



## Network theory-based analysis of risk interactions in large engineering projects

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### ABSTRACT

This paper presents an approach based on network theory to deal with risk interactions in large engineering projects. Indeed, such projects are exposed to numerous and interdependent risks of various nature, which makes their management more difficult. In this paper, a topological analysis based on network theory is presented, which aims at identifying key elements in the structure of interrelated risks potentially affecting a large engineering project. This analysis serves as a powerful complement to classical project risk analysis. Its originality lies in the application of some network theory indicators to the project risk management field. The construction of the risk network requires the involvement of the project manager and other team members assigned to the risk management process. Its interpretation improves their understanding of risks and their potential interactions. The outcomes of the analysis provide a support for decision-making regarding project risk management. An example of application to a real large engineering project is presented. The conclusion is that some new insights can be found about risks, about their interactions and about the global potential behavior of the project.

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### 1. Introduction

Projects are usually complex and risky. They require the timely accomplishment of a number of activities, carried out by a number of human and material resources. Unexpected conditions or planning errors may lead to failures which can undermine the successful realization of the project on numerous parameters, like time, cost, scope, quality, safety, security, health, and environment. We refer to such events as project risks, when they are identified, analyzed and treated before they occur. Within the same project, the existence of interrelated risks involves that the occurrence of one risk may trigger one or more other risks with potential propagation phenomena like reaction chains, amplification chains or loops. In this sense, in this paper we talk of risk interdependency between two risks. A consequence of a risk is then triggering of another risk and not the direct impact of the risk itself (e.g., on time, scope or cost), which of course exists but is not the focus here. The consequence of this complexity is a lack of capacity to anticipate and control the behavior of the project.

Large engineering projects are facing a growing complexity, in both their structure and context due to the involvement of numerous, diverse and strongly interrelated elements [1–3]. This has sparked research works on the concept of complexity, under two main scientific approaches [4]. The first one, usually known as the field of descriptive complexity, considers complexity as an intrinsic property of a system. For example, Baccharini in [1] considers project complexity through the concepts of technological complexity and organizational complexity. He regards them as the core components of project complexity which he tries to describe exhaustively. The second approach, usually known as the field of perceived complexity, considers complexity as subjective, since the complexity of a system is improperly understood through the perception of an observer. According to Vidal and co-workers, “project complexity is the property of a project which makes it difficult to understand, foresee and keep under control its overall behavior, even when given reasonably complete information about the project system. Its drivers are factors related to project size, project variety, project interdependence and project context” [5].

In this setting, Project Risk Management (PRM) is an indispensable activity for project management, even more for large engineering projects dealing with large stakes and involving interdependent activities and organizations [6–9]. In PRM, risk

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analysis is used for evaluating and prioritizing risks, essentially with respect to their probability and impact. The outputs of the analysis support decision-making, e.g., in terms of planning response actions and allocating resources.

In practice, the PRM methodologies are often used to analyze risks independently, according to their individual characteristics, with more or less detailed and quantitative approaches, based on experience and/or expertise [10–16]. Various methods can be used to identify causes and effects of a single risk. For instance, Failure Modes and Effects Analysis (FMEA) consists in a qualitative analysis of dysfunction modes followed by a quantitative analysis of their effects, in terms of probability and impact (or severity) [17,18]; fault tree and cause tree analyses determine the conditions which lead to an event and link them through logical connectors in a tree-structure which clearly displays causes and effects of the particular risk analyzed [19]. Other techniques, like Bayesian networks, system dynamics or Monte-Carlo simulation exist [20–22]. But these methods are focused on risk prioritization considering probability and/or impact of the risks, called Probability-Impact Grid (PIG). Some researchers highlight the weakness related to the fact that important interdependencies are not considered in PRM processes using the PIG approach [23–25]. The importance of modeling interdependencies, and techniques to do this, are presented in several works, whether directly on risk [26,27] or indirectly on other objects inside the project [28,29].

In the work here presented, the complexity of interactions among project risks is modeled and represented in terms of a risk network [30]. A topological analysis is then performed on this network, with the aim of giving complementary information, prioritizing some risks and risk interactions in relation to their position in the network. This is relevant because in some cases, it may happen that risks of minor concern are the source of a sequence of propagating effects whose outcome is of far higher severity.

A method based on Design Structure Matrix (DSM) [31] is introduced to build the network of risk interactions. A topological analysis typical of network theory is then performed to identify the characteristics of the resulting risk network. In the last decade, a number of studies have focused on the modeling of complex systems such as critical infrastructures from the standpoint of network theory, to understand how the topological network underlying the system influences its behavior, and eventually its characteristics of stability and robustness to faults and attacks [32]. Topological network analysis has been exploited to serve as a screening tool to identify key components in different types of infrastructure networks, like power transmission systems [33] and railway networks [34] for example. The originality of the work presented in this paper is the tailoring and application of network theory-based topological analysis in the context of project risk management. The application to a real large engineering project enables the usefulness and practicality of the approach to be validated.

The paper is organized as follows. In Section 2, the modeling of project risk network is introduced, with the identification and assessment of risks and risk interactions. Section 3 introduces some topological indicators and explains how the network theory-based topological analysis is performed on the project risk network. An example of application to a tramway implementation project is presented in Section 4. The added value and applications to decision support are discussed in Section 5. Some conclusions are drawn in Section 6, with perspectives on future work.

## 2. Building the structure of project risk network

To perform the topological analysis for exploring the risk interactions-based properties, the project risk network should

be constructed. In the following parts of this section, we introduce the process of building the project risk network structure.

### 2.1. Step 1. Risk identification using classical methods

Risk identification is usually the first step for project risk analysis, aimed at determining events which could affect project objectives positively or negatively [35]. This paper mainly focuses on the conventional risk events with negative effects. There are a number of classical methods for identifying individual project risks. They are based on analogy [36–38], on heuristics [39,40] or are analytic [41]. Our study uses directly the risks previously identified by the project manager using these classical methods. The result of these analyses, the project risk list, serves as an input for studying risk interactions. Even if some authors propose an approach to risk dynamics analysis [42], the process is performed with a stable list of risk with stable characteristics.

### 2.2. Step 2. Identification of risk interactions using DSM method

Identification of risk interactions is the step of determining the cause-effect relationship between risks. This is also the main step for building the project risk network structure. Risk interaction is considered as the existence of a possible precedence relationship between two risks  $R_i$  and  $R_j$ .

The Design Structure Matrix (DSM) method introduced by Steward [31] has proven to be a practical tool for representing and analyzing relations and dependencies among components in system design [43,44]. In our work, we propose to extend the concept of DSM to risks in project management. The interrelations between project objects, such as activities, actors and product components, can facilitate the identification of interrelations between the risks related to these objects. For instance, the project schedule gives information about activity-activity sequence relationships. This enables the relationship between two risks of delay for these activities to be identified. A component-component relationship (whether functional, structural or physical) means that risks, which may be related to product functions, quality, delay or cost, can be linked, since a problem on one component may have an influence on another (budget limits, for instance). In a similar way, the Domain Mapping Matrix (DMM) introduced by Danilovic and Browning [44] and Multiple-Domain Matrix (MDM) introduced by Lindemann, Maurer and Braun [45] are helpful in identifying risk interactions across different domains of the project.

We define the Risk Structure Matrix (RSM), which is a binary and square matrix with entry  $RSM_{ij}=1$  when there is a relationship link from  $R_i$  to  $R_j$ . Fig. 1 gives an example of the RSM representation of a network of risks.

When performing the risk interaction identification, new risks may appear, for two reasons. Some are a consequence or cause of other risks already present in the initial list; others are seen as

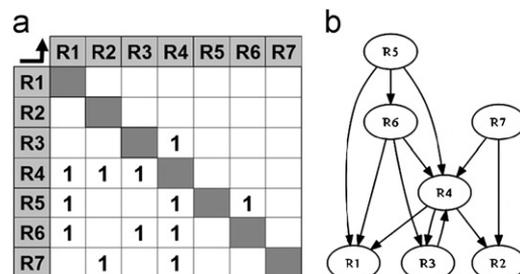


Fig. 1. Illustration of RSM and project risk network (adapted from [30]); (a) example of RSM; (b) example of project risk network.

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