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Research paper

Assessment of the effectiveness of communication between the participants of a construction project utilizing meta-network theory: a case study

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Abstract: This paper investigates the fact that construction projects, due to their specificity, are complex, temporary and dynamic. Over their course, participants change, successive construction works are done and new information becomes available. This carries over to difficulties in communication. In the literature, numerous studies note the fact that a network-based approach to the analysis and monitoring of communication as a part of complex construction projects is commendable. Relations between agents, knowledge and tasks in the context of communication within a construction project can be visualized in the form of a meta-network, and suitably developed structural measures can be used to analyze them.

In this paper, the authors used meta-network theory to analyze relations between project participants, knowledge and tasks in the context of communication within a construction project, on the basis of the construction of a housing estate located in Katowice, Poland. Meta-network structural analysis allowed for a deeper understanding of these relations and the detection of essential information about the level of communication in the project under investigation, which was a basis for further discussion. The authors also stress the benefits from the approach presented and argue that it should be a starting point for effective management in the sphere of communication in construction companies.

Keywords: construction management, communication, Dynamic Network Analysis (DNA), information flow, Meta-networks

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1. Introduction

The development of the construction industry led to a situation in which construction processes have become an increasingly dynamic and complex activity [1]. Likewise, awareness of the need to manage projects more efficiently in the construction industry has become greater [2]. In numerous publications, researchers identified difficulties and challenges to managing construction projects [3]. Managing construction projects following a traditional approach focuses primarily on planning tasks and assigning renewable (people, equipment) and non-renewable (materials) resources. Over the course of a construction project, attention is primarily focused on organizing and assigning resources to tasks and monitoring their progress, along with control of any deviations from the plan and budget, as well as any possible correcting procedures. The various management techniques used to do so do not include in their analysis the relations between construction project participants, the tasks that they work on and the knowledge they possess. It should be noted that such interactions between people, organizations and tasks are the basis for a complex system of communication in construction companies. Such systems cannot be described using simple equations – they must be expressed as networks [4].

Effective cooperation in the dimension of information binds complex systems. Examples of procedures that make partnering cooperation between construction project participants more effective, and which includes open, bilateral communication, was presented in [5, 6]. An analysis of partnering cooperation in construction projects in selected countries was presented in [7], and the impact of partnering cooperation on the success of a construction project was discussed in [8].

Monitoring information flow over the course of a construction project could provide information on the state of communication and cooperation between its actors. It would therefore be necessary to define key participants, knowledge and tasks, and to investigate their interrelations in the project. Verifying the actual state of communication between project actors would reveal any irregularities in this respect and identify change trajectories so as to effectively manage communication in the project.

2. Literature review

When one manages a construction project, it is essential to focus on communication management, as evidenced by a literature review and survey study presented in the authors' previous paper [9]. A network-based approach appears to be suitable for investigating this matter. Kisielnicki [10] found that network-based communication provides the most effective framework for project management. It should be noted that multiple authors utilized Social Network Analysis (SNA) in their studies on communication in the construction sector. The concept of SNA was first proposed by sociometry, introduced in the previous century by J.L. Moreno [11]. Since the 1970s, considerable progress has been made in research on social networks using graph theory, and they have been applied in many disciplines such as economics, information science and management. The subject matter of SNA application in construction is diverse, and it often applies to communication. One of the first applications of SNA in construction was an analysis of communication problems between key figures involved in a project, namely clients, project managers, architects and site directors [12, 13]. Using SNA, researchers investigated the dependence between the spread of integrated knowledge and the structure of links within a network [14]. The authors of [15] analyzed the frequency of communication, the modes of communication, and the impact of the connections structure on its effectiveness within specialist crews in the context of occupational health and safety (OHS). The authors of [16] applied SNA to manage shifts in a construction project via effective communication between various project participants with the intent to control delays and costs. Swan, McDermott and Khalfan [17] built a network model using SNA and presented how information can flow through a construction project's network model. In their study, they also noted the essentiality of trust in communication between project participants. Arriagada and Alarcón [18] proposed a model of designing strategies of knowledge management in a construction company, which was developed with the use of social network analysis (SNA). Trach and Bushuyev [19] argued that communication networks are an element of knowledge management systems in construction projects and aid in organizing and maintaining information links between project participants. The authors of this paper also used SNA in their previous studies [20, 21]. They investigated a self-organizing network of communication between agents who participated in the construction of a housing complex. The structural analysis of this network allowed for its deeper understanding and the detection of certain irregularities and dysfunctions on the part of certain participants [20]. Due to the detection of dysfunctional communication between the project's participants from the standpoint of the expectations of project management staff, the authors [21] identified potential avenues of intervention that could enhance communication within the network. They proposed an optimization method for planning such projects, that accounted for various constraints, and which led to the identification of possibilities for improving communication effectiveness within such a network [21].

However, analyzing communication between project participants from the standpoint of a single-mode network, whose analysis employs SNA, does not allow for the identification of direct factors that determine this communication. This analysis focuses solely on interactions between project participants and does not identify the direct relations between participants and the knowledge and tasks they perform. To understand the specificity of communication and to manage it within a construction project, one must first understand the formal organizational structure of the project, analyze its schedule and determine the necessary knowledge, whose exchange between project agents determines the character of said communication. Modeling and analyzing such a system of elements and relations is possible using meta-network theory. Studies using meta-networks and their dynamic analysis in the construction sector have only recently begun to develop. In [22], meta-networks were used to identify key agents, knowledge and resources needed to complete tasks performed as a part of construction projects. The authors of [23], using the case of the construction of a chain of car dealerships in China, used meta-network analysis to optimize the effectiveness of these projects based on the assignation of participants to individual tasks based on their knowledge, either pre-existing or obtained as a result of training. In [24, 25], researchers used value theory to analyze construction project resilience to risk factors.

Using the potential of meta-networks, the authors of proposed an optimization approach to planning and monitoring the required communication between construction project participants. In a continuation of this study [27], they proposed a quantitative approach to assessing communication between construction project participants in the aspect of its impact on project completion cost and time. The proposed method, due to the application of meta-network analysis, allowed for the dynamic identification of key information flow paths between project participants, and which significantly determined its performance.

However, the basis for the application of the communication management methods presented above should be formed by its detailed diagnosis at a given project completion stage. Selected meta-network structural measures can be used to perform such a diagnosis.

The objective of this paper is to determine key participants, knowledge and tasks and to identify their interdependences within a construction project using meta-network structural analysis. This analysis was performed on the example of the construction of a multi-family housing complex in Katowice, Poland. The findings yielded valuable information on communication and cooperation within this project.

3. Study overview

3.1. Meta-network model structure

To create the structure of dependences between project agents, knowledge and tasks, the authors used the concept of meta-networks [28].

A set of networks was constructed, wherein each network was based on a directed graph, which consisted of a set of two elements U and V, as well as a set of relations: : $E \subset U \times V$. Each pair of elements $(i, j) \in E$ for $i \in U$ and $j \in V$, denotes a relation between i and j. Network sets that express such relations is called a meta-network [22,23,27,29,30].

The set of networks within a meta-network can be represented by a set of matrices, whose graphical interpretation for the sample three node classes: agents (interpreted as either individuals or organizations), knowledge and tasks, has been presented in Table 1.

The literature includes numerous structural measures [31, 32] that provide a diverse array of information about dependences that a given network models. Some of these measures can be used in the context of analyzing the effectiveness of communication in a construction project. For the purposes of this paper, the measures were implemented in the Python programming language.

Table 1. Meta-network including matrices that represent six types of networks within three classes

V **U**	**A** (Agent)	**K** (Knowledge)	**T** (Task)
A (Agent)	**(AA)** Who communicates with whom	**(AK)** What knowledge does a given agent possess	**(AT)** What tasks a given agent performs
K (Knowledge)	*	**(KK)** What is the dependence between pieces of information	**(KT)** What tasks can be completed with specific knowledge
T (Task)	*	*	**(TT)** What is the dependence between tasks

3.2. Meta-network structure of the project under analysis

The construction project that was analyzed as a part of this study was the construction of a multi-family housing complex located in northern Katowice, Poland. The complex included four six-story buildings (around 12,000 m^2 of usable area), with service facilities on the ground floors, underground garages, utilities and road infrastructure. The project began in the first half of 2016 and concluded in December 2019. The project budget was around 40 million PLN. Up to September 2018, the project was conducted by a general contractor. Due to the situation on the construction market at the time (high material and service prices and the lack of qualified tradesmen), the General Contractor declared bankruptcy, which led to the Developer and General Contractor to end their partnership. The Developer decided to finish the project by employing a management cadre of their own and by signing contracts directly with contractor companies. These new contractual relations between parties (organizations) and the new formal project organizational structure were presented in the author's previous study [20]. The data for this study was collected after the restructuring of the project. Using a survey, information was collected from all of the project's 28 participants concerning who they communicated with over the project's course in the previous month and what knowledge/information they had access to and what were the tasks they performed.

On this basis, the authors determined the structure of dependences between the participants, knowledge and tasks within the project with the use of meta-network, as presented in Fig. 1 (the annotation of meta-network nodes has been presented in Tables 2, 3 and 4).

Table 2. Meta-network node description — participants (agents)

Symbol	Description
A1	Developer supervision coordinator
A2	Electrical supervision coordinator

Continued on next page

Table 2 – *Continued from previous page*

Symbol	Description
A3	Sanitary supervision coordinator
A4	Project Manager
A5	Site manager
A6	Works manager
A7	Site engineer
A8	Architect
A9	Coordinator in charge of client revisions
A10	Design office
A11	Electrical services design office
A12	Sanitary services design office
A13	Company responsible for applying plaster
A14	Company responsible for applying plaster finishes and drywalls
A15	Electrical company
A16	Subcontractor of the electrical company
A17	Flooring company
A18	Garage door supply and assembly company
A19	Window supplier
A20	Company building the roof and terraces
A21	Door supplier
A22	Central heating and plumbing services company
A23	HVAC company
A24	Facade and finish and balcony tiles company
A25	Railing supply and assembly company
A26	Masonry company erecting partition walls
A27	External building services company
A28	Landscaping company

Table 3. Meta-network node description – knowledge

Symbol	Description
K1	Technical design
K2	Detailed design – architecture
K3	Detailed design – structural system
K4	Detailed design – plumbing services
K5	Detailed design – electrical services
K6	Client amendment protocols

Continued on next page

Table 3 – *Continued from previous page*

Symbol	Description
K7	Surveying documentation (axis demarcation and as-built documentation)
K8	Facade works handover protocols
K9	Plumbing services handover protocols (tightness tests)
K10	Electrical services handover protocols
K11	External building services handover protocols
K12	HVAC handover protocols
K13	Technical approvals and compliance statements
K14	Material approval protocols
K15	Concrete strength test protocols

Table 4. Meta-network node description – tasks

Symbol	Description
T1	Reinforced concrete railing handrail delivery and assembly Bld B
T2	Northern facade, light-wet method Bld B
T3	Southern facade, light-wet method Bld B
T4	Western facade, light-wet mehod Bld B
T5	Balcony insulation Bld B
T6	Western facade – laying tiles on balconies Bld B
T7	Southern facade – laying tiles on balconies Bld B
T8	Western facade – balcony railings delivery and assembly Bld B
T9	Southern facade – balcony railings delivery and assembly Bld B
T10	Reinforced concrete railing flashing Bld B
T11	Primary electrical services Bld B
T12	Electrical services in apartments and premises Bld B
T13	Plasters Bld B
T14	Applying putty to partition walls Bld B
T15	Floor laying Bld B
T16	Apartment and corridor insulation mats (drywalls) Bld B
T17	Plumbing and storm drain services Bld B
T18	Domestic hot water services Bld B
T19	Central heating services Bld B
T20	Mechanical ventilation Bld B
T21	Assembly of technical doors and doors to tenant storage rooms Bld B
T22	Garage door assembly Bld B
T23	Western facade – roads and pavements Bld B

Continued on next page

Table 4 – *Continued from previous page*

Symbol	Description
T24	Building partition walls Bld C
T25	Plasters Bld C
T26	Applying putty to partition walls Bld C
T27	Window montage Bld C
T28	Primary electrical services C
T29	Electrical services in apartments and premises Bld C
T30	Plumbing and storm drain services Bld C
T31	Domestic hot water services Bld C
T32	Central heating services Bld C
T33	Mechanical ventilation Bld C
T34	External works – drainage and storm drain grid Bld C
T35	External works – water supply connection Bld C
T36	Storm drain connection Bld C
T37	Sewerage connection Bld C
T38	Water supply connection Bld C
T39	Building partition walls Bld D
T40	Building tenant storage rooms Bld D

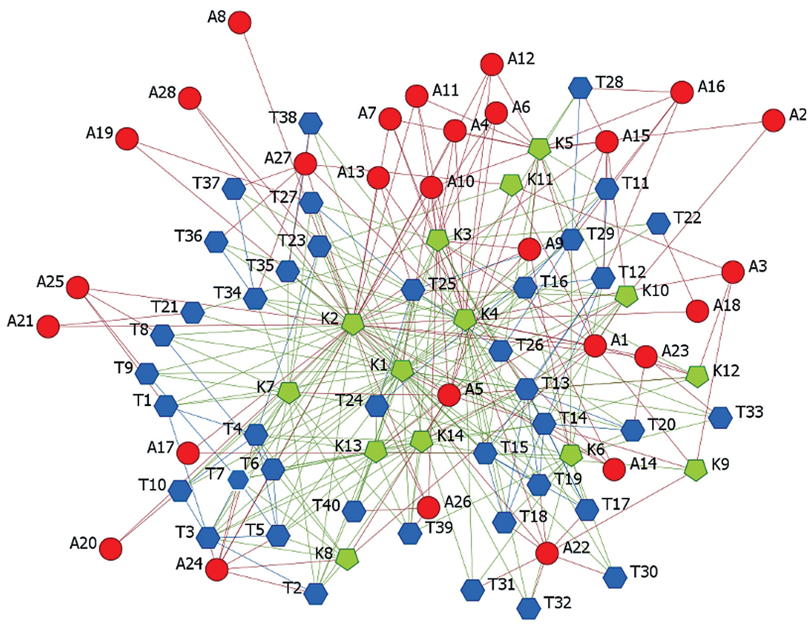

Fig. 1. Meta-network of the project under analysis

3.3. Structural analysis of the meta-network of the case under study

The structural analysis of the resultant meta-network of the construction project was based on selected distinctive structural measures for multi-modal networks [31] such as:

- Degree,
- Exclusivity,
- Redundancy,
- Access,
- Load,
- Congruence,
- Performance,
- Negotiation,
- Workload.

Essential symbols used in equations:

A	–	Capital letters denote square matrices, e.g., depicting linkages between agents
$\mathbf{A}$	–	Capital letters in bold denote a matrix that is the result of calculations
AK	–	A matrix, e.g., of the links between agents and knowledge
$\lvert A\rvert$	–	The number of elements within a matrix
$\lvert AK\rvert$	–	The product of the number of rows and columns within a matrix
$A(i;j)$	–	Position within a matrix's row i and column j
$\sum(A)$	–	The sum of all elements within a matrix
A'	–	A matrix's transposition, namely the rows and columns are switched
		card(set) Cardinality of a set

Degree is a measure that represents the number of connections between an agent and knowledge [32–34]. The degree value ranges between 0 and 1. In the case of an AK network, the standardized degree of row **d** for agent i has the following form [31, 33]:

$$\mathbf{d}_i = \frac{\sum_{j=1}^{|K|} AK(i,j)}{|K|} \tag{3.1}$$

When we analyze the measure of the degree of the connection with knowledge (Table 5), we can see that the site director has almost all the knowledge necessary to perform tasks within the period under study (93%). A slightly lower, yet still significant access to information belonged to the development supervision coordinator. In reference to previous research [20], which analyzed the measures of the network of communication between project participants, it was found that the site director was poorly linked with other agents. It should be noted that the site director has a significant amount of knowledge, which should carry over to the number of links with agents who need information to perform their tasks. At the same time, the previous study [20] indicated a high number of links with the development supervision coordinator, who also had a great deal of knowledge. It is possible that this situation was caused by the fact that the developer supervision coordinator, as a representative of the developer, was involved in engaging in cooperation with specific contractors, which means they had known them for longer than the site director, who was probably just beginning to form relations with contractors after the project's reorganization.

A network's analysis in terms of **exclusivity** allows one to find which agent in the network knows something that no other agent knows. The higher the value of this measure, the more exclusive information a given agent has access to. An agent's knowledge exclusivity index x is determined as follows [31, 35]:

$$x_i = \sum_{j=1}^{|K|} \left[AK(i,j) \cdot \exp\left(1 - \sum_{i}^{|A|} AK(i,j)\right)\right] \tag{3.2}$$

Based on the results for exclusivity (Table 5), it was found that key agents in terms of access to knowledge that no other agents had included the site director (a measure value of 3.07) and the coordinator in charge of client revisions (a measure value of 1.00). They were of unique significance to the functioning of the project. Due to the specific moment of the project's performance – a change in management mode from a general contractor model to a package system and the collection of data for study in the initial phase (a month after the reorganization), all the information may not have been available to relevant agents.

Table 5. The degree of connectedness between agents and knowledge in the project under analysis and the measure of the degree to which agents are linked to exclusive knowledge within the project

Agent	Degree	Exclusivity
Developer supervision coordinator	**0.71**	$7.03 \cdot 10^{-1}$
Electrical supervision coordinator	0.14	$4.98 \cdot 10^{-2}$
Sanitary supervision coordinator	0.29	$1.49 \cdot 10^{-1}$
Project Manager	0.29	$1.46 \cdot 10^{-4}$
Site manager	**0.93**	**3.07**
Works manager	0.29	$1.46 \cdot 10^{-4}$
Site engineer	0.29	$1.46 \cdot 10^{-4}$
Architect	0.07	$3.78 \cdot 10^{-11}$
Coordinator in charge of client revisions	0.36	**1.00**
Design office	0.36	$3.68 \cdot 10^{-1}$
Electrical services design office	0.29	$1.46 \cdot 10^{-4}$
Sanitary services design office	0.29	$1.46 \cdot 10^{-4}$
Company responsible for applying plaster	0.07	$3.78 \cdot 10^{-11}$
Company responsible for applying plaster finishes and drywalls	0.07	$3.78 \cdot 10^{-11}$
Electrical company	0.21	$4.98 \cdot 10^{-2}$
Subcontractor of the electrical company	0.07	$1.67 \cdot 10^{-12}$

Continued on next page

Table 5 – *Continued from previous page*

Agent	Degree	Exclusivity
Flooring company	0.07	$3.78{\cdot}10^{-11}$
Garage door supply and assembly company	0.07	$3.78{\cdot}10^{-11}$
Window supplier	0.07	$3.78E{\cdot}10^{-11}$
Company building the roof and terraces	0.07	$3.78{\cdot}10^{-11}$
Door supplier	0.07	$3.78{\cdot}10^{-11}$
Central heating and plumbing services company	0.21	$4.98{\cdot}10^{-2}$
HVAC company	0.21	$4.98{\cdot}10^{-2}$
Facade and finish and balcony tiles company	0.14	$1.35{\cdot}10^{-8}$
Railing supply and assembly company	0.07	$3.78{\cdot}10^{-11}$
Masonry company erecting partition walls	0.14	$1.23{\cdot}10^{-4}$
External building services company	0.21	$4.98{\cdot}10^{-2}$
Landscaping company	0.07	$3.78{\cdot}10^{-11}$

Redundancy allows us to determine the spread of a given piece of knowledge. Redundancy is a network-level measure.

This measure results in the average number of excess agents for every piece of knowledge. For every column j in matrix AK, we calculate the following [4, 31]:

(3.3) $$d_j = \max\left[0, \sum_{i}^{|A|} AK(i,j) - 1\right]$$

Redundancy $\mathbf{r}$ is thus:

(3.4) $$\mathbf{r} = \frac{\sum_{j=1}^{n} d_j}{|K|}$$

from:

(3.5) $$\mathbf{r}_{\max} = (|A| - 1)$$

Redundancy for the project under analysis indicated that, on average, 6 agents had the same scope of knowledge about the project. It is essential to note that an organization with low redundancy is more vulnerable to the negative consequences of the absence of an agent with a given piece of knowledge. On the other hand, excessive redundancy means that an organization is becoming ineffective due to information chaos [37]. As this number of agents in the project had access to the same information, this allows for accessing the necessary knowledge without unnecessary obstacles should a specific employee be absent.

It also does not rule out the previously mentioned fact, that some types of knowledge were in possession of only a single agent.

The **access** index identifies links to critical knowledge. The index of access to information first identifies agents who have exclusive links to specific knowledge [29]. If such an agent is also linked to just one other agent in the network, then both have critical access. For each agent, a set of exclusive knowledge is calculated in the case when an agent is linked to just one other agent [31,35]:

$$K_i = \{k|AK(ik) \wedge \left(\sum_{i}^{|A|} AK(i,j) = 1\right) \wedge \left(\sum_{j}^{|A|} AA(i,j) = 1\right) \tag{3.6}$$

For agent i, **a** is binary and is calculated as:

$$\mathbf{a}_i = ((K_i \neq \phi) \vee (\exists j | K_j \neq \phi \wedge A(j,i) = 1)) \tag{3.7}$$

As a result of calculating the access measure, we obtained a zero matrix. All agents who had access to knowledge were found to communicate with at least two other agents. This makes cooperation easier and speeds up information flow, which certainly had a beneficial effect on the project, especially as the agents had just been getting to know the project, which was put on hold for a period of time. This can be more difficult than working on a project from its inception, as some tasks had been initiated and did not conclude and had to be continued in a proper way so as not to adversely affect the quality of the end result.

The measure of **load** also reflects complexity. The value of this measure ranges between 0 and 1. It denotes the density of a meta-network, which emerges as result of the connections between all available network types [31,32]:

$$c = \frac{card\{\forall i, j \in A | i \neq j \wedge AA(i,j) > 0\} + card\{\forall i \in A \wedge \forall t \in T | AT(i,t) > 0\}}{|A|(|A|-1) + |AT| + |AK|} + \frac{card\{\forall i \in A \wedge \forall t \in K | AK(i,t) > 0\}}{|A|(|A|-1) + |AT| + |AK|} \tag{3.8}$$

For the meta-network under analysis, the load value was 0.157, which means that the degree of load was not too high but could also result from the early phase (the first month after a reorganization) of the formation of the network of dependences between agents, knowledge and tasks within the project.

Congruence measures the similarity between the knowledge possessed by agents assigned to completing tasks and what knowledge is required to complete said tasks. The congruence value ranges between 0 and 1. Perfect congruence is achieved when agents possess exactly the type of knowledge that is necessary to carry out their assigned tasks [4].

Let **KT** be a matrix that represents knowledge assigned to tasks by agents [4,31]:

$$\mathbf{KT} = AK' \cdot AT \tag{3.9}$$

Then the congruence of knowledge is the ratio of correctly assigned knowledge [31]:

$$c = \frac{card\{(i,j)|([\mathbf{KT}(i,j) > 0) = (KT(i,j) > 0)]\}}{|K| \cdot |T|} \tag{3.10}$$

The knowledge congruence for the project under study was 0.08393. This means that the agents assigned to performing specific tasks mostly did not have the knowledge necessary to complete those tasks. This was probably caused by the fact that the contractors had just begun performing their tasks (the first month after the project's reorganization). From analyzing the remaining measures, it was known that the requisite knowledge was available in the organization and it was possible to obtain it via effective communication between agents.

Another, more elaborate measure is communication congruence, which measures the degree to which agents communicate when and only when necessary to complete a task. We assume that agents i and j have to communicate with each other, even if at least one of the situations below is true.

– when i is assigned to task t_1, and j is assigned to task t_2 and task t_1 directly precedes task t (work takeover);
– when i is assigned to task t, and j is also assigned to task t (co-assignment);
– when i is assigned to task t, and j is not assigned to this task, and there exists knowledge K to which agent i does not have access to, but agent j does (negotiation to obtain the necessary knowledge).

These three cases are calculated as follows:

$$\mathbf{H} = AT \cdot TT \cdot AT' \tag{3.11}$$

$$\mathbf{C} = AT \cdot AT' \tag{3.12}$$

$$\mathbf{N} = AT \cdot Z \cdot AK' \text{ with } \mathbf{Z}(t,k) = \begin{Bmatrix} 1 & \text{if } [AT' \cdot AK - KT'](t,k) < 0 \\ 0 & \text{otherwise} \end{Bmatrix} \tag{3.13}$$

Let **Q** be an inverse matrix of required communication:

$$\mathbf{Q}(t,k) = \begin{Bmatrix} 1 & \text{if } \left[(\mathbf{H}+\mathbf{C}+\mathbf{N}) + (\mathbf{H}+\mathbf{C}+\mathbf{N})'\right](i,j) > 0 \\ 0 & \text{otherwise} \end{Bmatrix} \tag{3.14}$$

When we compare communication between agents in terms of the three cases of required communication (matrices H, C, N) as indicated above, we can observe excessive links. At the same time, there are gaps in communication. In terms of communication necessary to complete tasks in a sequence of direct precedence, namely work takeover, there was a lack of communication between the company that installs electrical utilities and the company that applied plasterwork, and the company that applied putty to the partition walls. In terms of communication due to performing the same tasks, no gaps in communication were detected. Meanwhile in terms of communication concerning the transfer of knowledge necessary to complete tasks, there was a specific lack of relations between the site manager (who had a sizeable body of knowledge), and most contractors, such as the company that installed electrical utilities, the company that installed heating and plumbing utilities, the company that installed HVAC systems, the company that assembled external utilities, the company that installed doors or the company that built masonry partition walls.

The returned required communication matrix (Q) substantially differed from the actual communication matrix created using the data collected for the project under analysis.

Numerous agents had an excessive number of links, especially the developer supervision coordinator and specialist supervision inspectors. The comparison of both matrices also detected gaps in communication at the level of relations between the site manager and contractors, between specialist inspectors and specialist design companies and among the contractors themselves. It was also noted that the required communication matrix was not an optimal matrix in terms of the number of communication links. Significant differences between both matrices confirmed the need to manage communication between the project's agents. At the same time, any interference by the project management team in the structure of the communication network should be performed optimally in the context of intended goals.

Knowledge-based **performance** allows us to calculate the ratio of tasks that can be completed by their assigned agents solely on the basis of whether these agents possess the requisite knowledge to complete them [4]. The performance value ranges between 0 and 1. First, we search for tasks that cannot be completed, because their assigned agents lack the requisite knowledge[31]:

$$\mathbf{N} = (AT' \cdot AK) - KT' \tag{3.15}$$

We then calculate the set of tasks that cannot be completed:

$$\mathbf{S} = \{t | t \in T \wedge \exists k : \mathbf{N}(t, k) < 0 \tag{3.16}$$

Knowledge-based performance is the percentage of tasks that can be completed:

$$\mathbf{c} = \frac{|T| - |\mathbf{S}|}{|T|} \tag{3.17}$$

Negotiation is the degree to which agents must cooperate with each other due to lacking the requisite knowledge to complete their assigned tasks. The measure of negotiation allows us to calculate the ratio of tasks for which at least one piece of requisite knowledge is missing [4]. The negotiation value ranges between 0 and 1. First, we calculate the TK congruence matrix using the formula below:

$$\mathbf{C} = (AT' \cdot AK) - KT' \tag{3.18}$$

to obtain the ratio of unassigned tasks:

$$\mathbf{n} = \frac{card\{t | t \in T \wedge \exists k : \mathbf{C}(t, k) < 0}{|T|} \tag{3.19}$$

In the project under analysis, the performance and negotiation values were analyzed together. This was because the result for the project performance based on the potential to complete tasks by their assigned agents, as based on whether the agents possessed the requisite knowledge to complete these tasks, was 0. At the same time, the negotiation measure value was 1, which meant that the knowledge was available within the project, but the agents assigned to each task had to obtain information from other agents. This was probably associated with the previously mentioned reorganization and preparations by each contractor to engage in work on the project, and familiarization with specific information.

Workload measures denote the knowledge used by an agent to complete the tasks they are assigned to [4]. Potential workload associated with knowledge is defined as [31]:

$$w_i = \frac{\sum_{j}^{|T|} (AK \cdot KT)(i, j)}{\sum KT} \tag{3.20}$$

while actual workload associated with knowledge also accounts for the actual AT matrix [31]:

$$w_i = \frac{\sum_{i}^{|A|} (AK \cdot KT \cdot AT')(i, i)}{\sum KT} \tag{3.21}$$

Both measures range between 0 and 1.

Potential workload based on knowledge was found to be especially high in the case of the site director (a measure value of 0.92), with other similar agents being the design office (a measure value of 0.55) and the developer supervision coordinator (0.50). Meanwhile, actual workload associated with knowledge painted a completely different picture. The highest measure values were calculated for the company working on the facade finishes and placing balcony tiles, the company in charge of external utilities, and the company in charge of heating and plumbing utilities. Based on analysis of these measures (Table 6), we learned that a sizeable share of knowledge was in possession of the management team, which did not directly participate in tasks, while contactors who actually needed specific knowledge to complete their tasks simply did not have it, but could negotiate necessary information from the management team.

Table 6. Potential workload and actual workload associated with an agent's knowledge in the project

Agent	Potential Workload	Actual Workload
Developer supervision coordinator	**0.50**	0
Electrical supervision coordinator	0.07	0
Sanitary supervision coordinator	0.12	0
Project Manager	0.32	0
Site manager	**0.92**	0
Works manager	0.32	0
Site engineer	0.32	0

Continued on next page

Table 6 – *Continued from previous page*

Agent	Potential Workload	Actual Workload
Architect	0.12	0
Coordinator in charge of client revisions	0.4	0
Design office	**0.55**	0
Electrical services design office	0.32	0
Sanitary services design office	0.32	0
Company responsible for applying plaster	0.12	0.01
Company responsible for applying plaster finishes and drywalls	0.12	0.02
Electrical company	0.19	0.02
Subcontractor of the electrical company	0.03	0.02
Flooring company	0.12	0.01
Garage door supply and assembly company	0.12	0
Window supplier	0.12	0.01
Company building the roof and terraces	0.12	0.01
Door supplier	0.12	0
Central heating and plumbing services company	0.21	0.03
HVAC company	0.23	0.01
Facade and finish and balcony tiles company	0.16	**0.07**
Railing supply and assembly company	0.12	0.02
Masonry company erecting partition walls	0.2	0.02
External building services company	0.21	**0.04**
Landscaping company	0.12	0.01

4. Conclusions

As a result of the structural analysis of the network of relations between agents, knowledge and tasks, a great deal of diverse information about the construction project under study was obtained. The findings were closely tied with the situation in which the project had found itself in (project reorganization due to the bankruptcy of the general contractor and the adoption of a package system for subsequent work) and the moment when the data had been collected (the first month after the reorganization). It must be noted that the entire knowledge necessary to complete project tasks was available in the organization, but the agents assigned to perform tasks where this knowledge was necessary did not have it. At the same time it was found that per every single information type there were 6 agents. This is an average value, as we knew from analyzing the degree measure that it was the site manager and developer supervision coordinator who had access to almost all the information. In terms of required communication, a lack of communication between agents who performed tasks in sequence of direct precedence (e.g., the railing contractor and the facade contractor), as well as in the transfer of communication necessary to perform tasks (e.g., communication between the site director and the company that installed doors). In addition, the actual communication network was characterized by a very high number of redundant links, which could potentially cause information chaos. Based on the structural analysis presented, it should be stated that in this initial phase of the (re-) emergence of the organization, it was necessary to quickly implement management procedures targeting information flow between project agents.

The case study presented demonstrates how essential communication can be during construction projects and it is recommended to manage it as a part of such projects. In practice, it pays to perform such investigations throughout the entire course of a project. Due to the fact that cosntruction projects are temporary and dynamic, such investigations hould be used to monitor how the communication network changes over time. Any intervention by the management cadre into the structure of the network of links between agents, knowledge and tasks, should be performed optimally. Particular attention should be paid to critical communication links, whose lack can lead to an extension of the project completion time and an increase in project cost. Directions of further action should focus on developing a model of optimizing communication in the context of the goals to be achieved over the course of the project.

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Ocena efektywności komunikacji pomiędzy uczestnikami przedsięwzięcia budowlanego z wykorzystaniem teorii metasieci

Słowa kluczowe: Dynamiczna Analiza Sieci (DNA), komunikacja, Metasieci, przepływ informacji, zarządzanie przedsięwzięciem budowlanym

Streszczenie:

W artykule zwrócono uwagę na fakt, że przedsięwzięcie budowlane ze względu na swój charakter jest złożone, tymczasowe i dynamiczne. Rozwój przemysłu budowlanego sprawił, iż zwiększyła się świadomość potrzeby lepszego zarządzania przedsięwzięciami w przemyśle budowlanym. W licznych publikacjach wskazano na utrudnienia i wyzwania w zarządzaniu przedsięwzięciami budowlanymi. Zarządzanie przedsięwzięciami budowlanymi w tradycyjnym podejściu skupia się w pierwszej kolejności na planowaniu zadań wraz z przydziałem do nich zasobów odnawialnych (ludzie, sprzęt) i nieodnawialnych (materiały). W czasie trwania realizacji przedsięwzięcia uwaga

skoncentrowana jest na organizowaniu i przydziale zasobów do zadań i monitorowaniu ich realizacji wraz z kontrolą ich odchyleń od planu i budżetu a także ewentualnymi działaniami korygującymi. Stosowane przy tym różne techniki zarządzania nie uwzględniają w analizie relacji między uczestnikami przedsięwzięcia budowlanego, a realizowanymi przez nich zadaniami i posiadaną wiedzą. Zauważyć należy, iż takie interakcje między ludźmi, organizacjami, zadaniami są podstawą złożonego systemu komunikacji w przedsięwzięciach budowlanych. Przekłada się to jednocześnie na utrudnioną komunikacje. W literaturze zwraca się uwagę na fakt, że podejście sieciowe do analizy i monitorowania komunikacji w ramach złożonych przedsięwzięć budowlanych jest odpowiednie. Zauważyć należy, że wielu autorów w swoich badaniach nad komunikacją w budownictwie wykorzystuje metodę analizy sieci społecznych (SNA). Jednak rozpatrywanie komunikacji pomiędzy uczestnikami przedsięwzięcia budowlanego z perspektywy sieci jednomodowej, do analizy, której wykorzystywane jest SNA nie pozwala na identyfikację bezpośrednich czynników determinujących tą komunikację. Analiza ta bowiem koncentruje się wyłącznie na interakcjach między uczestnikami projektu i nie identyfikuje bezpośrednich związków między uczestnikami a wiedzą i zadaniami, które realizują. W celu zrozumienia specyfiki komunikacji oraz zarządzanie nią w ramach procesu budowlanego należy zrozumieć formalną strukturę organizacyjną przedsięwzięcia, przeanalizować harmonogram jego realizacji oraz określić niezbędną wiedzę, której wymiana pomiędzy uczestnikami determinuje charakter tej komunikacji. Relacje pomiędzy uczestnikami, wiedzą i zadaniami w kontekście komunikacji w przedsięwzięciu budowlanym wizualizowane mogą być w formie metasieci a do ich analizy można użyć odpowiednio opracowane miary strukturalne. W artykule autorzy wykorzystując teorie metasieci przeanalizowali relacje pomiędzy uczestnikami, wiedzą i zadaniami w kontekście komunikacji w przedsięwzięciu budowlanym na przykładzie analizowanej budowy osiedla mieszkaniowego wielorodzinnego zlokalizowanego w Katowicach w Polsce. W skład kompleksu weszły cztery budynki sześciokondygnacyjne (około 12000 m^2 powierzchni użytkowej) z punktami usługowymi na parterze, garażami podziemnymi, infrastrukturą techniczną i drogową. Realizacja inwestycji rozpoczęła się w pierwszej połowie 2016 roku a zakończyła w grudniu 2019 roku. Budżet inwestycji wyniósł 40 mln złotych. Do września 2018 roku inwestycja była prowadzona w systemie generalnego wykonawstwa. Ze względu na panującą w czasie realizacji koniunkturą na rynku budowlanym (wysokie ceny materiałów i usług oraz braki w wykwalifikowanej kadrze robotniczej) Generalny Wykonawca inwestycji ogłosił upadłość firmy, co spowodowało zakończenie współpracy Inwestora i Generalnego Wykonawcy. Inwestor zdecydowało dokończeniu inwestycji poprzez zatrudnienie kadry zarządzającej oraz podpisanie umów bezpośrednio z przedsiębiorstwami wykonawczymi. Dane do badań zostały zebrane po wspomnianej reorganizacji przedsięwzięcia budowlanego. Uzyskano (stosując metodę ankiety) od wszystkich 28 uczestników przedsięwzięcia informacje z kim komunikowali się w ramach przedsięwzięcia w ciągu ostatniego miesiąca oraz do jakiej wiedzy/informacji mieli dostęp i jakie zadania były przez nich realizowane.

W wyniku przeprowadzonej analizy strukturalnej sieci relacji uczestników, wiedzy i zadań uzyskano wiele różnorodnych informacji na temat badanego przedsięwzięcia budowlanego. Otrzymane wyniki są ściśle związane z sytuacją w jakiej znalazło się realizowane przedsięwzięcie (reorganizacja przedsięwzięcia na skutek upadłości generalnego wykonawcy i przyjęcie systemu pakietowego na dalszy etap realizacji) i momentem, w którym zostały zebrane dane (pierwszy miesiąc po wspomnianej reorganizacji). Na szczególną uwagę zasługuje fakt, że cała niezbędna wiedza do realizacji zadań jest dostępna w organizacji, jednakże nie posiadają jej uczestnicy przypisani do realizacji zadań w których ta wiedza jest niezbędna. Jednocześnie wskazano, że na jeden rodzaj informacji przypada 6 uczestników. Jest to jednak średnia wartość, gdyż jak wiemy z analizy miary stopnia (ang. degree) to kierownik budowy i koordynator nadzoru inwestorskiego mają dostęp do prawie wszystkich informacji. W zakresie wymaganej komunikacji zauważono, że brakuje komunikacji pomiędzy uczestnikami realizującymi zadania w sekwencji bezpośredniego poprzedzania (np. wykonawca balustrad oraz wykonawca elewacji), jak również komunikacji ze względu na przekazywanie sobie wiedzy niezbędnej do realizacji zadań (np. komunikacja pomiędzy kierownikiem budowy a wykonawcami stolarki drzwiowej). Jednocześnie rzeczywista sieć komunikacji cechuje się bardzo dużą ilością zbędnych połączeń, które mogą powodować chaos informacyjny.

Na podstawie analizy strukturalnej należy stwierdzić, że w tej początkowej fazie tworzenia się (na nowo) organizacji konieczne jest szybkie wdrożenie zarządzania przepływem informacji pomiędzy uczestnikami przedsięwzięcia budowlanego. W praktyce badania te warto powtarzać przez cały okres trwania przedsięwzięcia. Ze względu na fakt, że przedsięwzięcie budowlane jest tymczasowe i dynamiczne należy badanie monitorować zmieniającą się w czasie sieć komunikacji. Ewentualna interwencja kadry menadżerskiej w strukturę sieci połączeń pomiędzy uczestnikami, wiedzą i zadaniami powinna być przeprowadzona w sposób optymalny. W szczególności zwracając uwagę na krytyczne połączenia komunikacyjne, których brak może spowodować wydłużenie czasu realizacji oraz wzrost kosztu przedsięwzięcia. Kierunki dalszych badań powinny skupiać się na wypracowaniu modelu optymalizacji komunikacji w kontekście osiąganych celów w ramach realizacji przedsięwzięcia budowlanego.

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