $(R = 1)$ is reached when there exists structure G, for which each substructure G^j guarantees a job assignment X^j that meets constraints (2)–(6) ($c^j = 1$). In other words, the solution to problem CS (11) is a competence structure G that guarantees timely completion of jobs for all cases of one-employee absence

3. COMPUTATIONAL EXPERIMENTS

Given is the production system from Fig. 1, in which orders are executed by a staff of employees $\{P_1, \dots, P_6\}$. Orders are processed according to the schedule from Fig. 2a). In the schedule, operations executed in the same time window are mutually exclusive. Information about which operations exclude one another in time (values of variable $w_{a,b}$) is given in Table 1. For example, because jobs Z_7 and Z_{12} are scheduled in the same time window (hours 3–5), they must be performed by different employees. As shown in Fig. 2b), competence structure G (Fig. 1) is not robust to an absence of a single employee. The model proposed in the present paper can be used to synthesize a competence structure robust to a given type of disruption, i.e. to answer the following question: *Does there exist a competence structure G that can guarantee full robustness ($R = 1$) in the situation when one employee is absent from duty?*

Table 1. Values of $w_{a,b}$ determined by schedule from Fig. 2a)

$w_{a,b}$	Z_1	Z_2	Z_3	Z_4	Z_5	Z_6	Z_7	Z_8	Z_9	Z_{10}	Z_{11}	Z_{12}	Z_{13}	Z_{14}
Z_1	0	0	0	0	0	1	1	1	0	0	1	0	0	0
Z_2	0	0	1	0	0	0	1	1	0	0	0	1	1	0
Z_3	0	1	0	1	0	0	1	1	1	1	0	1	1	1
Z_4	0	0	1	0	0	0	0	0	1	1	0	1	1	0
Z_5	0	0	0	0	0	0	0	0	0	1	0	0	0	1
Z_6	1	0	0	0	0	0	0	0	0	0	1	0	0	0
Z_7	1	1	1	0	0	0	0	1	0	0	1	1	1	0
Z_8	1	1	1	0	0	0	1	0	0	0	1	1	0	0
Z_9	0	0	1	1	0	0	0	0	0	0	0	1	1	0
Z_{10}	0	0	1	1	1	0	0	0	0	0	0	1	1	1
Z_{11}	1	0	0	0	0	1	1	1	0	0	0	0	0	0
Z_{12}	0	1	1	1	0	0	1	1	1	1	0	0	1	0
Z_{13}	0	1	1	1	0	0	1	0	1	1	0	1	0	0
Z_{14}	0	0	1	0	1	0	0	0	0	1	0	0	0	0

To answer this question one needs to solve *CS* (11), which contains competence structure G and parameters of the model from Fig. 1. The problem was implemented in the GUROBI environment (Intel i7-4770, 8GB RAM). The first admissible solution was obtained in less than 1s. The space of admissible solutions was searched for solutions that met the criterion of the minimum number of changes to the competence structure:

$$L(G) = \sum_{k=1}^{m} \sum_{i=1}^{n} g_{k,i}. \tag{12}$$

The minimum structure G_{OPT}, for which $R = 1$ is presented in a graphic form in Table 2. The value of $L(G_{OPT})$ is 29, which means that employees must improve their qualifications by acquiring a total of 11 new competences (Table 2): employee P_1 should acquire competences for jobs Z_2 and Z_9, P_2 competence for job Z_6; P_3 competences for jobs Z_3, Z_5 and Z_7; P_4 competences for jobs Z_1, Z_8 and Z_{13}; and P_5 competences for jobs Z_4 and Z_{14}. Acquisition of these competences will guarantee full ($R = 1$) robustness of the competence structure to the absence of any given staff member. Fig. 3 shows job assignments that guarantee timely completion (10h) of orders regardless of which employee is absent. The method was verified in a series of experiments involving different numbers of employees (5–15) and different numbers of tasks (16–32).

Table 2. Minimum competence structure robust to the absence of one employee

G_{OPT}	Z_1	Z_2	Z_3	Z_4	Z_5	Z_6	Z_7	Z_8	Z_9	Z_{10}	Z_{11}	Z_{12}	Z_{13}	Z_{14}
P_1	0	1*	0	0	0	0	1	0	1	1	1	1	0	0
P_2	0	0	0	0	1	1	0	1	0	0	0	0	1	0
P_3	1	0	1	1	1	0	1	0	0	0	0	0	0	1
P_4	1	0	1	0	0	1	0	1	0	0	0	0	1	0
P_5	0	0	0	1	0	0	1	0	0	0	0	1	0	1
P_6	0	1	0	0	0	0	0	0	1	1	1	0	0	0

* - colored fields represent newly acquired competences (relative to the structure from Table 1)

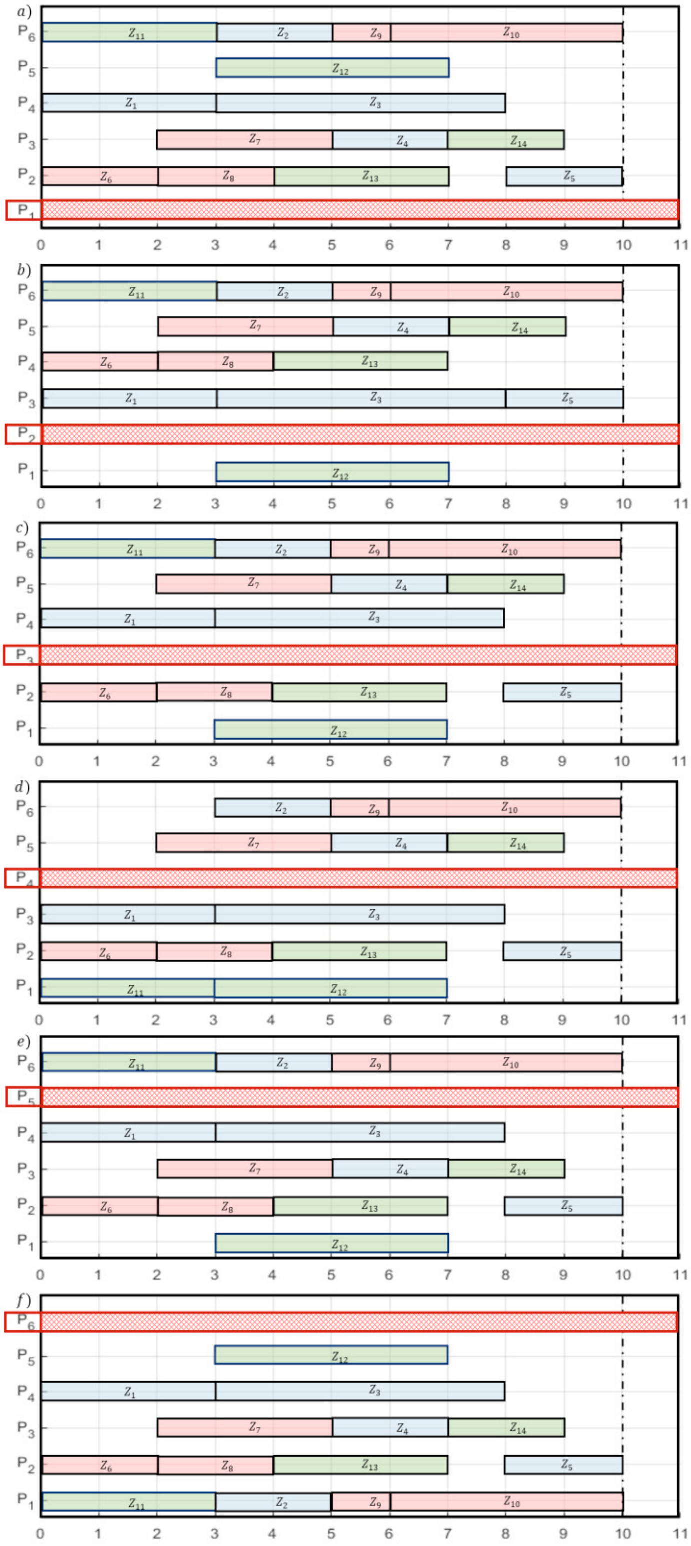

Fig. 3. Job assignments in the situation of an absence of one employee: absence of employee P_1 a), absence of employee P_2 b), absence of employee P_3 c), absence of employee P_4 d), absence of employee P_5 e), absence of employee P_6 f)

The calculations were carried out to determine the time needed to synthesize a competence structure robust ($R = 1$) to the absence of (any) one of the employees. The results are shown in Table 5. It is easy to notice that in cases in which the size of the structure does not exceed 10 employees and 32 jobs, a robust structure can be found in less than 1,000 seconds.

Table 4. Results of the computational experiment *

	1	2	3	4	5
Employees × Jobs	5x16	5x24	5x28	5x32	5x36
Number of variables	320	480	560	640	720
Changed competences	12	17	19	21	23
Robust structure determined in [s.]	1.14	4.18	6.62	10.46	14.75
	6	7	8	9	10
Employees × Jobs	10x16	10x24	10x28	10x32	10x36
Number of variables	1440	2160	2550	2880	3240
Changed competences	8	11	15	17	19
Robust structure determined in [s]	129	436	711	1046	>1000
	11	12	13	14	15
Employees × Jobs	15x16	15x24	15x28	15x32	15x36
Number of variables	3360	5040	5880	6720	7560
Changed competences	6	5	no data	no data	no data
Robust structure determined in [s.]	>1000	>1000	>1000	>1000	>1000

* computer parameters: Intel i7-4770, 8GB RAM

6. CONCLUSIONS

The proposed method of synthesizing competence structures robust to selected sets of disruptions allows to plan the allocation of production jobs (that require specific employee competences) to resources (employees with the given competences) in situations in which the disruptions are caused by employee absenteeism. According to this method, it is necessary to determine what additional (redundant) competences contractors need to have to compensate for competences lost as a result of employee absenteeism. The proposed measure of robustness of competence structures allows interactive, on-line synthesis of structures with a given level of robustness, in particular robustness to absences of single employees. Constraint programming techniques allow to extend and adapt the reference model developed in the present study to other areas of decision support which require the use of managerial decision-making support tools, for instance designing the competence structure of academic staff, recruiting panels of experts for reviewing project applications, proposing variants of the composition of medical teams, etc. The experiments have shown that the method can be effectively used in online mode to solve small-scale problems in organizational units of up to 10 employees and 32 tasks It may be possible to increase the scale of the problems solved by using hybrid methods (Wikarek and Sitek 2019) dedicated to models that use sparse data structures Implementation of this type of techniques will be one of the directions of our future research The results of these present studies will also be verified using selected extensions of the constraint satisfaction problem that take into account other measures of robustness to disruptions. They will also enable the development of other derivative methods of human resources management, such as methods of supporting the organization and planning of teamwork in situations in which the available workers have to step in for the absent colleagues.

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