Scientific Review – Engineering and Environmental Sciences (2019), 28 (2), 192–202
Sci. Rev. Eng. Env. Sci. (2019), 28 (2)
Przegląd Naukowy – Inżynieria i Kształtowanie Środowiska (2019), 28 (2), 192–202
Prz. Nauk. Inż. Kszt. Środ. (2019), 28 (2)
http://iks.pn.sggw.pl
DOI 10.22630/PNIKS.2019.28.2.18

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Using meta-networks to analyse the impact of adverse random events on the time and cost of completing construction work

Key words: meta-network, dynamic network analysis (DNA), planning construction projects, risk

Introduction

Exceeding the budget or delays in a project's schedule are one of the major problems of carrying out construction projects. The primary cause of such situations is a high level of risk and uncertainty that accompanies such projects. Kasprowicz (2001, 2003) divided risk and uncertainty in constructions projects into situational, works and resources-related risk and uncertainty. Quantifying risk requires the identification of risk factors, determining the probability (objective and, for some factors, also subjective) of their occurrence and defining their results (the impact of risk factors on carrying out a project) (Baloi & Price, 2003; Brooks, 2003; Skorupka, 2007; Zou, Zhang & Wang, 2007). When adopting a systemic approach, a construction project should be treated as a complex system composed of various elements, e.g. human, equipment and material resources, as well as knowledge and tasks that are mutually connected (they remain in specific relationships) (Zhu & Mostafavi, 2014). In recent years studies have noted the fact that in the traditional approach to risk quantifying, the impact of the system on relationships between risk factors and their consequences is often neglected (Zhang, 2007; Dikmen, Birgonul & Fidan, 2008; Vidal & Marle, 2012). In order to solve this problem, Zhang (2007) proposed to quantify risk in construction projects by assessing a project's vulnerability ("A system's vulnerability represents the extent or the capacity of this system to respond to or cope with a risk event".) Investigating those characteristics of a system that affect the possibility of the occurrence of a risk event is an essential element in vulnerability management (Adger, 1999; Brooks, 2003; Ezell, 2007). A system's vulnerability is its internal characteristic and plays no when no threats have emerged (Zhang, 2007). Lowering the impact of risk on a project does not cause a lowering of its vulnerability (Agarwal & Blockley, 2007). For instance, lowering a project's vulnerability to potential financial losses and delays associated with the theft of materials from the construction site is not a result of theft insurance (as a risk reaction strategy), but of appropriately securing a construction site, e.g. by properly posting security personnel, locking up storehouses etc. (Dikmen, Birgonul & Fidan, 2008). The lower a system's vulnerability to a threat is, the less probable its effects become and the system's capacity to cope with these effects is more effective (Buckle, Marsh & Smale, 2001). Identifying and eliminating a system's weak points is thus important in order to address risk and improve the system's adaptive capacity to undesirable occurrences (Prowse, 2003). Most of existing research on identifying construction project vulnerability has a qualitative character (Zhang, 2007; Dikmen, Birgonul & Fidan, 2008). A quantitative perspective on the problem was proposed by Zhu and Mostafavi (2014, 2015), who used network theory for this purpose. In their approach, projects are mapped as meta-networks featuring various types of nodes (i.e. human resources, information, equipment, materials and tasks) and links between them. A gap in a system (that is described using meta-networks) is defined as a decrease in the coherence (due to losing some of its nodes and links) of the meta-network as a result of perturbations caused by risk factors. Furthermore, Zhu and Mostafavi (2014, 2015), by combining the characteristic of a project's vulnerability to risk and its adaptive capacity, defined the concept of system or project resilience and then investigated the correlation between these characteristics.

Scope and goal of research

The concept of meta-networks presented in literature, as a basis for the modelling and analysis of planned construction projects to adverse events, has certain limitations.

First, system vulnerability is defined as a decrease in a meta-network's coherence (as a result of losing some of its nodes and links) due to perturbations caused by risk factors. However, construction projects evolve over the course of being carried out, e.g. additional or replacement works might become necessary, which means that new nodes and links should be introduced into the meta-network structure model of such a planned project, with specified probabilities of their occurrence.

Second, the meta-networks proposed in literature for analysing construction project vulnerability do not take the weight of links between nodes into consideration. Such weights could define a partial loss of a given link as a result of random events (e.g. a partial absence of a given contractor's human resources during a project's stage), instead of their complete loss.

Third, analysing a planned construction project solely features an analysis of deviations from the planned completion deadline. There are no analyses of deviations in terms of cost, which, apart from deviations involving delays, are the most often noted effect of risk on a construction project (Skorupka, 2007).

In this work, the author expanded the meta-network model and the scope of its analysis by eliminating the abovementioned constraints for the purposes of analysing construction project schedules in a more comprehensive manner. The approach was tested on an example of a project involving renovation work performed on a historical structure located in Kraków.

Problem modelling and structural analysis

Meta-network concept as a model of a planned construction project

In the 1990's Krackhardt and Carley (1998) introduced the concept of meta-networks with the PCANS model (Precedence, Commitment of resources, Assignment of individuals to tasks, Networks of relations among personnel and Skills linking individuals to resources), which became the foundation of network studies, along with the concept of dynamic network analysis.

In a mathematical sense, a meta-network is based one graph, which is composed of two sets of known units, U and V, and a set of relations: $E \in U \times V$. When for $i \in U$ and j $\in V$ element $(i, j) \in E$ that means that there exists a relationship between units i and j. These units and the relations between them are represented by a set of networks called a meta-network (Li, Qian, He & Duan, 2014; Śladowski, in print). The table presents a meta-matrix with 15 basic types of networks forming a meta-network that can be used to model a planned construction project.

Depending on needs, the node set can be supplemented to include new vertices. Ten types of such vertices have so far been distinguished in literature, making it possible to create 55 different networks as a part of a meta-network.

TABLE. Meta-matrix containing 15 basic types of networks which define the structure of a meta-network (based on Śladowski, in print)

U	*V*				
	Agent	Function	Knowledge	Resource	Task
Agent (individual or organisation)	Social Network (AA): *Who works with whom?*	Agent function network (AF): *Who does what?*	Agent knowledge access network (AK): *Who knows what?*	Agent resource access network (AR): *Who uses what machinery and what materials do they use*	Agent task assignment network (AT): *Who is assigned to which task?*
Function	×	Function network (FF): *What are the relationships between functions?*	Network of knowledge necessary to fulfil functions (FK): *What knowledge does fulfilling a given function require?*	Network of resources needed to perform functions (FR) *What resources does a given function require?*	Network of functions assigned to different tasks (FT): *What tasks are performed by each function?*

TABLE cont.

U	V				
	Agent	Function	Knowledge	Resource	Task
Knowledge	×	×	Knowledge network (KK): *What are the dependencies between knowledge*	Network of knowledge needed for resources to be used (KR): *What knowledge is necessary for the use of which resource*	Knowledge task assignment network (KT): *What knowledge is assigned to which task*
Resource	×	×	×	Resource network (RR): *What are the dependencies between resources*	Resource task assignment network (RT): *Which resources are assigned to which tasks*
Task	×	×	×	×	Task network (TT): *What are the dependencies between tasks*

Network model structural analysis using Monte Carlo simulation

The structural analysis of the impact of adverse random events on the time and cost of completing a planned project can be performed using Monte Carlo simulation. As a part of the simulation, existing nodes and links are removed from the meta network or new nodes and links are added, in addition to the weights of these links being changed, as a result of the impact of risk factors on the project modelled by the meta-network.

For an l number of random input generations, the following is computed after every l input generation.

Project vulnerability to the adverse effects of risk factors, for the assessment of which proposed structural coherence analysis (Reminga & Carley, 2003; Zhu & Mostafavi, 2015). A system's vulnerability will be defined by the number of tasks that cannot be performed due to the absence of the necessary knowledge, resources or agents fulfilling an appropriate function for said tasks. The number of these tasks can be determined using the following formulae.

For example, for the necessary knowledge:

$$\mathbf{N_k} = (\mathbf{AT'} \cdot \mathbf{AK}) - \mathbf{KT'} \tag{1}$$

$$S_k = \{t \mid t \in T, \exists k : \mathbf{N_k}(t,k) < 0\} \tag{2}$$

where:
$\mathbf{N_k}$ – knowledge gap matrix,
$\mathbf{AT'}$ – transposed agent-task relationship matrix,

AK' – matrix of agent-knowledge relationships,
KT' – transposed knowledge-task relationship matrix,
S_k – number of tasks that cannot be performed due to the lack of necessary knowledge.

Analogous formulae are used in the context of the remaining elements (agents, functions or resources). A task will not be possible to perform if even a single one of the elements required for it to be performed is missing.

The adaptive capacity of a planned project to new conditions.

Tasks $W = \{1, \ldots, n\}$ the dependencies between the tasks of a planned project are defined by the task neighbourhood matrix **TT**. Task i is the predecessor of task j.

The completion deadline of task j can be calculated based on the following formula (Zhu & Mostafavi, 2017):

$$S_j = \max\{S_i + t_i\}, \text{ if } i \to j i \in W, j \in W \tag{3}$$

where:
S_j – completion deadlines of predecessors of task j,
t_i – task predecessor completion times.

The project completion deadline is defined by the following formula:

$$D = S_n + t_n - S_1 \tag{4}$$

where:
D – project completion deadline,
S_n – completion deadline of the project's final task,
t_n – completion time of the project's final task,
S_1 – completion deadline of the project's initial task.

The project completion cost is determined by the following formula:

$$C = \sum_{i=1}^{n} c_i, \; i \in W \tag{5}$$

where:
C – project completion cost,
c_i – cost of performing task i as a part of carrying out the project.

Interference in the structural coherence of the planned project's meta-network as a result of perturbations caused by random events leads to a situation in which the completion times and cost of tasks that cannot be carried out due to the loss of an agent with an assigned function, knowledge or resource necessary for its completion can increase through the project's adaptive capacity.

The new completion time after its extension is calculated according to the following formula (Zhu & Mostafavi, 2017):

$$t_{in} = t_{ip} + \max\{d_l\} i \in W \tag{6}$$

where:
t_{in} – new completion time of a task i,
t_{ip} – initial completion time of a task's predecessors,
d_l – value by which the initial completion time of task i becomes extended as a result of a response to disruption l (the loss of: an agent with an assigned function, piece of knowledge or resource that is necessary to complete the task).

The new cost after the increase is calculated using the formula below:

$$c_{in} = c_{ip} + \sum_{l=1}^{L} c_l, \; i \in W \tag{7}$$

where:
c_{in} – new cost of completing task i,
c_{ip} – initial cost of completing task i,

c_l – value by which the initial cost of completing task *i* will increase in response to disruption *l* (the loss of: an agent with an assigned function, piece of knowledge or resource that is necessary to complete the task).

Ultimately, the effect of the impact of adverse effects on a planned project is defined by completion deadline *D* (Zhu & Mostafavi, 2017) and cost *C* deviations from the planned values: *PD* and *PC*, respectively, according to the following formulae:

$$\text{schedule deviation } (SD) = D - PD \quad (8)$$

$$\text{cost deviation } (CD) = C - PC \quad (9)$$

Based on the results of each random input generation *l* we can plot a histogram of the empirical distribution of deadline and cost deviations for a planned project, along with the parameters of this distribution.

Case study

The case study is associated with the remodelling of a manoeuvring area along with its building services installations at Westerplatte Street in Kraków, which was carried out in the period 2016/2017 (Fig. 1). The structure in question is listed as a heritage site. The reason for the State Fire Department manoeuvring area's remodelling was the worsening condition of its surface layer along with the necessity to increase its load bearing capacity for functional reasons and to improve surface runoff drainage. The scope of the project included: dismantling the existing porphyry cobblestone surface (assuming maximum possible reuse) along with its subbase, deepening the trench, remodel building services installations, constructing an improved subbase and base, and placing a new surface layer from granite and reused porphyry cobblestone. A series of previously unplanned events took place over the course of carrying out the construction work, e.g. the improved subbase layer turned out to have an insufficient load-bearing capacity, previously unknown and unsurveyed underground infrastructure was discovered along local findings of archaeological relic fragments. These events resulted in the performance of replacement and additional work. There were also problems with providing the necessary manpower, particularly during the stage of laying the surface cobble-stone layer, as well as the fact that procedures associated with analysing the stone materials and the load-bearing capacity of the sub-base took longer to complete than expected.

Due to the work taking place on a so-called active facility (the remodelled facility operated normally during construction work), the scope of the project was divided into several work plots (stages when referred to divisions of the area's surface), which were consecutively worked on. For the purposes of this article, the impact of adverse effects on the completion time and cost of the planned final project stage.

The author used a tool called the Organizational Risk Analyzer (ORA), developed at the Center for Computational Analysis of Social and Organizational Systems (CASOS) by Kathleen Carley (CASOS, 2018) to build the structure of the meta-network of the analysed stage of the planned project (Fig. 2).

FIGURE 1. State Fire Department in Kraków manoeuvring area's remodelling: a – trenching and constructing the structure of linear drainage; b – constructing the primary base from aggregate; c – primary base testing; d – laying the surface cobblestone layer from porphyry; e – the end result

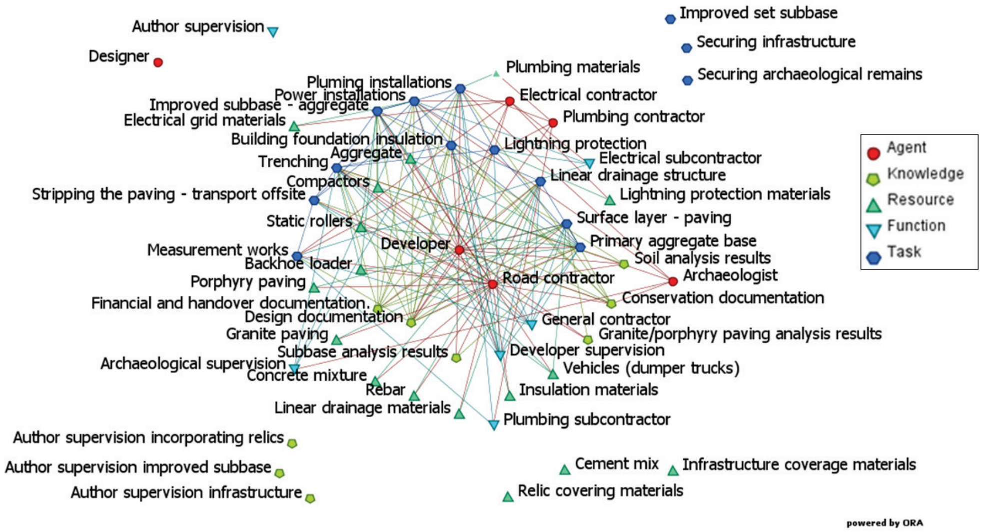

FIGURE 2. Meta-network of the analysed construction project stage (the Organizational Risk Analyzer)

TABLE 2. Events with a probability of their occurrence and their corresponding meta-network perturbations

Event along with the probability of its occurrence	Planned project meta-network perturbations
Lack of appropriate primary base analysis results (0.25)	Removing a knowledge node and its links – appropriate primary base analysis results
The existing cobblestone is not fit for reuse (0.10)	Removing a knowledge node and its links – appropriate existing porphyry cobblestone testing results
Discovery of unsurveyed underground infrastructure (0.30)	Adding the following nodes and their links: task node – securing infrastructure, knowledge node – author supervision of securing work, material node – materials for securing infrastructure, knowledge node – handover documentation, agents and their function nodes – contractor, designer, developer supervision inspector
Discovery of archaeological relic fragments (0.15)	As above, adding nodes and their links in reference to securing archaeological relic fragments
The existing subbase requires reinforcement (0.50)	As above, adding nodes and their links in reference to constructing a subbase reinforcement layer
Problems with author supervision concerning subbase reinforcement under the condition that the existing subbase requires reinforcement (0.30)	Removing a knowledge node and its links – author supervision concerning subbase reinforcement under the condition that the event necessitating subbase reinforcement takes place
Decrease in general contractor employee numbers by half (0.40)	Lowering the weight (from value 1.00 to 0.50) for general contractor node links with nodes representing tasks

The case study used findings from observations (repeatable in terms of scope) of previous stages of the project to identify direct events that are adverse to the project and that can potentially affect the carrying out of the analysed project stage. However, due to a lack of sufficient empirical data, the probability of the occurrence of these events was defined subjectively. Table 2 lists events with a probability of their occurrence and, for the purposes of analysing the schedule, their corresponding meta-network perturbations.

Results

As a result of using the Monte Carlo simulation method (random inputs generation l was performed 1,000 times) and using the abovementioned formulae for project vulnerability and its adaptive capacity (for the assessed completion time and cost increases for individual tasks after perturbations, e.g. lack of appropriate primary base analysis results in there being no possibility of work base approval, which extends completion time by $d_l = 3$ days), the author calculated the impact

TABLE 3. Mean values of time and cost deviations from planned values as a measure of the impact of adverse random events on the time and cost of completing the final stage of the planned project

Planned deadline (*PD*) [days]	Average value of completion deadline *D* as a result of adverse random events impact [days]	*SD* [days]	Average schedule deviation value (*SD*) [days]	Planned cost (*PC*) [PLN]	Average value of costs *C* as a result of adverse random events impact [PLN]	*SD* [PLN]	Average cost deviation value (*CD*) [PLN]
33	46.61	10.61	13.61	18 9140	217 026.30	24 773.25	27 886.30

of adverse random events on the time and cost of the final stage of the planned project (Table 3).

Conclusions

The analysis of the impact of adverse random events on completion time and cost of planned construction work is a starting point for considering the introduction of changes to the system in order to make it even less vulnerable to threats and even more adaptable to changes in conditions caused by risk factors. The proposed examples of changes include: hiring subcontractors as an answer to the potential absence of the general contractor's employees, securing shipments of new porphyry cobblestone in order to shorten wait time in cases when existing cobblestone is not fit for reuse, prior testing of the soil subbase reinforcement process, e.g. by pre-emptively setting up experimental fields.

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Summary

Using meta-networks to analyse the impact of adverse random events on the time and cost of completing construction work. According to the concept of a system--based approach, a construction project can be treated as a complex system composed of various elements, such as human, equipment and material resources, as well as knowledge and tasks that are mutually interlinked. In the classical approach to construction project risk assessment, the impact of the "system" in the analysis of relationships between risk sources and their consequences has so far been neglected. The concept of construction project vulnerability and its adaptability has appeared in literature in recent years. It is analysed on the basis of a project's vulnerability to the impact of risk factors and its adaptive capacity is seen an answer to project perturbations caused by adverse random events. As a part of developing the system-based approach to analysing construction project schedule, the author further developed the concept of modelling planned construction projects with relationship meta-networks composed of four types of nodes: agents (human resources), knowledge, equipment and material resources and tasks. The author included possible deviations from the planned project's budget in the schedule vulnerability and adaptability analysis, instead of only focusing on deviations from its completion deadline. An analysis of the occurrence of additional and replacement work was introduced by the author, which further developed the concept of the simulated evolution of such networks to include the capacity to introduce

new nodes and links into their structure. Furthermore, the author used the potential of weighted meta-networks to model certain dependencies within the planned project. A simulation-based approach as a part of DNA (dynamic network analysis) was used to analyse the vulnerability and adaptability of such networks. The proposed approach was presented on the example of a renovation project performed on a historical structure. The conclusions drawn from the author's analyses can be used to formulate construction project schedules that are less vulnerable to perturbations and are characterised by greater adaptability. In the future, the author plans to expand the analysis presented above to include dependencies in single-mode networks (e.g. in agent, resource or knowledge networks) on the meta-network of a project.

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