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Abstract: Engineering projects are facing a growing complexity and are thus exposed to numerous and interdependent risks. In this paper, we present a quantitative method for modelling propagation behaviour in the project risk network. The construction of the network requires the involvement of the project manager and related experts using the Design Structure Matrix (DSM) method. A matrix-based risk propagation model is introduced to calculate risk propagation and thus to re-evaluate risk characteristics such as probability and criticality. An eigenstructure analysis is also used based on the risk network, with the goal of measuring and prioritising risks with respect to their importance in terms of influence in the network. These supplemental project risk analyses provide project managers with improved insights on risks considering complexity and help them to design more effective response actions. An example of application to a real urban transportation system implementation project is presented to illustrate the utility of the proposed approach.

Keywords: risk interaction, complexity, design structure matrix, risk propagation, project risk management

1. Introduction

Project risk management (PRM) is crucial to the success of projects. Unexpected conditions or planning errors may lead to delays, over-costs and other failures which can undermine the successful realization of the project. We refer to such potential events which may affect positively or negatively project activities and project results as project risks. Risk analysis is an indispensable activity for project management, even more for complex projects dealing with large stakes and involving interdependent tasks and organizations (Eckert *et al.* 2004, Kloss-Grote and Moss 2008). In classical PRM, risk analysis is used for evaluating and prioritizing risks, essentially with respect to

their probability and impact (Chapman and Ward 2003, PMI 2008). The outputs of the analysis support decision-making, e.g., in terms of planning response actions and allocating resources.

Projects are facing a growing complexity, in both their structure and context. In addition to the organizational and technical complexities described by Baccarini (Baccarini 1996), project managers have to consider a growing number of parameters (e.g., environmental, social, safety, and security) and a growing number of stakeholders, both inside and outside the project. The existence of numerous and diverse elements which are strongly interrelated is one of the main characteristics of complexity (Corbett *et al.* 2002, Chu *et al.* 2003, Jones and Anderson 2005). The complexity of project leads to the existence of a network of interdependent risks (Fang and Marle 2012), where complex phenomena may occur, hard to anticipate and hard to keep under control. For instance, there might be propagation from one "upstream" risk to numerous "downstream" risks; on the other side, a "downstream" risk may arise from the occurrence of several "upstream" risks which may belong to different categories. The extreme case of this propagation behaviour is the chain reaction phenomenon or the "domino effect". Another phenomenon is the loop, namely a causal path that leads from the initial occurrence of an event to the triggering of subsequent consequences until the initial event occurs once more. An example of loop is that one initial risk, project schedule delay, may have an impact on a cost overrun risk, which will influence a technical risk, and then propagate to and amplify the original risk of schedule delay.

Many risk management methods and associated tools have now been developed. They are usually based on two concepts: probability and impact, assessed by qualitative or quantitative approaches. Many of these methods independently evaluate the

characteristics of risks, and focus on the analysis of individual risks. Risks are usually listed and ranked by one or more parameters (Williams 1995, Baccarini and Archer 2001, Raz and Michael 2001). Generally, these methods do not take into account the subsequent influence of risks and cannot represent the interrelation between them. We can also cite the creativity-based or the expertise-based techniques, like expert judgement using Delphi, affinity diagram, peer interviews or risk diagnosis methodology (RDM) (Kawakita 1991, Kerzner 1998, Keizer *et al.* 2002).

To comprehensively understand a risk, it is helpful to identify its causes as well as its effects. Several methods include this principle, but they still concentrate on a single risk for simplifying the problem (Carr and Tah 2001, Heal and Kunreuther 2007). 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 (Stamatis 2003); fault tree and cause tree analyses determine the conditions which lead to an event and use logical connector combinations (Pahl *et al.* 2007, Ferdous *et al.* 2011). These methods are unable to model complex interactions among different risks. Few specific methods are able to model risk correlations with a network structure. Several papers on the application of the Bayesian belief network (BBN) have appeared in recent years in the field of project risk management (Fan and Yu 2004, Lee *et al.* 2008, Trucco *et al.* 2008), which could model risk interrelations, from multiple inputs to multiple outputs. Nevertheless, BBN demands oriented links, is inherently acyclic, and hence does not easily model the loop phenomenon. These methods are thus not always applicable for practical purpose and fail in some cases to represent the real complexity of the interdependencies among risks.

In the last decade, a number of studies have focused on the modelling of complex systems such as critical infrastructures from the standpoint of network theory, to understand how the network underlying the system influences its behaviour, and eventually its characteristics of stability and robustness to faults and attacks (Zio 2007). Some network centrality measures have been applied, for the first time, to large-scale engineering design and product development networks by Braha and Bar-Yam in (Braha and Bar-Yam 2004b, Braha and Bar-Yam 2004a, Braha *et al.* 2006, Braha and Bar-Yam 2007). These works have provided two interesting results. First, they have shown by analysing large scale product design and development networks that many of these measures are highly correlated. Second, they have shown that the robustness and stability of complex engineering systems is closely linked with the existence of hubs, and that the network behaviour is sensitive to its structure. In addition, eigenstructure or eigenvector analysis has been used for identifying key features in the engineering design iterations in (Smith and Eppinger 1997) and for exploring some hiding information in the complex product development projects in (Yassine *et al.* 2003).

Since all these measures have been proven to be relevant for the analysis of complex networks, some of them are tailored and applied in this work, for the first time, in the area of project risk management. With a view to exploring the interrelationships among project risks, a matrix-based approach for building the project risk network and analysing risk propagation behaviour is proposed. Classical project risks lists are used as the inputs of the network model. They usually only take into account the negative aspects of risks. Existing methods like the Design Structure Matrix (DSM) for dependency modelling are employed to identify and evaluate risk interactions. An eigenstructure analysis is used with the goal of measuring the importance of risks in the

network. A risk propagation model is introduced to calculate risk propagation and thus to re-evaluate risk probability and criticality taking into account risk interactions. The aim is to provide project managers with an improved quantitative risk analysis method and thus to support them in making more reliable risk response planning decisions.

The paper is organized as follows. Section 2 describes the process of building the project risk network. Section 3 performs an eigenstructure analysis based on the risk network for measuring risk importance in terms of influence in the network. Section 4 presents a matrix-based risk propagation model for re-evaluating risk characteristics and updating risk prioritisation. An example of an application to a real project in the construction industry is presented in Section 5 to illustrate the proposed method. We conclude the paper in Section 6 with a discussion of the proposed approach and perspectives.

2. Modelling of project risk network

There are a number of classical methods for identifying individual project risks based on analogy (Riek 2001, Smith and Merritt 2002), on heuristics (Kerzner 1998, Chapman 2001) or analytically (Shimizu and Noguchi 2005). The resulting project risk list serves as an input for studying risk interactions in order to build the project risk network.

Nomenclature

R_i	*Risk i*
RSM_{ij}	*(i, j)-th element in the risk structure matrix*
RNM_{ij}	*(i, j)-th element in the risk numerical matrix*

p	*quantitative risk probability measure*
q	*qualitative scale of risk probability*
α, β	*parameters in the probability conversion equation*
M	*a square matrix*
λ	*eigenvalue of M*
v	*eigenvector of M*
A	*denotation of the RNM of the weighted risk network*
A^T	*transpose matrix of A*
a_{ij}	*(i,j)-th element of A, denotation of* RNM_{ij}
x_i	*importance score of* R_i
x	*vector of risk importance score*
$IN(i)$	*set of nodes that are direct predecessors of* R_i
$OUT(i)$	*set of nodes that are direct successors of* R_i
λ^*	*largest eigenvalue of* $A+A^T$
s	*vector of risk spontaneous probability*
I	*N-order identify matrix*
$P(R)$	*vector of refined risk probability*
$G(R)$	*vector of original evaluated risk impact (G for gravity)*
$C(R)$	*vector of refined risk criticality*
$P_{R_i}(R_j)$	*probability of* R_j *as the consequence of* $P(R_i)$

2.1. Identification of risk network

Identification is the first step of determining the dependency relationship between the identified risks. The design structure matrix (DSM) method introduced by Steward

(Steward 1981) has proven to be a practical tool for representing and analyzing relations and dependencies among system components (Browning 2001, Danilovic and Browning 2007). For our study, we use the concept of DSM with risks, in the context of project management. There are three ways to identify risk interactions. First, the formal interrelations between project objects such as tasks, actors and product components facilitate identifying the interrelations between the risks related to these objects. For instance, the project schedule gives information about task-task sequence relationships. This helps to identify the correlation between two risks of delay for these tasks. A component-component relationship (functional, structural or physical) means that the risks, which may be related to product functions, quality, delay or cost, can be linked, since one problem on one component may have an influence on another (e.g., budget limits). This may be modelled using DSM, which are square matrices linking homogeneous natures of objects. Second, in a similar way, the domain mapping matrix (DMM) introduced by Danilovic and Browning (Danilovic and Browning 2007) are helpful in identifying risk interactions across different domains of the project. This may be modelled in only one matrix, using the combination of square DSM and rectangular DMM, called multiple-domain matrix (MDM) introduced by Lindemann and co-workers (Lindemann *et al.* 2008). Third, there may be relationships between risks related to the same object, like for instance risk of delay and risk of overcost for a task.

Whatever the nature (or type) of dependency between two objects (homogeneous or heterogeneous) or two attributes of the same object, it is transformed into a single interaction between two risks. These risks may be related to the same object or not, and may be of the same nature or not. Risk interaction is thus considered as the existence of a possible precedence relationship between two risks. We define the

Risk Structure Matrix (RSM), which is a binary and square matrix with $RSM_{ij} = 1$ when there is a link from R_j to R_i. It does not address concerns about the probability or impact assessment of this interaction. We put a sanity check between R_i and R_j. Suppose we know that the actor who owns R_i declared R_j as a cause. If the actor who owns R_j did not declare R_i as a consequence, then there is a mismatch. This means that the two actors are not always mutually aware of their interaction, and this is the case in reality. Each mismatch is studied and solved by asking simultaneously to both actors if there is or not a potential dependency relationship between the two risks they own respectively, like the analogous works by Sosa and co-workers about the interactions between project actors (Sosa *et al.* 2004).

Figure 1 gives an example to show the use of such a RSM to represent the structure of the risk network.

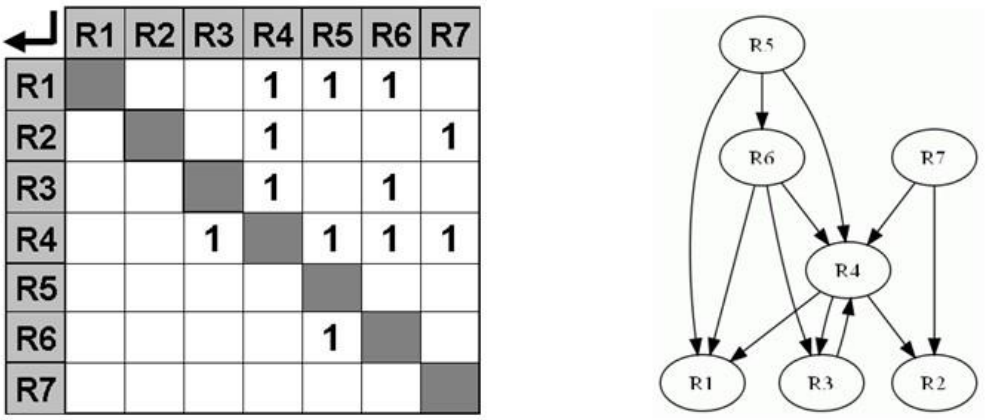

Figure 1. Illustration of RSM (adapted from (Fang and Marle 2012))

2.2. Assessment of risk network

In the assessment step, we not only evaluate risk characteristics such as risk probability and risk impact, but also assess the strength of risk interactions, which is interpreted as

transition probability between risks.

Risk impact may be assessed on a qualitative scale (ordinal or cardinal scale with 5 or 10 levels for instance) or on a quantitative scale (financial loss for instance). Risk impact is assessed by classical methods, based upon a mix of previous experience and expert judgement.

For the probability assessment, we make a distinction between the probability of a risk to be triggered by another risk inside the network and its probability caused by external events or risks which are outside the system. Spontaneous probability can be interpreted as the evaluated likelihood of a risk, which is not the effect from other activated risks inside the system. On the other hand, transition probability is the evaluation of direct cause-effect relation between two risks. For the example in Figure 1, Risk 5 occurs only in accordance with its spontaneous probability; and Risk 6 may arise from both its spontaneous probability and the transition probability between Risk 5 and Risk 6.

Qualitative scales are often used to express probability with 5 to 10 levels (e.g., very rare, rare, unlikely, etc.) which correspond to non-linear probability measures (e.g., 10^{-4}, 10^{-3}, 10^{-2}, etc.). Logarithmic scales have been used by statisticians for decades (Fleiss 1981). They allow to distribute probabilities unevenly. In practice, they devote more space to small values, imposing a compressed, logarithmic mapping. Based on this principle, we can use, for example, the following equation for converting qualitative scales into quantitative measures of risk probability:

$$p = \alpha * 10^{(\frac{-\beta}{q})} \quad (1)$$

where p indicates the quantitative probability measure, q indicates the qualitative scale

value, with parameters $\alpha > 0, \beta > 0$ which are set by experience and are case-dependent.

A numerical structure matrix can provide more detailed information than a binary one about the risk network for assisting decision-making. Thus the RSM can be converted into the Risk Numerical Matrix (RNM) through assessing the risk interaction. RNM_{ij} is defined as the strength value of the cause-effect interaction from R_j to R_i. With regard to the project risk network, values in the RNM can also be interpreted as the transition probability between risks. For example, if the element *RNM(4,3)* is equal to 0.25, then the probability of Risk 4 originating from Risk 3 is considered to be 25% under the condition that risk 3 is activated.

3. Eigenstructure analysis

In mathematics, eigenvalues and eigenvectors are related concepts in the field of linear algebra, which describe characteristics of a matrix. Analysing these eigenstructure properties gives important information about the adjacency matrix and its related network. The mathematical expression of eigenstructure decomposition is as follows: if M is a square matrix, a non-zero vector v is an eigenvector of M if and only if there is a scalar λ such that

$$Mv = \lambda v \tag{2}$$

The scalar λ is said to be the eigenvalue of M corresponding to v.

Bonacich suggested that the eigenvector of the largest eigenvalue of an adjacency matrix could make a good network centrality measure (Bonacich 1972). For example, the variant of the eigenvector centrality measure is used in Google's PageRank® algorithm (Page *et al.* 1999). Another closely correlated centrality measure

is the Katz centrality measure (Katz 1953). In our study, we perform eigenstructure analysis on the risk network with the intention of exploring importance measurement of project risks within the network context.

Let x_i denote the score of the *i*-th node, i.e., the measure of the importance of Risk *i*. We use the square matrix *A* to represent the RNM of the weighted risk network. Hence, $A = (a_{ij}) = RNM_{ij}$ and

$$\begin{cases} 0 < a_{ij} < 1 & \text{if there is an edge joining node } j \text{ to } i \\ a_{ij} = 0 & \text{otherwise} \end{cases} \tag{3}$$

For the *i*-th node, let its score x_i be proportional to the sum of the scores of all the nodes which are directly connected to it. Here we take into account both the input and output links, i.e., both the immediate predecessor and successor risks of Risk *i* in the network. Thus, we get the following equation:

$$x_i = \frac{1}{\lambda} \sum_{j \in IN(i)} a_{ij} \cdot x_j + \frac{1}{\lambda} \sum_{j \in OUT(i)} a_{ji} \cdot x_j = \frac{1}{\lambda} \sum_{j=1}^{N} (a_{ij} + a_{ji}) x_j \tag{4}$$

where *IN*(*i*) is the set of nodes that are direct predecessors of the *i*-th node and *OUT*(*i*) is the set of nodes that are direct successors of the *i*-th node. In this way, the importance score of R_i is equal to the average importance score of all its neighbour risks. Then we can reformulate the Eq. (4) as:

$$x = \frac{1}{\lambda} (A + A^T) x \tag{5}$$

where A^T is the transpose matrix of *A*, and then as the eigenvalue equation:

$$(A + A^T) x = \lambda x \tag{6}$$

In general, there will be many different eigenvalues λ for which an eigenvector solution exists. However, in linear algebra, the Perron–Frobenius theorem, proved by Perron and Frobenius (Perron 1907), (Frobenius *et al.* 1912), asserts that a real square matrix with positive entries has a unique largest real eigenvalue and that the corresponding eigenvector has strictly positive components, and also asserts a similar statement for certain classes of nonnegative matrices. Usually, the Perron-Frobenius theorem applies to our case of risk network and the matrix $A+A^T$.

We define the *i*-th element x_i of the eigenvector corresponding to the largest eigenvalue λ^* as the eigenvector centrality of R_i in the risk network. Eigenvector centrality is a measure of the importance of a node in the risk network. It assigns relative centrality scores to all nodes in the network based on the principles: (1) connections to more nodes contribute more to the score of the node; (2) connections to high-scoring, namely important nodes, contribute more to the score of the node; (3) higher strength of the connection to other nodes contributes more to the score of the node.

In this sense, eigenvector centrality calculates not only direct connections but also indirect long-term propagations. Thus the complete risk network is taken into account. Mathematically, eigenvector centrality is closely related to the influence measures, such as those proposed in (Katz 1953, Taylor 1969, Friedkin 1991, Hadi 1992). The idea is that even if a node influences directly only one other node, which subsequently influences many other nodes (who themselves influence still more others), then the first node in that chain is highly influential (Borgatti 2005). For calculating the risk eigenvector centrality, besides the output links of a risk which contribute to its impact measure in the network, we also incorporate its input links for measuring its

importance in terms of probability. That is why the matrix $A+A^T$ is based on for the proposed eigenstructure analysis with regard to project risk management.

4. Risk propagation model

In the project risk network, the nodes (risks) are assessed in terms of spontaneous probability and impact; the edges (risk interactions) are assessed as the transition probability from one risk to another. In the matrix-based risk propagation model, we assign the original risk probability evaluated by classical methods without considering interactions to each risk as its spontaneous probability. The assessed values in the RNM are used as transition probability between the related risks. Some assumptions are made in order to calculate risk propagation in the network:

(1) A risk may occur more than one time during the project (as witnessed in practical situations). Risk frequency is thus accumulative if arising from different causes or if arising several times from the same cause.

(2) The structure and values of RNM do not vary during the analysis time. In other words, there is no added or removed risk, and the transition probability between risks will not change during the analysis.

Hence, the RNM can be regarded as similar to the stochastic matrix or transition matrix used to describe the transition of a Markov chain (Buzacott and Shanthikumar 1993, Latouche *et al.* 1999). This principle has been applied to industrial engineering, for example, Smith and Eppinger introduced a work transformation matrix based on the DSM method to model the engineering design iteration process (Smith and Eppinger 1997). However, different from conventional stochastic matrix, in our model the RNM is a square matrix where all entries are nonnegative real numbers and inferior to 1, but

the sum of each row or column is not necessarily equal to 1. A foundation work with respect to modelling risk interactions for propagation analysis has been presented by the authors in (Fang *et al.* 2010).

Suppose there are *N* identified risks in the network. We use vector *s* to represent the spontaneous probability of risks and *A* still denotes the RNM of transition probabilities. *P(R)* is the vector of risk probability or frequency after propagation analysis.

We define one step of risk propagation as that the occurrence of one risk R_i may propagate to impact the risks that have direct cause-effect relationship with it (i.e., R_j if $RNM_{ji} \neq 0$). For the example of risk network in Figure 1, R5 can propagate to trigger R1 directly within one step; it may also influence R1 in two steps of propagation through R6 or R4, and within three steps through the chain R5->R6->R4->R1, and so on. As vector *s* also represents the initial vector of risk probabilities, after *m* steps of propagation, the probability vector of risks propagated from the initial state is thus equal to $A^m \cdot s$. If we only consider *m* steps of propagation and according to the assumption of accumulative risk frequency, the re-evaluated risk probability vector can be obtained by the following equation:

$$P(R) = s + \sum_{i=1}^{m} A^i \cdot s = (I + \sum_{i=1}^{m} A^i) \cdot s = (\sum_{i=0}^{m} A^i) \cdot s \tag{7}$$

where I is the *N*-order identity matrix. In the limit of infinite propagation steps in the project development:

$$P(R) = \lim_{m \to \infty} (\sum_{i=0}^{m} A^i) \cdot s \tag{8}$$

Multiplying both sides of Eq. (8) by *(I - A)*, and then we get that

$$(I - A) \cdot P(R) = (I - A) \cdot (\sum_{i=0}^{m} A^i) \cdot s = (I - A^{m+1}) \cdot s \tag{9}$$

It is not guaranteed that the infinite power of the matrix *A* would converge to 0, as in the following equation:

$$\lim_{m \to \infty} A^{m+1} = 0 \tag{10}$$

Some research papers established sufficient conditions for the convergence of infinite product of matrix, e.g., in (Thomason 1977, Daubechies and Lagarias 1992, Bru *et al.* 1994, Holtz 2000). In the project risk network, for example, if a risk is involved in several loops and the sum of the products of all the transition probabilities along these loops is greater than 1, the risk propagation process does not converge. This type of risk propagation is not likely to occur in practice and is outside the scope considered by our model.

Nevertheless, since *A* is the risk numerical matrix which is usually sparse and composed of transition probabilities at small values less than 1, usually the condition of Eq. (10) is satisfied. Thus, risk probability can be re-evaluated by the following equation:

$$P(R) = (I - A)^{-1} \cdot s \tag{11}$$

Moreover, it is possible to predict the consequences of the occurrence of one or several initial risks using this model. We assign, for instance, 100% to the spontaneous probability of R_i, while all the other risks have 0% initial values. That is to say, the

initial vector $s = I^i$, where I^i is the i-th column of the identity matrix I. We can then anticipate the occurrence of the rest of the network, and thus evaluate the global consequences of R_i.

Criticality is an important indicator used for prioritizing risks and usually defined as the product of risk probability and impact. Similar to risk probability, we can refine risk criticality by integrating all the potential consequences in the network of a given risk. Giving R_i with its re-evaluated probability (risk frequency), we redefine its criticality by:

$$C(R_i) = \sum_{j=1}^{n} G(R_j) \cdot P_{R_i}(R_j) \tag{12}$$

where $C(R_i)$ is the criticality of R_i; $G(R_j)$ is the original evaluated impact (G for gravity) of R_j; and $P_{R_i}(R_j)$ denotes the probability of R_j as the consequence of $P(R_i)$. According to Eq. (11), the re-evaluated risk criticality is expressed by:

$$C(R_i) = G^T \cdot (I - A)^{-1} \cdot (I^i \cdot P(R_i)) \tag{13}$$

The vector of risk criticalities can be calculated by the following equation:

$$C(R) = (I - A^T)^{-1} \cdot G.*P(R) \tag{14}$$

Here the symbol ".*" represents the array multiplication or the Hadamard product (Johnson 1974) of matrices. For example, the Hadamard product $c = a.*b$ of two vectors $a = [a_1, a_2, \ldots, a_n]$ and $b = [b_1, b_2, \ldots, b_n]$ is still an n-order vector and its elements are defined as:

$$c(i) = a(i) \cdot b(i) \tag{15}$$

The re-evaluation of risk characteristics such as probability and criticality enables us to update the risk prioritization results and then to design new risk response actions.

5. Application to a tramway infrastructure project

In this study, we implement the proposed approach to a real large project, aimed at building the infrastructure and associated systems of a tramway. This project takes place in a city with a population of 750 000. Both the classical project risk analysis and the proposed matrix-based risk propagation analysis are carried out.

The project includes the construction and implementation of tramway, equipments, and civil work, with 10 years duration and hundreds of millions € of budget. The leading company is a designer and manufacturer of trains, which recently extended its scope by proposing "turn key" projects, including not only the trains, but also the complete infrastructure around the trains. The project thus comprises:

- The construction of a depot to stock trains and to execute their control and maintenance;
- The installation of tracks throughout the city, over land with many steep slopes;
- The delivery of the corresponding trains, including redesign activities if the current version does not fit with the city's specific requirements;
- The establishment of a traffic signalling operating system, which gives priority to the tramway so as to guarantee travel time performance levels.

5.1. Building the project risk network

The first step is to build the project risk network. An original project risk list has been

provided by the project manager and the expert team, which contains 42 project risks. The risk list has been updated when performing the risk interaction identification. Some new risks have been added into the list, for two reasons: some were a consequence or cause of other risks already present in the initial list; others were seen as intermediary risks which were useful to explain the link between two or more risks of the initial list. Thus, the resulting project risk list contains 56 identified risks at the main level, with their name, domain and risk owner information, as shown in Table 1.

Identification of the risk interactions defines the structure of the project risk network. Using the DSM-based method described in Section 2.1, we get the RSM and the corresponding risk network structure (shown in Figure 2).

Table 1. Project risk list with classical risk characteristics of the tramway project

Risk ID	Risk Name	Risk Domain	Risk Owner	Qualitative Risk Probability	Qualitative Risk Impact	Criticality
1	Safety studies	Technical	1	1	1	1
2	Liquidated damages on intermadiate milestone and delay of Progress Payment Threshold	Contractual	2	7	8	56
3	Vehicle storage in another city	Contractual	1	9	5	45
4	Vandalism on site	Contractual	3	1	3	3
5	Traction/braking function : behaviour in degraded mode on slope	Technical	1	3	2	6
6	New local laws and regulations	Contractual	1	1	3	3
7	Traffic signalling, priority at intersections	Contractual	4	6	5	30
8	Unclear Interface with the Client, for Infrastructure equipment	Contractual	5	1	2	2
9	Delays due to client late decisions	Contractual	5	9	1	9
10	Travel Time performance	Technical	4	1	3	3
11	Limited Force majeure definition	Contractual	2	1	4	4
12	Operating certificate delay	Contractual	2	9	4	36
13	Reliability & availability targets	Technical	4	3	3	9
14	Permits & authorisations	Contractual	2	9	2	18
15	Insurance deductibles	Financial	6	1	3	3
16	Archeological findings	Contractual	2	9	3	27
17	Discrepancies Client / Operator / Concessionaire	Contractual	7	3	5	15
18	Civil Work delay & continuity	Contractual	8	9	4	36
19	Responsibility of client on Civil Work delay	Contractual	2	9	2	18
20	On board CCTV scope	Technical	9	5	1	5
21	Noise & vibration attenuation	Technical	4	3	6	18
22	Potential risks of claim from Civil Work subcontractor	Contractual	2	5	5	25
23	Harmonics level	Technical	5	1	2	2
24	Non compliance contractual Rolling Stock	Technical	1	1	6	6
25	Non compliance technical specifications Rolling Stock	Contractual	1	3	4	12
26	Exchange risk on suppliers	Financial	6	1	3	3
27	Track installation machine performance	Client/Partner/Subcontractor	10	3	2	6
28	Tax risk on onshore	Financial	6	1	2	2
29	Additional poles overcost for Tramway Company	Contractual	5	9	4	36
30	Overcost due to Security requirements for trains	Technical	4	5	4	20
31	Track insulation	Technical	9	1	1	1
32	Delay for energising	Project management, Construction site	5	3	2	6
33	Fare collection requirements	Contractual	7	5	3	15
34	Construction safety interfaces	Technical	3	1	1	1
35	Electromagnetic interferences	Technical	4	1	2	2
36	Exchange risk	Financial	6	1	2	2
37	Risk of partial rejection of our request for EOT (Extension Of Time)	Contractual	2	9	7	63
38	Interface rail / wheel	Technical	4	3	2	6
39	Risk on Certification of our equipement	Country	11	1	2	2
40	OCS installation	Project management, Construction site	3	7	5	35
41	Banks stop financing the project	Contractual	2	7	3	21
42	Costs of modifications not covered by EOT agreement	Contractual	2	1	4	4
43	Return profit decrease	Financial	2	9	8	72
44	Extra trains	Contractual	4	1	6	6
45	Pedestrian zones	Technical	4	1	2	2
46	Train performance	Technical	1	3	2	6
47	Waiting time at stations	Contractual	4	5	1	5
48	Depot delay	Technical	3	9	2	18
49	Error in the Survey (topography)	Technical	4	1	1	1
50	Ticketing design delays	Contractual	7	7	1	7
51	Track installation delay	Technical	3	7	2	14
52	Reengineering / Redesign	Technical	4	9	2	18
53	Slabs pouring delay	Technical	3	5	1	5
54	Initial specifications of CW (Civil Work)	Technical	3	5	1	5
55	Available cash flow decrease	Financial	2	9	7	63
56	Rolling stock delivery delay	Technical	1	3	1	3

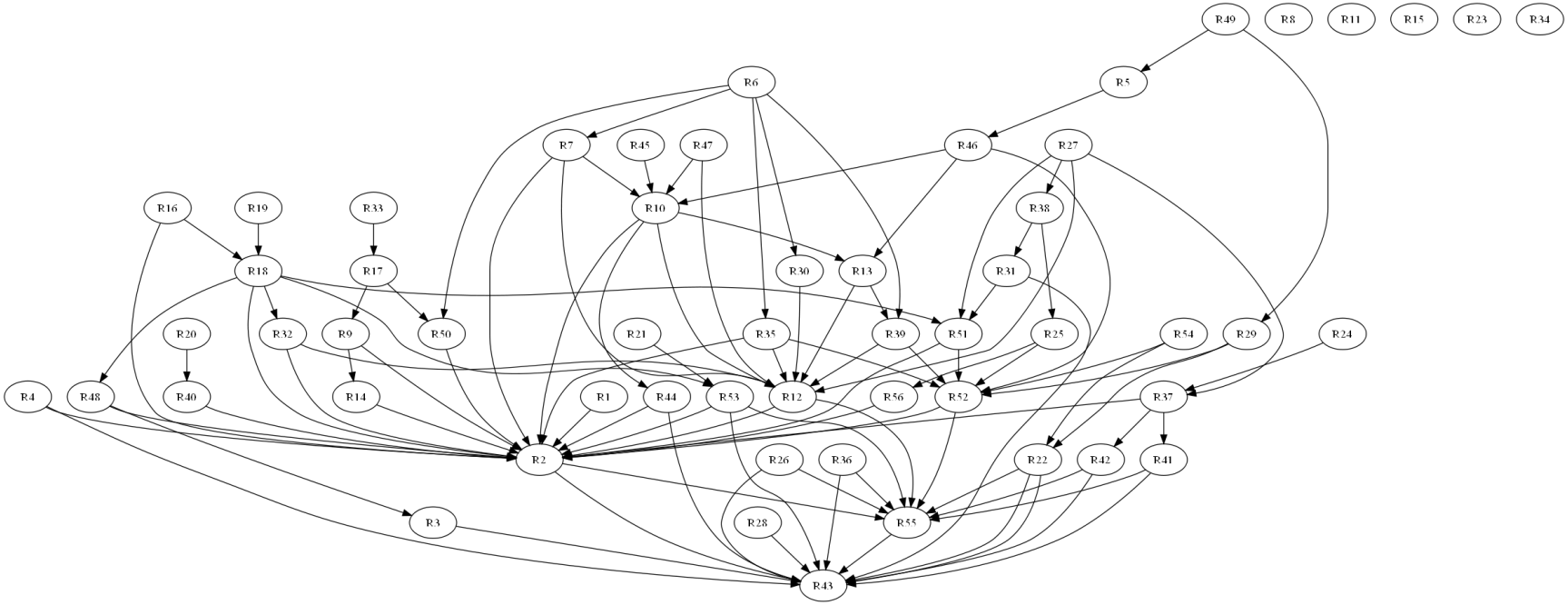

Figure 2. Project risk network structure of the tramway project

The direct assessment by experts is used on this case study for evaluating the strength of risk interactions. The assessment of the potential risk interactions was performed on a 10-level Likert scale (Likert 1932, Maurer and Pierce 1998), thanks to the high expertise of interviewees. In particular, this step requires the participation of several experts involved in the project since it necessitates a very wide overview of the project elements and stakes. In the end, the RNM of the project was obtained. It is displayed in Figure 3. Various gray scales are used to indicate the strength levels of the risk interactions.

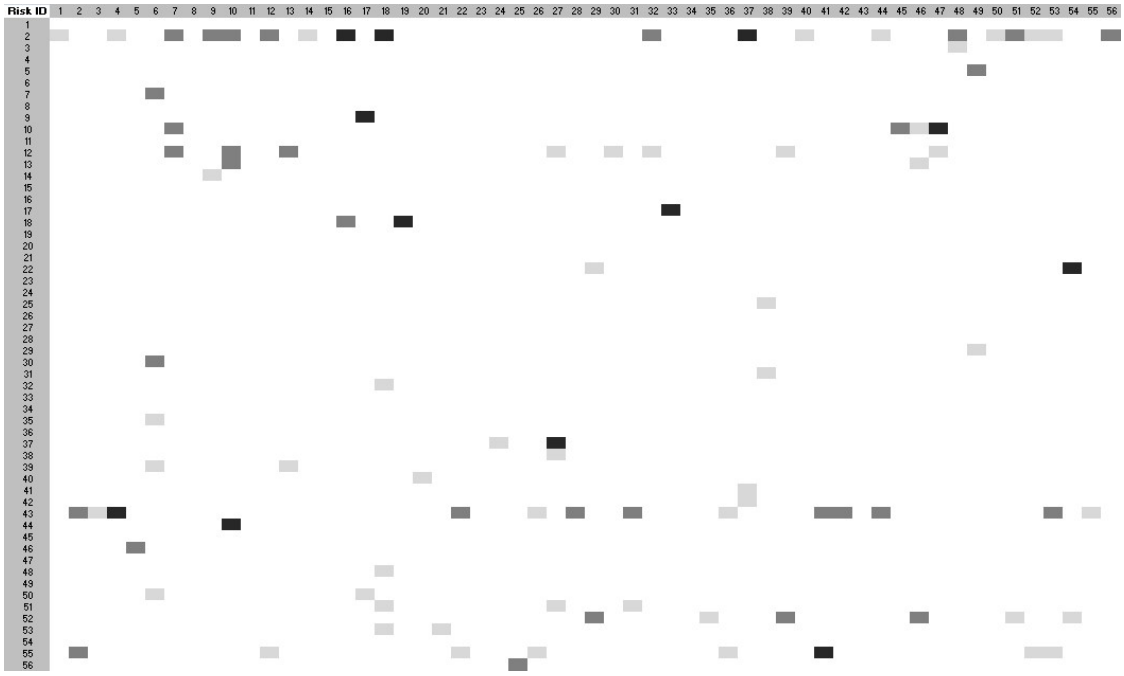

Figure 3. RNM of the tramway project

5.2. Classical project risk analysis

As we can see in the classical project risk list (Table 1), basic characteristics of project risks have been assessed by the project manager and associated experts, including qualitative probability (or likelihood) and impact (or severity) scales, as well as criticality (aggregation of probability and impact). In classical project risk analysis,

risks are considered most important if having both high probability and impact. The results of this type of analysis are used by the project manager for risk response planning. Resources are firstly allocated to manage the risks prioritized with high criticality.

In Figure 4, the classical project risk analysis results are displayed in a risk probability vs. impact diagram, where each risk identified in Table 1 is represented by a dot. The limits between different criticality levels should be defined a priori, before the risk assessment. For example, risks can be categorized into several levels of criticality, such as critical, high, moderate and low risks. In Figure 4, we have highlighted the top-ten risks (displayed by their IDs) according to their criticality value.

The project is based on a contract including many contractual terms involving financial penalties in case of failure, whether on time or quality aspects. Almost every problem is potentially transformed directly or indirectly into an additional cost and then a profit loss. It is thus not surprising to see that R2 (Liquidated damages on intermediate milestone and delay of progress payment threshold), R37 (Rejection of Extension Of Time), R43 (Return profit decrease) and R55 (Available cash flow decrease) are among the most critical risks. Other risks with high criticality are generally related to the final delivery, like R12 (Operating certificate), or some big parts of the project, like R18 (Civil Work delay) and R40 (Operating Centre installation).

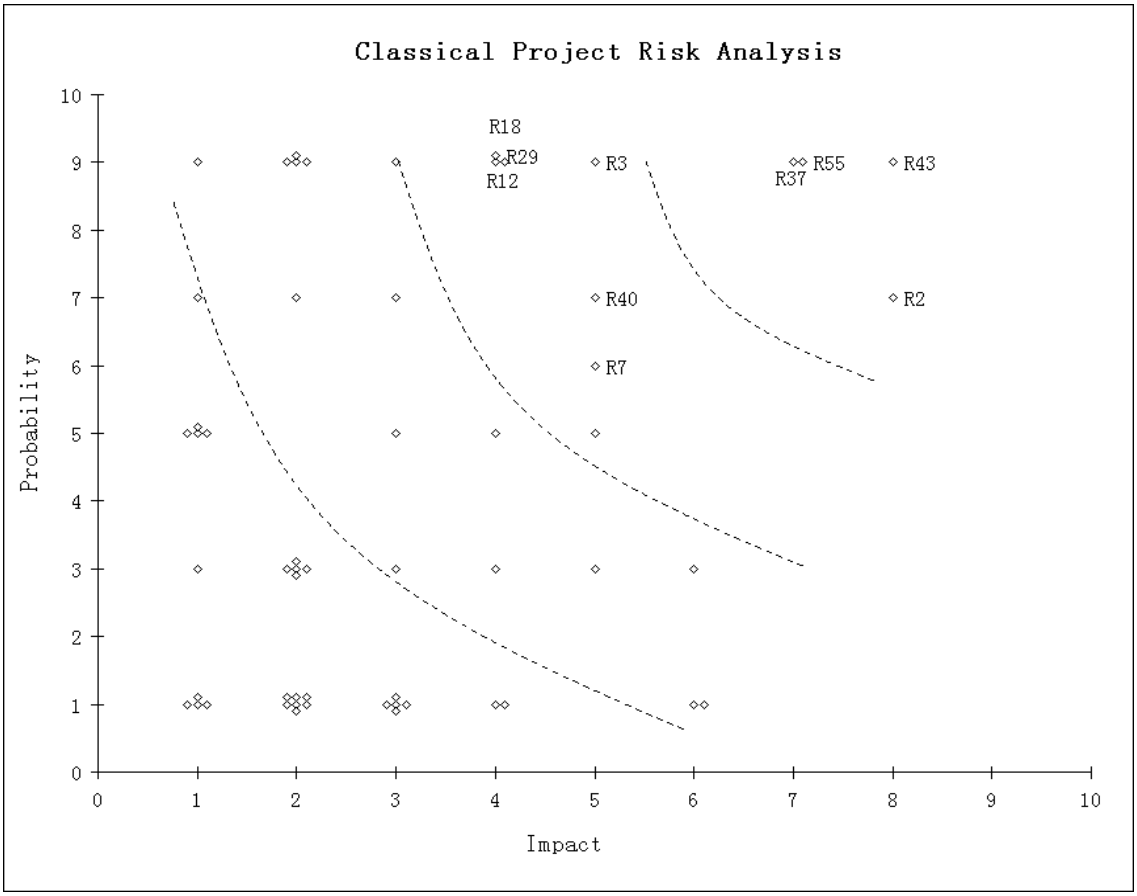

Figure 4. Display of classical project risk analysis results

5.3. Results using the proposed methods

In Table 2, we consolidate the risk analysis results by the risk propagation model and the eigenstructure analysis. They are compared with the original risk estimates obtained by classical methods. Conducting the eigenstructure analysis by Matlab software, we get the unique largest real eigenvalue $\lambda^* = 1.4866$ of the RNM. The eigenvector centralities of each risk are also given in Table 2.

Table 2. Project risk analysis results of the tramway project

Risk ID	By Classical methods				By Risk Propagation Model				By Eigenstructure Analysis
	Original Evaluated Risk Probability	Evaluated Risk Impact	Original Risk Criticality	Original Risk Ranking	Re-Evaluated Risk Frequency	Re-Evaluated Risk Criticality	Updated Risk Ranking	Ranking Shift	Eigenvector Centrality based on RNM
R1	0.001	1	0.001	53	0.001	0.00	55	-2	0.000
R2	0.308	8	2.465	4	1.737	23.36	1	+3	0.555
R3	0.381	5	1.905	5	0.381	2.17	14	-9	0.017
R4	0.001	3	0.003	41	0.001	0.01	43	-2	0.114
R5	0.086	2	0.173	35	0.086	0.22	39	-4	0.001
R6	0.001	3	0.003	42	0.001	0.01	42	0	0.062
R7	0.263	5	1.314	10	0.263	4.29	8	+2	0.238
R8	0.001	2	0.002	46	0.001	0.00	52	-6	0.000
R9	0.381	1	0.381	23	0.452	2.68	11	+12	0.144
R10	0.001	3	0.003	43	0.179	2.69	10	+33	0.325
R11	0.001	4	0.004	39	0.001	0.00	47	-8	0.000
R12	0.381	4	1.524	7	0.607	5.67	5	+2	0.297
R13	0.086	3	0.259	26	0.148	0.96	26	0	0.146
R14	0.381	2	0.762	15	0.420	1.33	21	-6	0.041
R15	0.001	3	0.003	44	0.001	0.00	49	-5	0.000
R16	0.381	3	1.143	11	0.381	4.46	7	+4	0.200
R17	0.086	5	0.432	22	0.172	1.28	23	-1	0.043
R18	0.381	4	1.524	8	0.655	6.79	4	+4	0.223
R19	0.381	2	0.762	16	0.381	2.38	12	+4	0.062
R20	0.210	1	0.210	27	0.210	0.32	35	-8	0.002
R21	0.086	6	0.518	21	0.086	0.52	31	-10	0.000
R22	0.210	5	1.052	12	0.297	2.22	13	-1	0.068
R23	0.001	2	0.002	47	0.001	0.00	53	-6	0.000
R24	0.001	6	0.006	37	0.001	0.01	44	-7	0.010
R25	0.086	4	0.346	24	0.093	0.45	32	-8	0.012
R26	0.001	3	0.003	45	0.001	0.00	46	-1	0.029
R27	0.086	2	0.173	31	0.086	0.67	29	+2	0.053
R28	0.001	2	0.002	48	0.001	0.00	48	0	0.042
R29	0.381	4	1.524	9	0.381	1.78	17	-8	0.006
R30	0.210	4	0.842	14	0.210	1.01	25	-11	0.030
R31	0.001	1	0.001	54	0.008	0.02	41	+13	0.042
R32	0.086	2	0.173	32	0.087	0.42	33	-1	0.079
R33	0.210	3	0.631	19	0.210	1.27	24	-5	0.012
R34	0.001	1	0.001	55	0.001	0.00	56	-1	0.000
R35	0.001	2	0.002	49	0.001	0.00	51	-2	0.006
R36	0.001	2	0.002	50	0.001	0.00	50	0	0.017
R37	0.381	7	2.667	2	0.416	5.45	6	-4	0.173
R38	0.086	2	0.173	33	0.086	0.23	38	-5	0.003
R39	0.001	2	0.002	51	0.014	0.04	40	+11	0.017
R40	0.308	5	1.541	6	0.326	2.01	16	-10	0.032
R41	0.308	3	0.925	13	0.308	2.76	9	+4	0.127
R42	0.001	4	0.004	40	0.037	0.24	37	+3	0.072
R43	0.381	8	3.048	1	1.422	11.37	2	-1	0.298
R44	0.001	6	0.006	38	0.074	0.69	28	+10	0.175
R45	0.001	2	0.002	52	0.001	0.01	45	+7	0.046
R46	0.086	2	0.173	34	0.104	0.28	36	-2	0.006
R47	0.210	1	0.210	28	0.210	1.68	18	+10	0.107
R48	0.381	2	0.762	17	0.438	2.12	15	+2	0.092
R49	0.001	1	0.001	56	0.001	0.00	54	+2	0.000
R50	0.308	1	0.308	25	0.308	0.67	30	-5	0.032
R51	0.308	2	0.616	20	0.316	1.53	20	0	0.082
R52	0.381	2	0.762	18	0.506	1.60	19	-1	0.039
R53	0.210	1	0.210	29	0.267	1.31	22	+7	0.110
R54	0.210	1	0.210	30	0.210	0.91	27	+3	0.021
R55	0.381	7	2.667	3	1.187	9.13	3	0	0.207
R56	0.086	1	0.086	36	0.106	0.40	34	+2	0.080

Based on the risk analysis results in Table 2, risks are prioritised by different indicators. The top-ten risks are listed in Table 3.

Table 3. Risk prioritisation results according to different indicators

Ranking	Risk Criticality by Classical Method		Re-Evaluated Risk Criticality by Risk Propagation Model		Eigenvector Centrality based on RNM	
	Risk ID	Value	Risk ID	Value	Risk ID	Value
1	R43	3.048	R2	23.4	R2	0.5553
2	R37	2.667	R43	11.4	R10	0.3248
3	R55	2.667	R55	9.1	R43	0.2980
4	R2	2.465	R18	6.8	R12	0.2971
5	R3	1.905	R12	5.7	R7	0.2384
6	R40	1.541	R37	5.4	R18	0.2235
7	R12	1.524	R16	4.5	R55	0.2075
8	R18	1.524	R7	4.3	R16	0.1996
9	R29	1.524	R41	2.8	R44	0.1746
10	R7	1.314	R10	2.7	R37	0.1726

In our risk propagation model, risk probability can be re-evaluated through Eq. (11) into risk frequency. As we can see in Table 2, the frequency of risks has increased to varying extent taking into account the interactions with other risks in the network. Some risks have high risk frequency which is greater than one. As mentioned in the assumption of the model, this is consistent with the reality that one risk may occur more than once during the project. The examples are R2 (Liquidated damages on intermediate milestone and delay of progress payment threshold), R43 (Return profit decrease) and R55 (Available cash flow decrease). Shown in Figure 2 of the risk network structure, many other risks lead to these nodes which are closely related to financial performance. Consequently, they have high frequency to occur during the project, and even more than one time (accumulation).

Risk criticalities can also be refined by the risk propagation model. As a result, the risk rankings have also changed. Seen from Table 3 and the column of ranking shift

in Table 2, some important risks based on classical risk analysis remain in high positions, such as R43, R2, R55, R37 (Risk of partial rejection of our request for extension of time)), R7 (Traffic signalling, priority at intersections), R12 (Operating certificate delay), and R18 (Civil Work delay & continuity). On the other hand, some risks have dropped out of the top-ten rankings, such as R3 (Vehicle storage in another city), R40 (OCS installation), R29 (Additional poles overcost for Tramway Company). Several risks have greatly risen with respect to their rankings. For example, the ranking of R10 (Travel time performance) has increased from No.43 to No.10 with an upgrade of +33. Moreover, in the new prioritisation results, the value gap between risks becomes different from that in the classical method. For example, R43 and R37 are two risks with high criticalities and R43 is ranked superior to R37. After re-evaluation by modelling risk propagation, R43 is still regarded more critical than R37, but the gap between their relative criticality values becomes much larger, shown in Table 3. This is the opposite for R43 and R7, where R7 is still behind after re-revaluation, but closer. The shift of priorities reflects the intensity of risk interactions in the network.

The eigenvector centrality provides a measurement of risks in terms of their position and importance in the network. As we can see in Table 3, most of the critical risks by risk propagation model are included in this top-ten list according to eigenvector centrality. Some risks like the accumulation risks R2, R43 and R55 have high eigenvector centralities because they have many predecessors, namely many input links from other risks. Thus, the consequences of many other risks are revealed through them, either directly or after propagation of several steps. R7 (Traffic signalling, priority at intersections) and R16 (Archeological findings) are important because they are the source of many other risks in the network. R10 (Travel time performance), R12 (Operating certificate delay) and R18 (Civil Work delay & continuity) with many inputs

as well as many outputs act as transition risks in the risk network. R44 (Extra trains) is in the top-ten list because it has direct contacts with some key nodes such as R2, R7 and R43, which enhance the measure of its influence in the network.

6. Discussion

This paper has presented a matrix-based method for modelling risk interactions and then re-evaluating risks in terms of various indicators. A realistic application to a tramway implementation project is performed with the involvement of the project manager and the team of experts.

The DSM method is used in the field of PRM for identifying risk interactions. The parameters in the constructed project risk network are assessed so that we are able to analyse the risk propagation behaviour in a quantitative manner. An eigenstructure analysis is performed based on the risk network. The eigenvector centrality provides a measure of the importance of risks which reflects the influence of a risk taking into account both its direct and indirect connections with the other risks in the network. The introduced risk propagation model enables us to anticipate the risk propagation in the risk network. The risk prioritisation has been updated in terms of criticality ranking. The underestimation of some risks in classical methods is due to the neglect of the complexity-related information. Thus, the proposed model provides the project manager with more and new insights on risks and their role in the risk network. Several critical risks identified by classical project risk analysis are confirmed by our analysis to play an important role in the risk network. But in addition, some new risks are highlighted as key elements by this analysis, which are supplement results to classical analysis. This information enables complementary mitigation actions suitable for the particular type of risks to be planned by the project manager. These actions are included in the global risk

response plan, as part of the project plan, to adequately manage the required resources, budget and time. Without this analysis, the project manager would probably not have decided to plan actions on these specific risks.

It is shown that the refined risk criticality analysis results are closely correlated with the eigenvector centrality-based risk prioritisation. The risks with high eigenvector centrality are also ranked as top risks in the refined risk criticality analysis. For example, in the case study presented, night risks (R2, R7, R10, R12, R16, R18, R37, R43, R55) are the same in the top-ten risk list respectively based on these two measures. It is due to the fact that the risks with high eigenvector centrality act as "hubs" which play the role of key passages for risk propagation. This is helpful for the project manager in giving priority to certain risks and in designing more effective response actions. For example, paying attention and making effort to prevent the source risks like R7 and R16 may help avoid many problems arising at later stages; corrective or protection actions are often designed for the critical accumulation risks such as R2, R43 and R55 to reduce losses; a mix of strategies, e.g., preventive and confinement actions can be applied to transition risks in the network like R10, R12, R18 and R44 for mitigating the risk propagation and thus reducing the global risk exposure. It should be noted that these findings coincide with the conclusions drawn by Braha and Bar-Yam in (Braha and Bar-Yam 2004a, Braha and Bar-Yam 2007) on the analysis of large production development networks.

The proposed approach can be used as a supplement to the classical project risk analysis. It can support project managers in making subsequent managerial decisions, such as risk response planning and allocating available budget or resources. Our approach encourages people to meet together and communicate/ coordinate better, in order to manage potential interactions and potential propagations. It underlines the need

for cooperation and transversal communication within the project team. Fieldwork proves us that it does indeed improve communication between people, since this approach does not seek the identification of responsibility and/or accountability, but the identification of propagation chains and human interfaces. Allocating resources and conducting actions on these key risks or interactions can then be efficient for mitigating the propagation phenomena and reducing the overall risk exposure.

As a next step, some other network centrality measures in literatures will be used to analyse and prioritise risks, and the results will be compared with the refined risk criticality analysis and eigenstructure analysis with respect to project risk management. The uncertainties of estimated inputs on risks and risk interactions will be modelled and their propagation in the risk network should be calculated, e.g., though a sensitivity analysis. The concept of robustness, e.g., the traditional static robustness and the dynamic robustness raised in (Braha and Bar-Yam 2004a, Braha and Bar-Yam 2007), will also be investigated in terms of the project risk network.

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