A MULTILAYER GRAPH NETWORK-BASED TOOL FOR IDENTIFYING KEY PROJECT ACTORS

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ABSTRACT

As the demands for new complex products/services increase, leading to strict constraints on budget and time-to-market, it is hard to learn from experience and improve practice. Improvement can be exercised in all aspects contributing to project management: the skill set of project personnel, the project structure, and the development process. People are the key asset of the project. Identifying the key participants in a project whose role is influential is important for improving the project's success. These people can receive support, remove their burdens, make sure their communication channels work well, etc. This paper offers a multilayer network-based method to examine an actor's influence in a project while combining two additional organizational key aspects: products and processes. Considering these three aspects together allows for a more informed evaluation of the actors' influence on the project. Using the insight from graph theory, we gain indicators related to each network actor. The influence of the actors in a multidimensional network makes it possible to present a clearer picture to decision-makers in the organization to make better decisions related to increasing the effectiveness of the development project.

Keywords: Project management, Design management, Organizational processes, Teamwork

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1 INTRODUCTION

Many projects reach the finish line in excess of time and budget and with less content than initially planned. Some of them are canceled along the way (Milosevic, 2003). Despite all the technological progress, experience, tools, and knowledge – we still witness failures in projects in all types of organizations or industries, including in establishing a government electronic website for the American Ministry of Health (Anthopoulos et al., 2016); in software projects with an emphasis on requirements engineering (Hussain and Mkpojiogu, 2016); in IT projects (Al-Ahmad et al., 2009), in open source projects (Coelho and Valente, 2017), or in new business development (Burgers et al., 2008).

For decades, researchers have been trying to understand the reasons for failure and offer solutions to prevent or reduce it. Dorsey (2000) tries to give ten reasons for the failure of system projects. Analysis based on three pillars: the failure criterion, the type of project, and the stage of the project in the life cycle is done by (Pinto and Mantel, 1990). Beyond common reasons such as a lack of management skills (especially of the project managers), lack of clarity regarding the project's goals, and poor risk management, many of the above analyzes point to a lack of resources or partial resource management. On the other hand, Attarzadeh and Ow (2008) point to factors leading to project success including the involvement of the team and good planning.

A survey document covers some common methods for creating a “learning organization” (Williams, 2008), while Turner and Müller (2003) expand the definition of the project to include the actual role of the project manager as the CEO of the enterprise with corresponding responsibilities. The ability of an organization to create a learning culture from the performance of past projects while utilizing the collective knowledge found in the organization (Swan et al., 2010) is excellent, but this method, like many similar methods, is characterized by hindsight. Usually, after the project is completed.

We offer a method to optimize project planning already at the stage of the project kick-off and as it progresses. This method maps on a multidimensional graphic network the three aspects of the project: process, people, and product, and uses algorithms to gain insights into the importance of each network element – with an emphasis on the team members. In this way, a team member of high importance in the execution of a project will be able to gain high priority for access to resources or optimal management that will prevent him from dealing with other tasks which are not relevant to the project.

The structure of the article is as follows: Section 2 includes a background review of modeling methods and tools, with an emphasis on the three P (Product), S (Social), and I (Institutional) spaces. Section 3 details the PSI framework. Section 4 details the methodology required to build the supportive decision tool, and Section 5 presents a pilot study of a PCB (Printed Circuit Board) development project with hardware and software layers. In Sections 6 and 7, we discuss and conclude the results, respectively.

2 BACKGROUND ON MODELING TOOLS

The power of actors in design organizations is one of the most significant forces, with the ability to directly influence organizations' success as a whole (Griffin and Moorhead, 2011; Pfeffer, 2020). Power in an organization refers to the influence exerted on an employee or group through another employee or team (Emerson, 1962; Zigarmi et al., 2015). Although there are more than a dozen definitions of power in an organization, none is widely accepted (Griffin and Moorhead, 2011; Sturm and Antonakis, 2015).

One of the prominent tools for both mapping and determining an employee's power is the Organization Network Analysis (ONA) (Foster and Falkowski, 1999; Novak et al., 2011). This tool analyzes the interaction between people and groups within an organization and provides a "network perspective" (Cullen et al., 2014) beyond the hierarchal organization chart that does not sufficiently describe the actual dealings between organization people. Multiple communication channels build the inter-workers framework: formal/informal, emails, meetings, corridor conversations, instant messages (IMs), and telephone calls. Mapping these connections, either manually or with dedicated platforms, can reveal a completely different picture and insights (Lin et al., 2012). ONA relies on

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social network theory to display and scrutinize business interactions, exposing the hidden interpersonal business layers (Cullen et al., 2014) when it graphs the network for organization managers and other decision-makers.

A network can be of many types: bipartite, directed, random, complete, or weighted (Gross and Yellen, 2004). One can apply various metrics/algorithms to a network, especially a centrality (Chen et al., 2018), clustering, and degree (Diestel, 2000). Applying these metrics to networks broadens the network's insights, particularly for the specific nodes/actors. Centrality measurements of social networks make it possible to find the actors in key positions on the network (Wasserman et al., 1994). Actors with a high score in these centrality indices tend to feature more influence than actors with low centrality indices, especially those with the betweenness centrality score (Zbieg et al., 2016).

The people/teams are just one dimension in the organization's ecosystem, and there are more dimensions to be considered. Identifying the crucial ingredients needed to formulate a successful organization is arduous; Kreimeyer et al. (2008) suggest some common domains in the organization processes, such as tasks, information objects, events, resources, etc. A "periodic table" containing five domains of the enterprise: goal system, process system, agent system, tool system, and product system, was suggested by (Browning et al., 2006; Danilovic and Browning, 2007). Eppinger (2002) talks about the following three domains to be considered when analyzing product development: component, process, and organizational structure. The process analysis discipline contains dozens of organizational mapping procedures (Von Rosing et al., 2014). Whatever the method of process methodology, an organization must adopt process mapping and analysis as part of its core activities (König et al., 2008).

The complexity of products is constantly growing and posing challenges to organizations that manufacture them. The multiplicity of disciplines, changing market demands, and many factors inside and outside the organization directly affect the products, all of which need to be considered (Maurer, 2007; Maurer and Lindemann, 2008).

During the 1960s, researchers began using matrices to describe and analyze systems (Maurer and Lindemann, 2008). The matrices were a convenient platform for a concise description that combines the components of the system and the flow of information between them (Kreimeyer et al., 2008; Steward, 1981; Yassine, 2004). The Design Structure Matrix (DSM) is a square matrix that allows the mapping of elements and their relationships. This type of matrix has gained popularity in recent decades and is used for product development, project management, systems engineering, and organizational design (Kannengiesser, 2015; Maurer and Lindemann, 2008).

While the DSM is used to map a single domain, a description of multiple domains is needed to extend this representation method. The Domain Mapping Matrix (DMM) is a matrix that maps two domains (Eppinger and Browning, 2012; Kreimeyer et al., 2008; Maurer and Lindemann, 2008). Combining the DSM and the DMM yields the Multiple Domain Matrix (MDM), a squared matrix that describes multiple domains and their connections (Maurer and Lindemann, 2008). Harnessing the power of multidimensional matrix representation can serve as a powerful tool for modeling and analyzing problems in multiple domains (König et al., 2008).

A graph is an equivalent representation of the matrix representation and provides additional insights through the tools it offers (Eppinger and Browning, 2012; Maurer, 2007). Multilayer networks, also known as multidimensional networks, multiplex networks, or multivariate networks (Kivelä et al., 2014), encompass single-layer (or monolayer) network structures, modeling complex systems into one framework. Each layer portrays a unique feature of its intra-layer connectivity while using the inter-layer connectivity to indicate the relationships between monolayer networks (Aleta and Moreno, 2019).

Although many studies are concerned with mapping the dimensions of the organization in order to optimize its functioning, no attempt has been made to map several aspects of the organization over a multilayered graphic network, to use algorithms and techniques from the field of graph theory to gain insights for key actors in the organization.

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3 THE PSI FRAMEWORK

System analysis framework, such as the Problem/Product, Social, and Institutional (PSI), integrates several key spaces (aspects) into one unified platform. The PSI framework is used for analyzing and designing complex systems (Reich and Subrahmanian, 2015, 2020). This framework can be implemented to examine various abstraction levels. Using the PSI framework's primary principles combined with the 3Ps from the marketing mix (Product, Process, People) (Gronroos, 1994) gives a three-layer platform for evaluating organizational performance. We take advantage of this flexible framework for analyzing organizations in the following three dimensions:

- P Space or Layer – represents the product, project, or problem space. The product can be tangible (i.e., a printer) or intangible (i.e., a piece of software). Several interface types can be considered between blocks: information, material, energy, and spatial alignment or mechanical force transfer (Engel et al., 2017; Eppinger and Browning, 2012). Since a block diagram can describe the system architecture, it can easily be expressed using a graph network: replacing the blocks with nodes. The arrows indicating the interfaces and their directionality remain in place.
- S Space or Layer – represents the social aspects or people involved in achieving the P. It may contain either individuals or groups/teams. Scholars use social networks to map and analyze the interaction between two actors, especially informal ones (Burt et al., 2013). The interactions between the actors in the S-Layer can be formal as widely known as an organization chart (Haskell and Breaznell, 1922), or include other aspects of interactions such as advice, trust, and communication interactions (Krackhardt and Hanson, 1993).
- I Space or Layer – represents the institutional aspects or the process that has to be carried out to achieve the P. It is a broad word describing the environment of both P and S Layers. We can model the I-Layer as the process needed to produce the P. Although there are many ways to describe a business process, we suggest using a subset of the Data Flow Diagram (DFD) (Tom, 1979): Nodes to represent operations and edges to convey the information flow direction.

Multilayer networks can be exploited for describing all three P, S, and I monolayers using one comprehensive graph. This allows us to express all the project's key aspects using descriptive language. Figure 1 shows a generic PSI network in two phases: the first as three separate monolayers (a) and the second as a multilayer network (b). Each layer indicates one project aspect with the layered interactions. Layer P represents the product with the directional relationships between the system elements. Layer S represents the group of people associated with some activity for the product and with their interactions. Layer I identifies the process required for the product. Figure 1(b) shows a connection between the different layers using bi-directional edges. In this way, the three networks in (a) became one multidimensional network. The outcome is relationships between the different layers that link the parts of the product to the parts of the process, together with the group of people who take part in it.

There is a meaning to the connections between the different layers: the interactions between the P and S layers indicate the relationship between the actors and the parts of the product, for example, who is the engineer involved in the design of a certain system element. The connections between the S-Layer and the I-Layer indicate the relationship between the actors and the process, for example, at which stage in the development process the engineer is involved or even serves as the process owner. The connections between the I-Layer and the P-Layer indicate the connectivity of the process to the product parts. That is, which step in the process relates to a specific system part.

Please note that the network is directional, and the connections have different meanings in each layer. For example, the relationships between people will often be two-way by nature of human interaction, while relationships between process parts or system parts can also be one-directional. The connections between the layers are bidirectional since every element X in the first layer is connected to element Y in the second layer and vice versa.

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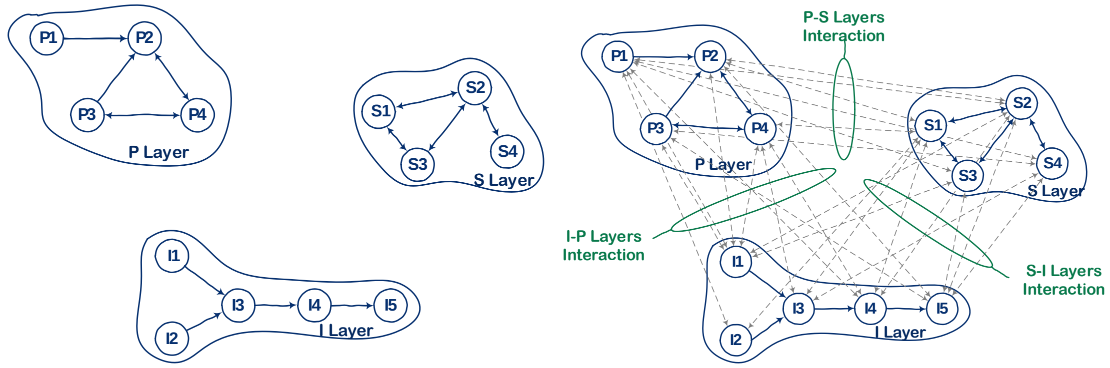
After building the multidimensional network, we will be able to use algorithms and metrics from network theory in order to gain insights that the organization's personnel can use as a tool for making project decisions.



(a) (b)

Figure 1. Generic PSI monolayers (a) and as multilayer network (b)

4 METHODOLOGY

Assuming that the organization that develops products or provides services includes professional personnel and work processes, we can create a multilayer network for PSI dimensions according to the following steps:

1. **Collecting the data -** Data collection will be done differently for each of the layers:
   - For the product layer (P-Layer), the system architect, the product engineer, the system engineer, or any organizational function familiar with the product structure should be consulted. Producing a graph for the P-Layer is almost immediate, given a block diagram for a hardware product or a software architecture for a software product. It is also possible to build a more simplified network if not all the design details are known, see section 5.
   - The data regarding the process layer (I-Layer) might be obtained from the project manager, the process engineer, or any organizational function familiar with the organizational processes. The processes of developing products or providing services are part of organizational processes that can be retrieved from the organization's procedures, observations or from questionnaires.
   - The data for the people layer (S-Layer) can be obtained in a questionnaire that will be distributed to the project personnel, in which they will be required to indicate which of the other project team members they interact with. Alternatively, an organizational function (preferably from within the project), such as the human resources personnel, can be used to describe the various interactions between the staff members. In order to map the connections between the people of the organization, one can use a simple questionnaire that requests from each actor to indicate with whom they are interacting.

The I and P layers are composed of networks that rely on solid information from organizational processes or product structure. The depiction of processes and product architecture in architectural diagrams are rigid, with minimal potential for bias. However, there is a possibility for biasing in mapping interactions among actors in an organization. To reduce this biasing, we made a concerted effort to carefully word the questionnaire and cross-reference the data.

2. **Data processing and presentation -** the data collected in the previous step is modeled, e.g., by an adjacency matrix, and presented, e.g., as a graph. Plotting the network graphs can be easily done with software such as Gephi, an open-source software that can read and display the data from the adjacency matrix.

3. **Running network algorithms** such as centrality. This analysis can be achieved by using network tools (such as Gephi).

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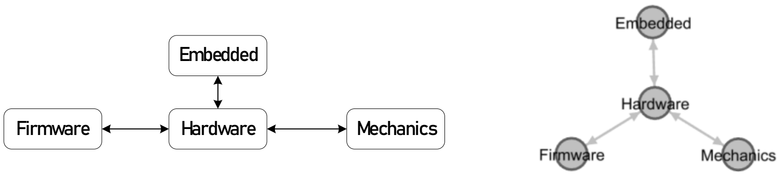
4. **Deriving insights** – using the graph representation and algorithms results to obtain insight.
The efforts and resources required to map and analyze PSI-based multilayer networks for organizations are low.

5 PILOT STUDY

This section examines the approach in developing a typical Printed Circuit Board (PCB), which includes, in addition to the electronic components, Firmware, and Embedded code that are part of the PCB's programmable devices. For this purpose, we will map the disciplines associated with the product and the layer of people involved in the project. We will present the typical diagrams for some layers, their network graphs, and the results obtained from applying the centrality algorithms.

The product is a Printed Circuit Board, which contains both passive and active electronic components. Among the active components, there are two programmable devices: one is a Micro Controller Unit (MCU), and the other is a Field Programmable Gate Array (FPGA). The code that is written for the FPGA is referred to as Firmware (FW), and the code for the MCU is referred to as Embedded. Figure 2 describes a simplified block diagram for the product. It contains four main disciplines: hardware, embedded, firmware, and mechanics. The product block diagram and the associated graph network for the P-Layer is described in Figure 2. Please note that according to the desired level of abstraction, the P-Layer can be more detailed to reflect additional system elements such as modules and components.



(a) (b)

Figure 2. (a) Simplified block diagram for the PCB (the product) and P-Layer network graph representation (b)

The Social Layer includes the people involved in the development, production, and testing of the PCB. The nodes represent the people, while the edges represent the interaction between them. This layer contains 16 officials, such as the project manager, system engineer, consultants, subcontractors, and other engineers. The network graph is described in Figure 3(a). Applying the betweenness centrality algorithm on the S-Layer yields the most influential actors, as can be seen in Figure 3(b).

The third layer, I, contains the development process – described in Figure 4 – having 29 different stages from project kickoff to mass production readiness. Please note that the development process is part of the product life cycle, which includes additional phases such as mass production and disposal.
After we map each of the P, S, and I Layers, we combine them into a single multilayer network and apply the betweenness centrality algorithms, whose results are shown in Figure 5. The bottom layer is the product layer, the middle layer is the people layer, and the top layer is the Social Layer. We can see the many connections within the layers and between the layers. The next step applies the betweenness centrality on the network for evaluating the most influential actor in the S-Layer. The node size indicates the magnitude of the centrality of the specific node. The bigger the node is, the more influential it is.

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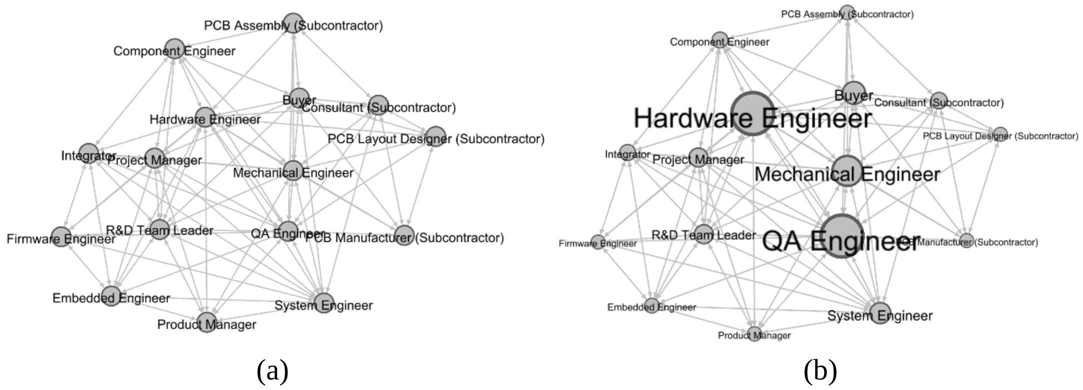

Figure 3. S-Layer network graph (a) and S-Layer with betweenness centrality featured in the node size (b)

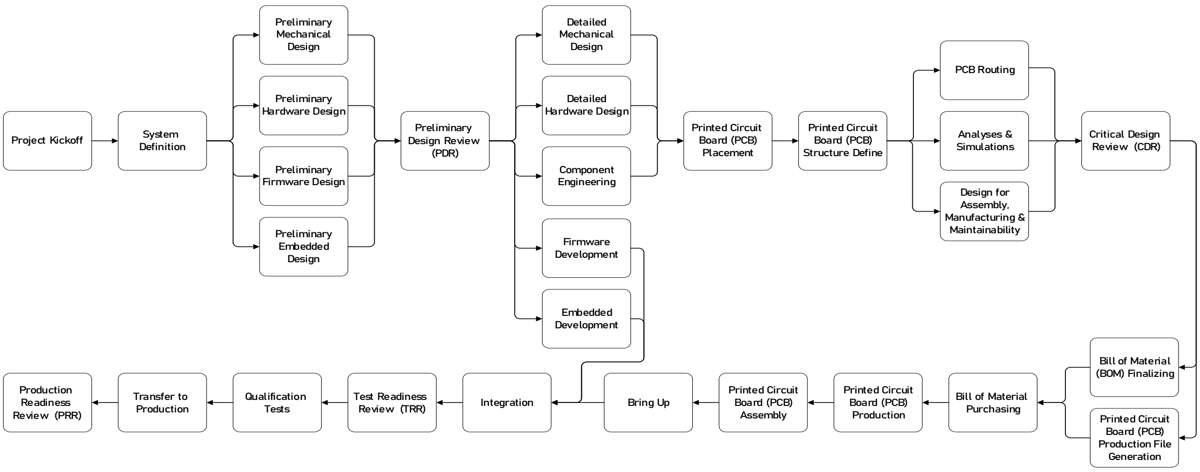

Figure 4. PCB developing, manufacturing, and testing process

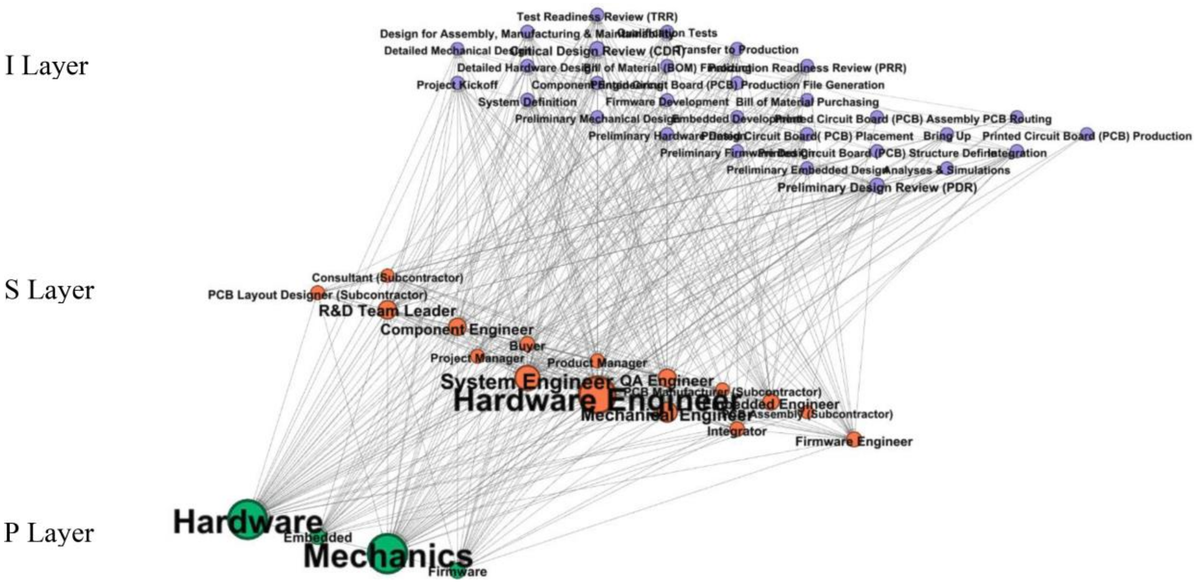

Figure 5. PSI multilayer graph network with betweenness centrality algorithm applied

While the centrality algorithm calculates the importance of the nodes in all the layers, we focus here on the centrality index of the people layer. According to this index, the hardware engineer is the most important person in the development of the PCB, together with the system engineer, who also receives a high score. These results were validated according to the experience of one of the authors, who serves as an electronics engineer with 30 years of experience in the field. The hardware engineer is indeed the most important player in PCB design, together with the system engineer.

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6 DISCUSSION

Studies that exploit tools derived from network theory for the S-Layer only (Zbieg et al., 2016), and the optimization of product development processes using the DSM (Eppinger and Browning, 2012) method algorithms show the benefits of using mathematical tools to obtain insights related to organizational aspects.

The integration of different aspects of the organization with the S-Layer, enables determining the actor's power. Examining the interaction between people only, as shown in Figure 3(b), indicates that the hardware (HW) engineer, the quality assurance (QA) engineer, and the mechanical engineer are the most powerful actors. But, once the process and product layers are taken into account, the picture changes to reflect a more accurate situation. In the case of the multilayer network (see Figure 5), the significant actors are now: the hardware engineer and the system engineer, which are indeed the two main functions in the PCB development process. The analysis also provides the relative power for each actor, so there is a numerical score for every actor in the project.

In the execution of the betweenness algorithm, other layers also have more central nodes, which indicates that even in these layers, different elements (in I-Layer or P-Layer) have more influence when considering additional aspects.

It is important to note that these results reflect the existing relationship network. In another project, given a different map of relationships, the key actors can be changed as part of the nature of the network. Another dimension that can contribute to change is the time during which the network of relationships changes, mainly because of the dynamics of the organization. Therefore the resulting network and its centrality measures, reflect the momentary state, a kind of snapshot of the organization. If the connections have changed for any reason - it is necessary to repeat the process again.

The importance of the actors can be used to provide them support for executing their regular tasks as depicted in the process model but, no less important, allow them to exercise their role as information channels to other actors involved in the project. It is clear that a challenge in the process may hamper their role in information exchange. This awareness can lead to process improvement.

While we focused here on the people working on the project, we could also consider the two other layers, the product and the process, and derive insight from them. In another study, we used information from a separate product network and process information to derive insight into project risks (Efrati and Reich, 2023). The multilevel network model can support such analysis as well as others that could address other causes of project failures.

Our analysis was an initial demonstration of a new capability that made use of a simple network representation in which all links are identical. We are currently working to enhance the analysis by using different types of links as well as with different properties, such as connection strength. Such refinement will provide a more accurate representation of reality.

7 CONCLUSIONS

We suggest a new decision-support tool with roots in several disciplines: PSI framework, graph theory, social networks, and organizational management. The objective is to expand the toolbox for the organization analyst or the enterprise system engineer while designing and analyzing projects conducted in an enterprise.

Considering the main project aspects of Product, Social, and Institutional (PSI) while applying them on a single multilayer graph network and producing across-the-board insights can increase business efficiency. This tool can be used by both enterprise system engineers and business consultants for mapping and optimizing project performance. Since the organizations, in general, and the projects within them, in particular, are dynamic and under constant changes in all dimensions – it is possible to carry out repeated PSI multilayer graph mappings during the lifecycle of the project. In this way, the stakeholders will be able to receive an up-to-date situational picture as a supporting tool in making their decisions.

An additional advantage of this decision-support tool is its ability to provide feedback for the project that is in the execution stages and not only after its completion. Using this tool, the human resource person can define more precisely the job description for the more important project members.

It should be noted that the multilayer network analysis was carried out on individual cases and is insufficient to validate it as an established method. Therefore, more examinations should be performed on different products from different projects in different organizations.

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Further work may contain additional analysis of the different metrics and algorithms to gain more insight into the PSI multilayer network in product development and service providing (such as consulting services, education, etc.). Another suggestion is to consider expanding the three-dimensional layers into multiple layers that contain more than one P/S/I Layers.

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