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Multilayer Analysis in Complex Large Infrastructure Projects

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Abstract

The complexity of large infrastructure projects requires the use of methodological methods that can examine how various systems interact rather than just evaluating isolated systems (e.g., either risks or stakeholders). Although the project management literature has invested major efforts into unidimensional networks to study risks or stakeholders separately, there are missing multidimensional analyses that combine complementary perspectives. This study develops a multilayer network analysis by integrating the economic transaction between stakeholders and risks to expose the motives of project underperformances. A large infrastructure education project in Italy is used to demonstrate the application of this technique for identifying potential issues in risk allocation that may result in underperformance among stakeholders. The implementation of the multilayer network demonstrated that stakeholders within the public sector with active participation in the monetary transfers but low-risk exposition tend to perform adequately, which emphasizes the relevance of risk transfer to the contractor. Conversely, lower eigenvector and betweenness values in the multilayer network respecting these metrics in the money flow network expose risk allocation issues affecting the performance of the project.

Keywords: Performance management, Project success factors, Stakeholder Management, Risk Propagation, Network Analysis

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1. Introduction

Large infrastructure projects involve large investments (from public and private sources) and lengthy durations (in some cases various decades) [1]. These initiatives are complex because of the numerous interrelated impacts they may have on the environment, society, and economy [2], [3].

The analysis of risks and stakeholders using unidimensional networks has received considerable attention in the project management literature [2], [4]–[6]. Nevertheless, the limitations of one-dimensional analysis neglect the complexity of these projects. In effect, complex large infrastructure projects could not be fully comprehended by just unbundling their components to analyze each of them in an isolated way; rather, they must be examined in an integrated multidimensional way [7].

Social Network Analysis has become the most representative network analysis technique in the body of knowledge to identify, evaluate, and prioritize stakeholders and their role in the outcomes of projects [4], [5], [8]. In contrast, fewer research efforts have been dedicated to applying Social Network Analysis to risks [4]. Moreover, rather than building the networks on quantitative data, they used to rely on semi-qualitative sources derived from workshops with a small number of participants (i.e., less than 10 people) [4].

To handle the complexity of large infrastructure projects, this research develops a multilayer network that incorporates the monetary transaction between stakeholders and risks. This approach is applied in a large infrastructure education project in Italy.

The structure of the paper is as follows. The Literature Review section offers a comprehensive analysis of existing research. Subsequently, the Research Methods section details the development of a multilayer network. The Findings and Discussion section presents empirical results based on the case study analyzed. Finally, the Conclusion section summarizes the key findings, contributions, limitations, and outlines potential directions for future research.

2. Literature Review

2.1. Unidimensional network analysis shortcomings

Network science has become one of the primary quantitative methods for examining systems in heterogenous disciplines. A network defines a system as a collection of entities, known as nodes, that communicate with one another through links (that can be direct, i.e., with a specific direction, or indirect, i.e., without a direction). Networks offer a comprehensive and encompassing perspective of the system and also highlight novel aspects that other techniques can not explore. Furthermore, the attributes and evolution of a system are uniquely captured by the interaction pattern between nodes [9].

Despite the multiple benefits of traditional network analysis, frequently they are excessively reductive in describing the systems [10]. For instance, a system of stakeholders would describe them as nodes (i.e., organizations or people) and their connections/links. Although this understanding would be helpful in describing underlying mechanisms of significant dynamics like polarization or information spreading, some other mechanisms (e.g., collaboration) are beyond the scope of this unidimensional analysis and may result from multiple dynamic processes like information sharing or negotiations, which exacerbates their complexity [11]–[13]. This limitation is exacerbated by the fact that additional social dimensions, such as economic, cultural, or historical considerations, can affect the dynamics of a social network.

In the project management field, unidimensional networks are too reductive to describe simultaneously the various relationships among project stakeholders and their interactions (e.g., trust, collaboration, financial transactions) that may be influenced by exogenous factors. Therefore, it is vital to enhance existing unidimensional network models while maintaining them as powerful and tractable.

2.2. Multidimensional networks

To address the above-mentioned constraints of unidimensional networks multidimensional networks have recently been developed [10]. In these multilayer networks, each layer corresponds to a different complexity dimension of the system. Overall, a multidimensional network is a collection of various unidimensional networks known as layers. Communication between layers is possible: two layers are linked if at least one node in layer A is linked to one node in layer B. Conversely, two nodes that are in the same layer are connected through “intra-layer” links.

Nodes in distinct layers may overlap, meaning that there may be various copies of the same node in several layers. For example, a multilayer representation of online social networks where each layer shows the network of each online platform (such as Twitter, Instagram, and Facebook), and since each person may have accounts on multiple platforms, there could be nodes present simultaneously in various layers. Nevertheless, the multilayer network proposed in this paper considers all nodes different and there are no copies of any node.

Traditional networks, also known as monoplex or unidimensional networks, could consider multilayer networks with only one layer. Besides the potential of incorporating increasing information and describing the system in a more accurate way, the analysis of multilayer networks may expose novel system properties impossible to detect in unidimensional networks. As a result, diffusion and navigability properties can be significantly different between unidimensional and multidimensional networks [14]. Similarly, node centrality measures also may vary between both networks [15].

In order to achieve accurate analysis of complex systems in the project management field that prevents large losses of time and money, it is more relevant the adoption of multilayer networks.

3. Research Methods

3.1. Data gathering

For putting the multilayer network into practice, a large education infrastructure project in Italy was chosen. This project was purposely chosen because it has the relevant characteristics of complex large infrastructure projects, as follows:

- Comprehends significant financial transfers of over 200 million euros.
- Involves a long contract life-cycle: twenty-four years among the design, construction, and operation phases.
- Incorporates diverse risks represented in significant monetary valuations.

In order to compile the pertinent information from the project, a triangulation of diverse data sources was conducted. First, the legislation was retrieved to obtain all the background data stated in the adjudication decree regarding the financial sources, responsibilities, and transactions between stakeholders. Second, the contractual information, including financial transactions among the contractor and the owner and risk valuation, was gathered. Third, the internal reports from the project management team were collected to compare the projected money and risk transfer with the real ones that occurred during the project execution.

3.2. Multilayer network development

Utilizing data collected from economic transactions between stakeholders and risk factors in the project, a 2-layer network was created. The first layer consisted of nodes representing the stakeholders, where a direct link between node i and node j existed if there was an economic transaction from stakeholder i to stakeholder j. In the second layer, nodes represented the risk factors, and a direct link between node a and node b existed if there was a potential cause-and-effect relationship between the occurrence of risk a and risk b. The two layers were connected through "inter-layer" links, where a link between a node in the first layer i and a node in the second layer a existed if stakeholder i was responsible for risk factor a. Inter-layer links were considered bidirectional to account for the possibility of a cause-and-effect relationship in both directions.

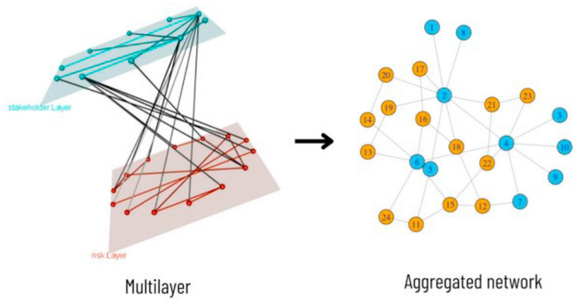

Fig. 1. Multilayer and Aggregated Networks.

The multilayer network described belongs to the "networks of networks" class of multilayer networks, which are interlaced with different types of nodes without overlapping sets [16]. These networks can be reduced to an aggregate network without losing information, as demonstrated in previous research [17]. The aggregate network is a single layer network that includes all nodes from the original multilayer network without distinction between inter-layer and intra-layer links.

Fig. 1 (left) represents the multilayer network of the project, where blue nodes and links represent stakeholders, orange nodes and links represent risk factors, and black links represent inter-layer connections. Fig. 1 (right) shows the corresponding aggregated network, where nodes and links are drawn on the same plane without distinction between intra-layer and inter-layer links. Working with the aggregated network eliminates the need for the tensor formalism typically used for multilayer network analysis [16], allowing for traditional network metrics to be implemented instead.

3.3. Metrics calculation

The centrality of stakeholders was analyzed in both an aggregated network and a single-layer network comprising only stakeholders. Node degree centrality is the most common measure of centrality, defined as the number of a node's neighbors divided by the total number of nodes in the network. Fig.1 shows that the node degree of stakeholders in the aggregated network differs from that in the single-layer network, indicating a variation in the number of neighbors for each node when considering all nodes versus only blue nodes. However, the node degree centrality is not informative enough because of its simplicity, resulting in the inclusion of eigenvector and betweenness centrality as alternative measures of centrality. Eigenvector centrality calculates the transitive influence of a node, while betweenness centrality measures how many shortest paths pass through a given node [8], [18].

Unlike degree centrality, it is not evident how betweenness and eigenvector metrics vary in the presence of multiple layers of networks, such as the risk network layer. Therefore, this study adopted interdependence to measure the extent to which a stakeholder's reachability varies from the single-layer network to the multilayer network [19]. A stakeholder with a high interdependence value can influence and be influenced by other stakeholders mainly through the risk layer network, while a stakeholder with a low interdependence value can influence and be influenced by other stakeholders mainly through the stakeholders' layer network. The interdependence is calculated as the ratio of the total number of shortest paths between two stakeholders to the number of shortest paths that make use of nodes in the risk layer.

3.4. Risk network

Data on potential risk factors and economic transactions among stakeholders were collected, but did not identify cause-effect relationships among them. While existing approaches rely on expert judgment or probabilistic inference [20], this study implemented a different approach by assuming a random network of risk factors, modeled after the Erdos-Reny network with a connection probability p [21]. This assumption is reasonable given the complexity of the underlying phenomena and the difficulty in identifying cause-and-effect relationships. The study then performed Monte Carlo simulations to compute various metrics for stakeholders in both the single-layer network and the aggregated network, with p set to 0.1 for the specific project presented in the study. The results of the metrics obtained in the simulations are compared with those obtained from the initial calculations. Different values of p can be used to better describe projects with different properties.

4. Findings and Discussion

For network development, the stakeholders are represented as nodes. In order to identify the stakeholders, a top-down analytical categorization was carried out, resulting in ten stakeholders from both the private and public sectors. Four public sector stakeholders: The Ministry of Education (MoE) that gave the project approval; the university (Owner) that serves as the contracting party; the municipality (Mun) where the project is taking place that plays a key role in the permit approvals; the Ministry of Finance (MoF) provides the funds for the project’s feasibility phase.

The six stakeholders remaining are made up of members of the private sector. On the one hand, the contracts are comprised of: The Responsible of Financing (RfF), which is responsible for the short-term private funds for the capital expenditures and operational expenses that will be reimbursed by the owner only in the long-term; the Responsible for Maintenance (RfM) that conduce the facilities maintenance during two decades of the operation phase; the Responsible for the Execution, which must conduct the contraction of the facilities; the Responsible for Design (RfD), which is in charge of the detailed design before the construction phase; the provider of Furniture (Forn) must supply the furniture and equipment. The Project Management Office (PMO) must support the owner with the project management processes.

4.1. Interdependence analysis

This research carried out a stakeholders' interdependence analysis (Table 1 and Fig. 2) to provide detailed information regarding the relationship between stakeholders and risks. The higher the stakeholders' interdependence the higher the influence of risk propagation. Alternatively, the stakeholders with lower interdependence are less vulnerable to risks but mostly influenced by the financial transfers among stakeholders.

Table 1. Interdependence network metrics.

Stakeholder	MoE	Owner	Mun	RfF	RfM	RfE	RfD	PMO	MoF	Forn
Metric	0.00	0.15	0.16	0.30	0.47	0.61	0.30	0.24	0.16	0.16

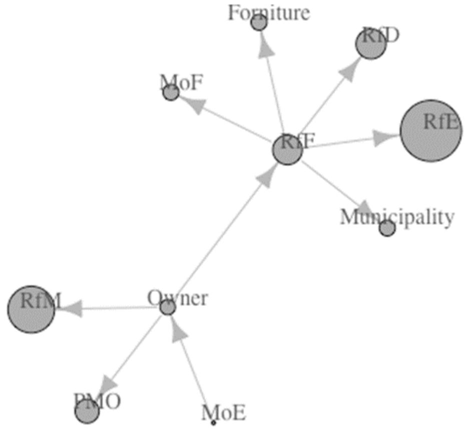

Fig. 2. Aggregated Network. Note: The size of the nodes are proportional to the interdependence value of the stakeholders

According to the interdependence analysis, two contractor's stakeholders - Responsible for Maintenance and Responsible for Execution- presented the highest risk exposure (Table 1). Conversely, all the stakeholders within the public sector (i.e., the Ministry of Finance, the Ministry of Education, the Municipality, and the Owner) showed the lowest risk exposure. Public sector stakeholders played a more significant role in the financial transfers and simultaneously transferred the majority of the risks to the contractor.

4.2. Unidimensional and Multilayer Networks Comparison

In order to analyze the stakeholders' roles based on quantitative measures, social network analysis was used for providing complementary stakeholders' insights in regard to their roles. As a result, unidimensional networks were created based on the information gathered from contractual documents concerning the money exchange between stakeholders. The links' directions indicate the recipient and the source of the money transfers.

Unidimensional and aggregated multilayer networks are compared according to the betweenness of the nodes in Fig. 3 and Table 2. This comparative analysis demonstrated a misalignment between the preponderance of the Responsible for Finance and the Owner. In the unidimensional network, the role of the Responsible for Finance is significant due to its financing role to the contractor companies and the tax payments to the Municipality. Conversely, in the aggregated multidimensional network, this stakeholder loses preponderance because of its low-risk exposure. Since the Owner must authorize all disbursements of the Responsible for Finance, there is no risk exposure for the latter but the cost overrun risks and their potential disputes derived are only bear by the former. The contractual provisions also stipulate that the macroeconomic risk should be borne by the owner. As a result, the Responsible for Finance is merely a financial intermediary with neither risk exposure nor competence.

Table 2. Betweenness centrality.

Stakeholder	MoE	Owner	Mun	RfF	RfM	RfE	RfD	PMO	MoF	Forn
Before aggregation	0.00	0.44	0.00	0.56	0.00	0.00	0.00	0.00	0.00	0.00
After aggregation	0.00	0.51	0.00	0.23	0.02	0.22	0.02	0.00	0.00	0.00

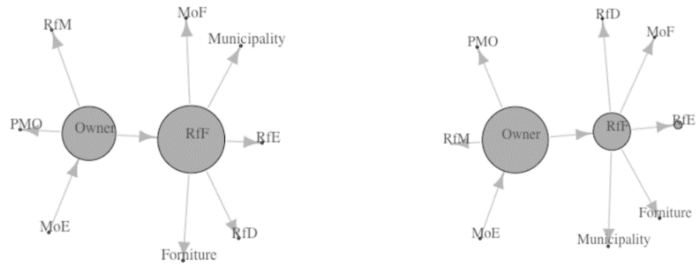

Fig. 3. Betweenness Centrality. Note: Note: The size of the node is proportional to the stakeholder's betweenness centrality computed before (left) and after (right) the aggregation.

The misalignment of both stakeholders between unidimensional and aggregated networks reveals a crucial pitfall in the contractor's scheme. In the Build-Lease-Transfer project analyzed, the financial corporation within the contractor consortium did not add value for the project execution or bear any risk, in contrast to similar project delivery methods that integrates financing within the contractual arrangement (e.g., Design-Finance-Built-Operate-Transfer), which rely on concessionaires made of companies with expertise in the development of the projects and the project finance scheme allows projects to get long-term private debt under competitive conditions. Due to these risk allocation pitfalls, the Responsible for Finance showed a considerable lack of interest regarding the project performance during the execution.

This finding illustrated that unidimensional social networks are unable to accurately capture misalignments between risk allocation and monetary transactions (and profits), contrary to the advised practice in risk management [22]–[33].

Complementary, Fig. 4 and Table 3 compare unidimensional and aggregated networks based on the eigenvector centrality. Along with the previously mentioned misalignment, this metric makes it possible to identify a significant shift in the responsibilities of the Responsible for Design and the Responsible for Execution among the networks. In the unidimensional network, both private sector stakeholders have comparable representativeness. Nevertheless, the representativeness of the Responsible for Execution is doubled when the risk is taken into account by the multidimensional network, whereas the Responsible for Design halves its eigenvector.

This misalignment shows that a significant proportion of the risks are allocated to the Responsible for Execution as the risk management literature advises regarding the allocation of the construction risks to the private partner. On the contrary, the Responsible for Design is the opposite case with no significant allocation of risks, which later resulted in a significant time underperformance in delivering the design affecting the project schedule in more than one year.

Table 3. Eigenvector centrality.

Stakeholder	MoE	Owner	Mun	RfF	RfM	RfE	RfD	PMO	MoF	Forn
Before aggregation	0.06	0.16	0.09	0.23	0.06	0.09	0.09	0.06	0.09	0.09
After aggregation	0.06	0.38	0.02	0.11	0.10	0.18	0.04	0.06	0.02	0.02

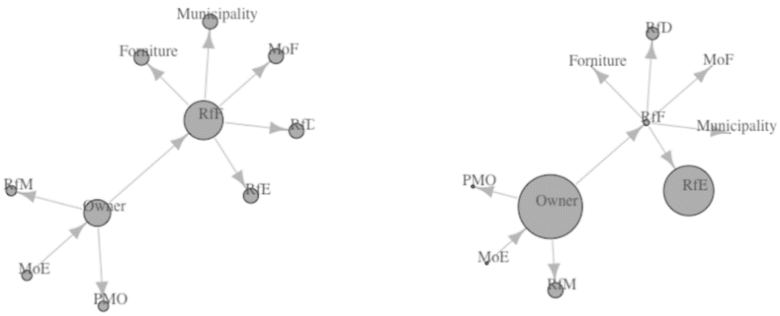

Fig. 4. Eigenvector Centrality. Note: The size of the node is proportional to the stakeholder's eigenvector centrality computed before (left) and after (right) the aggregation.

5. Conclusions

For dealing with the complexity of large infrastructure projects, it is required the development of innovative methodological approaches that can identify the interaction between systems in an integrated manner as opposed to the traditional approach of isolating components (e.g., risks or stakeholders). Although significant efforts have been devoted by project management researchers on unidimensional networks to study either risk or stakeholders separately, the body of knowledge still lacks studies that implement multidimensional analyses that integrate complementary perspectives to address complexity.

This study aims to advance the project management literature by proposing a multidimensional network analysis to reveal misbehaviors that are hindered by unidimensional analysis by incorporating monetary transactions and risk among stakeholders. Using a large education infrastructure project in Italy, this paper highlights the risk allocation patterns that could lead to underperformance among stakeholders and project pitfalls.

Findings revealed that public stakeholders with low-risk exposition and significant monetary transfer performed adequately, according to the risk management recommendation of transferring most of the risk to the private sector. Conversely, the analysis of the eigenvector and betweenness metrics in the aggregated network shows that a significant decrease in those metrics of a contractor company respecting the money transfer unidimensional network reflects a potential suboptimal risk allocation that may result in future underperformance and misbehaviors of this stakeholder.

This research illustrates that multidimensional analysis, as opposed to traditional unidimensional analysis, is necessary due to the complexity of large infrastructure projects. The multidimensional network analysis conducted is key to integrating the benefits of risk propagation and social network analysis.

This paper also showed that a significant decrease in the multilayer eigenvector or betweenness of a contractor company respecting the money transfer unidimensional network reflects a potential suboptimal risk allocation, which is reflected in future underperformance and misbehaviors of this stakeholder.

This pioneering study aims to introduce the concept of multilayer analysis in the context of complex infrastructure projects, with a focus on a single representative megaproject. The findings and insights derived from this study can pave the way for future research endeavors that extend this methodology to multiple megaprojects, thereby enhancing the generalizability and applicability of this technique. By expanding the scope of analysis to encompass various megaprojects, researchers can gain a deeper understanding of the underlying patterns, dynamics, and systemic risks inherent in these complex endeavors. This will foster a more comprehensive and robust understanding of multilayer networks in the context of infrastructure projects and facilitate evidence-based decision-making, planning, and risk management strategies in the field of project management and infrastructure development.

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