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Topological Analysis of Project Risks Network: A Case of Rabat Tramway Project

Younes Bourass and Saoudi Taibi

Laboratory Quality, Safety and Maintenance, Mohammadia Engineering School,
Mohammed 5 University, Rabat, Morocco
younes_bourass@live.fr

ABSTRACT

Topological analysis based on graph theory, has the merit of revealing the relevant properties of the structure of a network system. In this working paper, the topological analysis is used to analyse the structural properties of the project risk network. The main idea here is that the risks faced by a large infrastructure project are not independent but are often interrelated and can evolve by propagation, whence their structuration in network. Therefore, the appeal to the network theory is not trivial but is a significant development in the field of research on the analysis and management of project risks. The aim of this study is to identify critical risks and interactions among risks with regard to their roles in the network. This will provide valuable information that complements the traditional analysis based on the evaluation of the likelihood and impact of risks. The originality of this work manifests itself, particularly, through the application of topological analysis in the field of project risks management, and the adaptation of indicators of network theory, in particular, the indicators of connectivity, interface and betweenness centrality. The application on a real complex engineering project allows us to validate the usefulness and feasibility of the proposed approach.

Keywords: Graph theory, topological analysis, project risks

INTRODUCTION

Today, all professionals agree that we live in a risk society. The complexity, uncertainty and extreme competition in the economic and social environment in which companies operate, are causing difficulties in managing their projects, which leads them to take on new challenges, and confront several constraints. Moreover, it is not uncommon to see projects lead to failures and huge losses, both from a technical point of view, that financial or commercial. Some projects are even dropped altogether. Therefore, management of project risks has become, in recent years, for many companies a major concern. Recognizing this, it is essential, if not imperative, for the various persons responsible for conducting projects (project managers, business managers, members of project-teams ...), to better understand the potential risks associated with their project, to consider how anticipate, analyse and better control those risks. Indeed, it is no longer possible or conceivable today to accept, with certain fatalism, that the failure to take account of risks in managing a project could compromise its success, but also, the sustainability of the company. It now appears that the success of a project is strongly influenced by how its managers can recognize potential risks that threaten the project, study them and overcome them.

For all these reasons, we introduce the topological analysis based on graph theory to analyse the structural properties of the project risks network. The key idea here is that the risks faced by a large infrastructure project are not independent but are often interrelated and can change by propagation, hence their structuration in a network.

TOPOLOGICAL ANALYSIS OF PROJECT RISKS NETWORK: THEORETICAL ASPECTS

Network theory is a mathematical branch of graph theory [1]. Today, its practical applications emerge from both the mathematical and computer field. Because of its proven value and simplistic approach, graph theory has a very wide range of applications in engineering, physical, biological and social sciences, linguistics, and in many other areas [2]. A graph can be used to represent almost any network structure involving discrete objects and interrelationships.

The topological analysis based on graph theory, has the merit of revealing relevant properties of a networked system structure [3]. It can be used for:
- Highlight the role of the network components, nodes and connecting arcs [4];
- Make preliminary assessments of vulnerability based on the simulation of defects (mainly represented by deleting nodes and arcs) and subsequent reevaluation of topological properties of the network [5].

During the last two decades a number of studies based on network theory, focused on the modeling of complex systems such as public transport infrastructure. They aim to understand how the network constituting a system influences the evolution of this one, in particular from standpoint of its characteristics of stability and robustness against vulnerabilities and attacks. The topological analysis of the network has been exploited for use as a screening tool to identify the key components in various types of infrastructure networks such railway networks [6]. In our study, the topological analysis based on network theory, is used to analyze the structural properties of the project risks network. The main idea here is that the risks faced by a large infrastructure project are not independent but are often interrelated and can change by propagation, hence their structuration in a network.

Therefore, the appeal to the network theory is not trivial but is a significant development in the field of research on the analysis and management of project risks. The purpose of this study is to identify critical risks and interactions among risks with regard to their roles in the network. This will provide valuable information that complements the traditional analysis based on the evaluation of the likelihood and impact of risks. The originality of this work manifests itself, particularly, through the application of topological analysis in the field of project risks management, and the adaptation of network theory indicators, in particular, the indicators of connectivity, interface and betweenness centrality. The application on a real complex engineering project allows us to validate the usefulness and feasibility of the proposed approach.

Topological Indicators for Project Risks Analysis

We represent the risks network by a graph G (N, K), wherein the identified risks are N nodes interconnected by K edges (also called arcs). The risks network is a directed network, where each arc Ri to Rj means that there is a cause-effect relation between the two potential risks Ri and Rj. We note MxRN the adjacent matrix of risks network [7]. This representation allows us to study the structural properties of the risks network topology with some relevant topological indicators adapted to our case study. These indicators can help identify key factors (critical risks or risks interactions) and improve understanding network vulnerabilities by the project manager [8]. In the following paragraphs we will introduce some common indicators and discuss their implications on the management of risks project.

Connectivity Indicators

Referring to the network theory, the density of the graph can be measured by the equation (1). We note that the numbers of nodes and risk areas describe the size and diversity of risks network. Usually, we can find that some pairs of nodes are disconnected, or even some non-connected nodes representing individual risks, which means that risk has no correlation with other risks in the network.

$$\text{Density (G)} = \frac{K}{N(N-1)} = \frac{\sum_{i,j \in G} MSRij}{N(N-1)} \quad (1)$$

The local connectivity characteristic of a risk is provided by the degree of nodes. The latter focuses on two key aspects that reflect the relationship of a risk with its immediate neighbor risks. The number of outgoing arcs measures the activity degree of a risk (Equation 2) and the incoming arcs give the passivity degree of it (Equation 3).

$$Activity\ Degree\ (R_i) = \sum_{j \in G} MxRNji \quad (2)$$

$$Passivity\ Degree\ (R_i) = \sum_{j \in G} MxRNij \quad (3)$$

Inside the risk network, there could be several different paths connecting a risk (node) to another via one or more stages (arcs). We define the network diameter as the upper value of the length of the shortest path from Ri to Rj [9]. This metric indicates the maximum number of steps required to spread the impact between two randomly chosen risks in the network.

To obtain more information on the global connectivity property of the risks, we study the accessibility degree of nodes. We introduce the concept of Risk Accessibility Matrix (RAMx), with $RAMx_{ij} = 1$ if there is at least one path from Ri to Rj. The shortest path between each pair of risks and RAMx can be achieved using the iterative algorithm of the shortest sequential path of Floyd [10-11].

The accessibility density defined by the equation (4) is a measure of the risk network complexity (RNC) based on the accessibility of risks.

$$RNC\ (G) = \sum_{i,j \in G} RAMxij\ /\ N(N-1) \tag{4}$$

In order to understand the generalized consequences and sources of a risk, and rank risks in different categories we introduce two helpful metrics. The Number of Accessible Nodes (Equation 5) shows the number of other risks that a particular risk may directly or indirectly influences. The Number of Possible Sources (Equation 6) shows that the occurrence of a designated risk can possibly come from many other risks in the network.

$$NAN\ (R_i) = \sum_{j \in G} RAMxji \tag{5}$$

$$NPS\ (R_i) = \sum_{j \in G} RAMxij \tag{6}$$

Interface Indicators

The interface indicators help project managers identify the interconnections between the different domains of risks, and enable them to improve the intercommunication between two correlated risk owners. It allows the grouping of risk owners to improve and coordinate decision-making.

In project management, risks are generally classified into different areas such as financial, contractual, technical and managerial domains. In addition, from the organizational perspective, different actors or project team officials are generally in charge of one or more risks. These are called risk owners. The number of interfaces between the domains/owners is defined as the number of arcs between each pair thereof. We distinguish two types of indicators counting the number of interfaces.

The indicators defined in equations (7) and (8) below, indicate the number of direct local interfaces from Dv to Du and from Pv to Pu respectively, where Dv and Pu represent the domain ‘v’ and the risk owner ‘u’.

$$IL_{Duv} = \sum_{Ri \in Du, Rj \in Dv} MxRN\ ij \tag{7}$$

$$IL_{Ouv} = \sum_{Ri \in Ou, Rj \in Ov} MxRN\ ij \tag{8}$$

The indicators defined in equations (9) and (10) indicate the global number of accessible interfaces from Dv to Du and from Pv to Pu respectively.

$$IG_{Duv} = \sum_{Ri \in Du, Rj \in Dv} RAMx\ ij \tag{9}$$

$$IG_{Ouv} = \sum_{Ri \in Ou, Rj \in Ov} RAMx\ ij \tag{10}$$

Betweeness Centrality

In order to anticipate the potential propagation of risks within the network we introduce another indicator of the graph theory to the analysis. In a risks network, a risk node or interaction arc between risks is considered as central if it lies in at least one of the connecting links of a pair of other nodes [12]. We focus here on the risk propagation phenomenon usually characterizing the complex projects. The Betweeness Centrality (*BC*) of the risk R_p and the Betweeness Centrality of the arc linking R_s to R_t can then be calculated by the following equations:

$$BC_p = \sum_{i,j \in G, i \neq j \neq p} RAMx_{pi}\ and\ RAMx_{jp} \tag{11}$$

$$BC_{s \to t} = \sum_{i,j \in G, i \neq j \neq s \neq t} RAMx_{si}\ and\ RAMx_{jt} \tag{12}$$

Knowing these centralities will help us to identify network hubs that act as key passages for the risk propagation. Consequently, the project manager must consider how to prevent the propagation of risks through these hubs by controlling risks and neutralizing their interactions.

APPLICATION OF TOPOLOGICAL ANALYSIS ON THE RISKS NETWORK OF RABAT TRAMWAY PROJECT

Presentation of the Project Selected for the Study

The Rabat tramway project allowed the realization of studies conducted by Transroute (Transportation Plan of 1976, and studies of 1982 and 2003) on the feasibility of transit lines in separate lanes in the agglomeration of Rabat-Salé. The objective of this project is to accompany the demographic growth of this agglomeration which increased from 1.318 million people in 2004 to over 2.2 million in 2014. In this context, based on the design studies conducted between 2005 and 2006, a public body, the Agency for the development of the Bouregreg valley, was appointed project master in partnership with urban municipalities of Rabat and Salé. The network will eventually include four lines requiring two crossings of the Bouregreg River. At present (December 2015), the network comprises two lines.

The work on the new tram started in the middle of 2006. The overall project cost is estimated at 3.8 billion dirhams, and commercial operation was launched May 23, 2011.

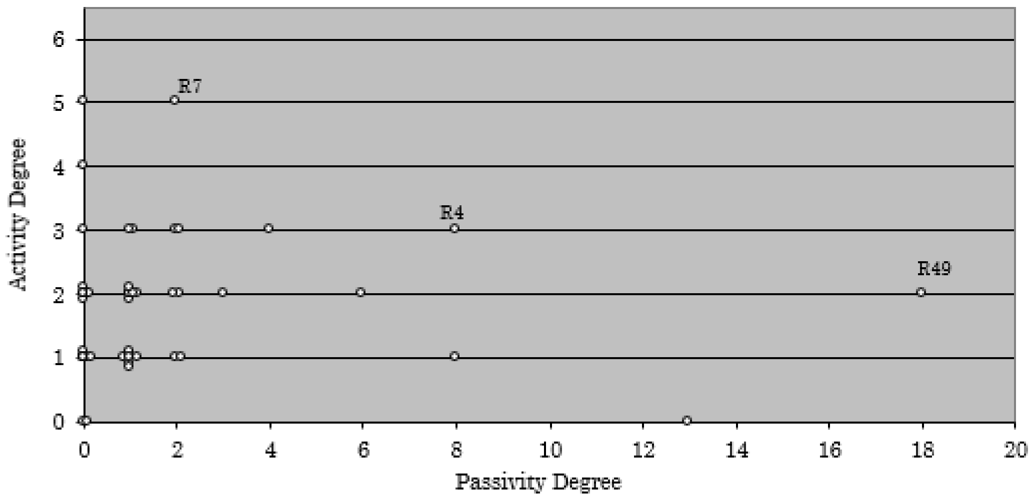
Topological Analysis of Risks Network in Rabat Tramway Project

Once the project risks network elaborated (work done upstream which we are not dealing in this paper), the network topological analysis can be realized by calculation and analysis of the indicators defined above. The project risk network (Figure 1, page 9) consists of 51 nodes (risks) and 95 arcs (interactions of risks), with only one non-connected node (R34) (see attached the full list of risks incurred by the Tramway project). The density of the graph is equal to 0.0401, indicating that the network is relatively scattered and dispersed. Furthermore, the hierarchical structure of the network is relatively flat (network diameter = 4). This means that a risk can provoke and influence another so a little easier through a shorter path under 4 steps. Most risks have one or two immediate inputs and outputs, implying that local connectivity of this network is not significant

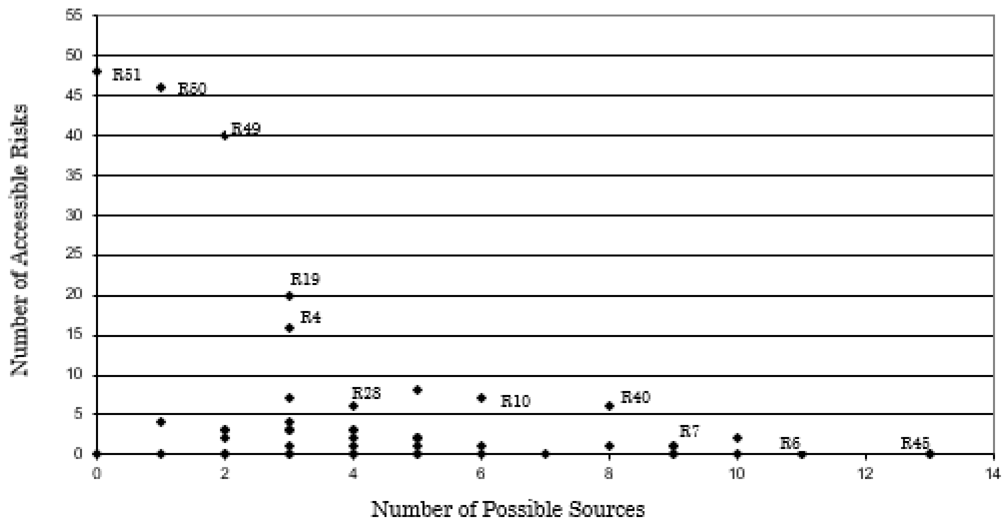
In the graphic 1 below, we represent the degree of activity and passivity of risks in a matrix diagram. The reading of result allows us to say that some risks can directly affect five other risks. Moreover, more risks have a large number of direct predecessors since the degree of passivity varies from 0 to 19.

In the graphic 2, we represent the accessibility degree of risks, which means the number of accessible nodes and the number of possible sources. Network accessibility density is equal to 0.0803. This shows that the risks network is more complex from the point of view of its accessibility compared to the low density of the graph equal to 0.0401. Some risks having few predecessors are likely to be sources of risk in their interactions with other risks. We cite, as an indication, the risks R6, R49, R27, R16 and R19.

Graphic -1 Activity and Passivity Degree of Risks



Graphic -2 Accessibility Degree of Risks



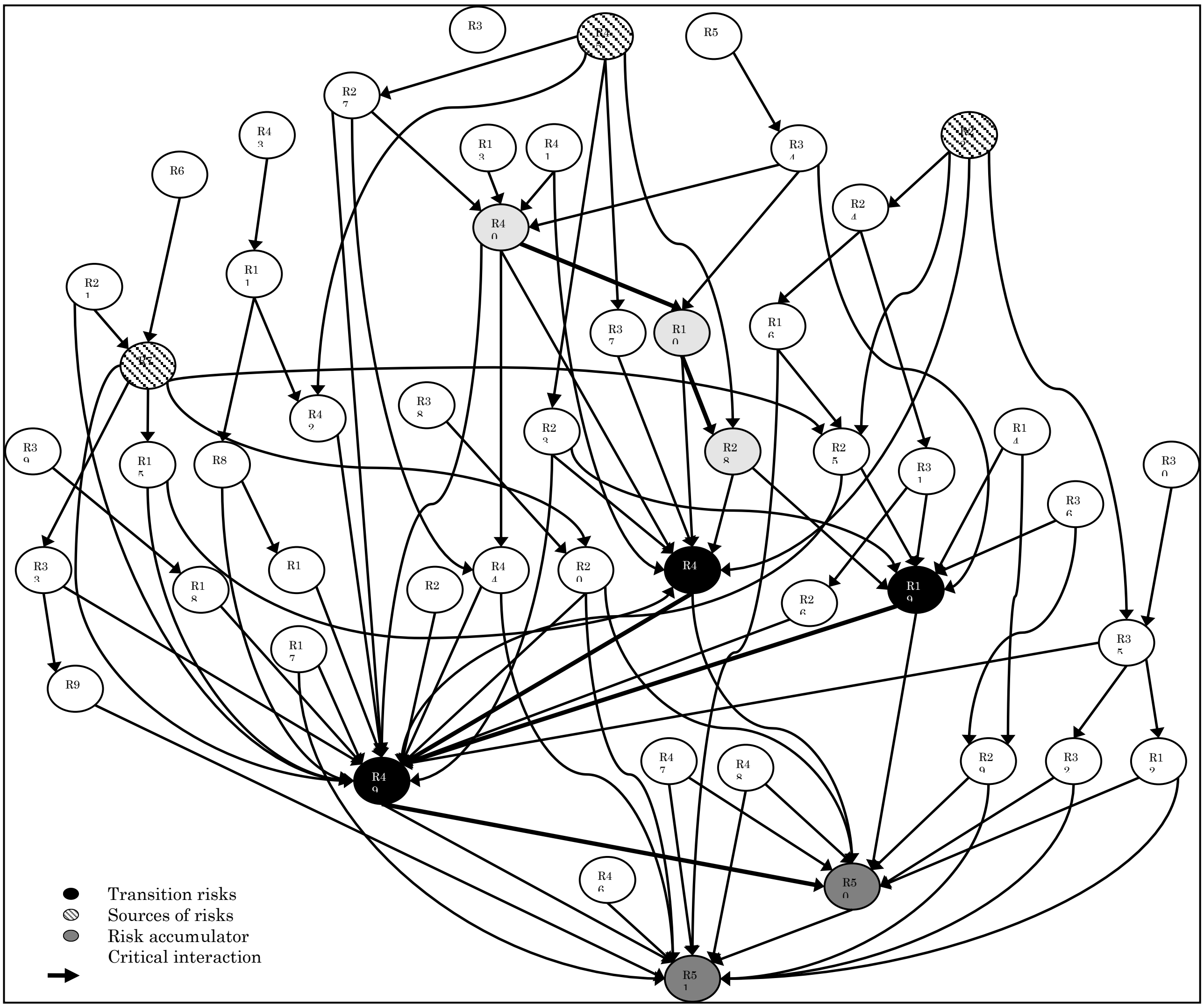


Fig. 1 Structure of Project Risks Network with Coloration of Critical Risks and Interactions

The reading of this graphic let us to distinguish three groups of risks. At first, the risks having few successors are considered risk accumulators when they arise from many possible sources of risk. They are often related to project results, such as financial performance (R50 and R51). Then, the risks lying in the middle of the area away from the graphic axes act as transition risks. Some of these risks, having several inputs and few outputs, are closer to risk accumulators. We cite particularly the risks R49 (damages and penalties for delay in payment), R19 (Reengineering) and R12 (Delay operating certificate). Other risks are closely related to risks source such as R45 (New local laws and regulations) and R7 (delay in civil works). Furthermore, have approximately the same number of possible sources and accessible nodes such as R40 (Performance in travel time), R10 (reliable and achievable goals) and R28 (Risk on certification of our equipment). These categories of risks are schematized by different forms in the risks network shown in Figure 1. This risks classification according to their number of inputs and outputs helps the project manager in his decision of how to treat them, regardless of their individual assessment.

Tables 1 and 2 below show the number of interfaces between risk domains on the one hand, and risk responsible (we note them P) on the other hand, from local and global perspective. We mean by local perspective the direct interactions, and by global perspective the indirect interactions. Since most risks belong to the domains D1-technical, D2-contractual, and D3-financial, many interactions involved them.

In the first table (Table 1), we ascertain that a lot of direct connections are inside a specific domain (local perspective). However, in the global perspective many interfaces between different domains have emerged. That is to say that the risks of a given domain may indirectly cause the risk of another. For example, the risks from D1-technical will cause indirectly the risks belonging to domains D2 and D3 (contractual or financial). Contrariwise, the risks of domains: D4-customer/partner/subcontractor, D5-project management and D6-countries have no direct influence on the financial risks (D3), but can reach them after several propagation stages.

Similarly, many indirect interfaces appear between risks responsible. In the table of interfaces between risks responsible from a local perspective, we find that the responsible P2 is the only to be influenced by all the other responsible. In the table of interfaces between risk responsible from a global perspective, the potential influences are significantly increased due to several actors (cases of P1, P3 and P4). In addition, the risks of propagation for certain responsible are imminent, and they must therefore take this phenomenon into consideration seriously. We cite the case of the P2-P3 interaction which went from 0 to 8.

Table 3 shows the first five nodes and the first five arcs having the highest betweeness centrality. The risks with higher betweeness centrality as R49 (damages and penalties for delay in payment) and R19 (Reengineering) act as hubs connecting many pairs of risks. Furthermore, as can be seen, the major arcs are related to the same main risks (those whose betweeness centrality is very high). R40 and R10 are the sources of many events and should, therefore be treated with caution, especially through preventive or encirclement measures or by containment actions (the arcs from R40 or from R10). The encirclement measures are a very recent innovation of the project risks management, where the actions have focused only on the nodes.

Table 1- Interfaces Between Risk Domains from a Local and Global Perspective

Local	D1	D2	D3	D4	D5	D6
D1	11	8	0	2	0	1
D2	14	22	0	1	2	1
D3	4	10	5	0	0	0
D4	0	0	0	0	0	0
D5	1	1	0	0	0	0
D6	1	1	0	0	0	0

Global	D1	D2	D3	D4	D5	D6
D1	24	25	0	5	0	1
D2	38	40	0	4	3	3
D3	34	37	5	2	4	2
D4	0	0	0	0	0	0
D5	1	2	0	0	0	0
D6	5	2	0	0	0	0

Table 2- Interfaces Between Risk Owners from a Local and Global Perspective

Local	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11
P1	1	1	1	2	0	0	0	1	0	0	0
P2	5	12	8	10	4	4	2	0	1	2	1
P3	0	0	0	1	0	0	0	2	2	1	0
P4	4	0	2	4	1	0	0	0	0	1	1
P5	0	0	0	1	0	0	1	1	0	0	0
P6	0	0	0	0	0	0	0	0	0	0	0
P7	1	0	0	0	0	0	2	0	0	0	0
P8	0	2	0	0	0	0	0	0	0	0	0
P9	0	0	0	1	0	0	0	0	0	0	0
P10	0	0	0	0	0	0	0	0	0	0	0
P11	1	0	0	1	0	0	0	0	0	0	0

Global	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11
P1	2	2	3	4	0	0	0	2	0	3	0
P2	26	27	17	46	14	4	10	2	4	6	3
P3	0	8	0	1	0	0	0	2	2	1	0
P4	13	2	2	20	1	0	0	0	1	2	1
P5	0	2	0	1	0	0	2	1	0	0	0
P6	0	0	0	0	0	0	0	0	0	0	0
P7	1	0	0	0	0	0	3	0	0	0	0
P8	0	2	0	0	0	0	0	0	0	0	0
P9	0	0	0	1	0	0	0	0	0	1	0
P10	0	0	0	0	0	0	0	0	0	0	0
P11	2	0	0	5	0	0	0	0	0	0	0

Table 3- The Most Important Risks and Arcs According to their Betweeness Centrality

Rank	Risk n°	Betweeness Centrality	Arc	Betweeness Centrality
1	R49	92	R40-R10	40
2	R19	65	R49-R50	38
3	R40	53	R10-R28	36
4	R4	45	R19-R49	32
5	R10	44	R4-R49	31

CONCLUSION

This working paper presents an original analysis of project risks based on network theory. The aim is mainly to understand how risks affect the network and what their roles are. First, the risks project network must be built and set up, according to well-defined steps. The attention at this level is put on the particularity of a risks project network compared to other physical infrastructure networks, such as electricity transmission networks. A risks project network links elements (risk nodes) which may possibly be affected by the potential propagation (arcs of risk interactions) of the effects of various kinds. The specificity of this network is to involve potential interactions between nodes that are not necessarily related to physical and material characteristics, such as the risk of delays for example.

The indicators of network theory are specifically tailored to project risk analysis, in order to complement the traditional approach to modeling the complexity of interrelated risks. Some connectivity indicators and betweeness centrality are introduced to identify critical risks and interactions among risks within the network. The interface indicators, which indicate the interconnections between different domains and between different owners in terms of risks propagation, are useful for the project manager to make decisions concerning the organization of the project and to undertake reallocations.

The empirical study included in this work concerning a major project, the tramway of Rabat, is done with the participation of the project manager and the team of experts. The results obtained show that the topological analysis of risks network is a considerable added value that complements the classical analysis of risks project by following a robust mathematical approach, making use of network theory and matrix calculus. This analysis is able to identify both the critical risks and interactions among risks. This analysis provides additional information to use in the next step, that of decision making. As a matter of fact, risk taken individually can be non-critical, but by its interactions with other risks could become the source of some other risks and critical risks. Based on the analysis results, a combination of feasible and possible mitigation measures must be proposed and applied to the initial risk network.

Finally, we can say that the implementation of this method on the management of project risks should be applicable to a wide range of engineering projects to facilitate decision-making, especially for programming of risk mitigation measures and the reallocation of work teams.

ANNEXURE: Exhaustive List of Project Risks and their Characteristics

Risk n°	Nature	Domain	Number of risk owners	Likelihood of risk	Impact of risk	Criticality of risk
1	Permits and authorizations	Contractual	2	7	4	28
2	Security Studies	Technical	2	1	1	1
3	Safety of building sites	Contractual	3	2	1	2
4	Delay of the operating certificate	Contractual	2	6	4	24
5	Error in topographic survey	Technical	4	1	2	2
6	Responsibility of the building owner in delays in civil works	Contractual	2	8	3	24
7	Delays in civil works	Contractual	7	8	4	32
8	Delays due to late decisions of the project owner	Contractual	4	8	2	16
9	Storage of wagons in other city	Contractual	1	8	5	40
10	Reliable and achievable goals	Technical	4	2	3	6
11	Gap building owner / operator / dealer	Contractual	7	3	5	15
12	Banks stop financing the project	Contractual	2	5	3	15
13	Pedestrian zones	Technical	5	2	2	4
14	Initial specifications of civil works	Technical	3	4	2	8
15	Delay in energy supply	project Management	4	2	2	4
16	Isolation of the track	Technical	8	1	3	3
17	Vandalism on the construction site	Contractual	6	1	4	4
18	Installing the operating center (control center)	project Management	11	6	5	30
19	Reorganization of production process and working methods (Reengineering)	Technical	3	8	2	16
20	Delay in slabs delivery	Technical	3	5	1	5
21	Archaeological objects in excavations	Contractual	3	9	2	18
22	Performance of the rails Installation Machine	Operator/ST/PO	10	3	3	9
23	Electromagnetic interferences	Technical	4	1	2	2
24	Interface rail / wheel	Technical	4	3	3	9
25	Installation rails delay	Technical	3	7	3	21
26	Delay in delivery of rolling stock	Technical	1	3	1	3
27	Signaling traffic, priority at intersections	Contractual	6	5	5	25
28	Risk on the certification of our equipment	Country	4	1	2	2
29	Potential claims of subcontractors	Contractual	2	4	5	20
30	Non conformity of rolling stock to specifications	Technical	1	1	7	7
31	Non-compliance of the rolling stock with the technical specifications	Contractual	1	3	3	9
32	Modification costs not covered by the extension of time agreement	Contractual	4	2	4	8
33	Depot delay	Technical	3	7	2	14

34	Train performance	Technical	2	2	2	4
35	Risk of partial rejection of our demand for extension of time limit	Contractual	2	9	7	63
36	Additional overcost	Contractual	4	8	5	40
37	Overcost due to train security requirements	Technical	4	4	4	16
38	Attenuation of noise and vibration	Technical	4	4	5	20
39	Scope of video surveillance	Technical	9	6	1	6
40	Performance in travel time	Technical	4	1	4	4
41	Waiting time at stations	Contractual	3	5	1	5
42	Ticketing operation delay	Contractual	6	6	1	6
43	Requirements in collecting customer payments	Contractual	5	5	4	20
44	Additional trains	Contractual	4	2	6	12
45	New local laws and regulations	Contractual	1	1	3	3
46	Inherent tax risk	Financial	2	2	2	4
47	Exchange risk on supplier	Financial	2	1	3	3
48	Exchange risk	Financial	4	2	2	4
49	Damages and penalties for delay in payment	Contractual	2	6	7	42
50	Cash flow Decrease	Financial	2	8	7	56
51	Profit decrease	Financial	2	8	8	64

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