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*Research Article*

# Organizing Project Actors for Collective Decision-Making about Interdependent Risks

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The way project actors are organized is crucial in determining how they will be able to collectively cope with nontrivial complex problems and risks. Current project organizations are generally based on single-criterion decomposition, whether product, process, or organization based. The proposed approach forms complementary clusters of actors based on the interdependencies between the risks they manage. More precisely, distinction has been made between the interdependencies connecting two risks that are owned by different actors and those owned by the same actor. We argue that interdependency between two risks managed by the same actor is less dangerous, meaning that clustering algorithm is tailored to distinguish mono- and biactor risk interdependencies. The complementary structure offered by interdependency-based clustering tends to put together strongly interconnected actors, albeit they were often initially not grouped together. It increases the likelihood of a better communication, coordination, and collective decision-making in complex situations. Some risks remain out of proposed clusters and are declared transverse, which means that their owners act as information hubs and are not involved in a single cluster. An industrial application is presented with operational results and perspectives for further work are drawn from it.

## 1. Introduction

Project risks have to be properly managed in order to mitigate as best as possible their occurrence and the impact that they may have on the project, either on its process, organization, or its result/outcome [1]. Potential events may be seen as potential changes in the project. Each change is accompanied by intended and unintended impacts, both of which being likely to propagate. Such risk propagation (called domino, cascade, butterfly, and snowball effects) causes uncertainty in project domains such as cost, time, and quality and thus needs to be predicted and controlled. However, single-domain change propagation methods overlook most dependencies across domains and suffer of reliability due to these cross-boundaries dependencies. It has been studied that global anticipation and protection strategies are better than local single-domain ones [2–4]. This is why we prefer modeling an element that can embrace all domains, such as project risk.

It is a challenge for project organizations to coordinate the interactions between system components, project objectives, project activities, and actors [5, 6]. Interdependencies between technical and human systems increase global project risk because local problems in one subsystem may propagate to other connected subsystems. The way interdependencies are modeled and treated is crucial to analysis and decision capacities [7, 8], notably for anticipating potential project behavior and avoiding potential delays and overruns [9]. Otherwise, there is a significant risk of poor coordination and locally optimal decisions [10]. Moreover, interdependencies between the actors involved in the risk management process create difficulty when proposing an appropriate Risk Breakdown Structure and project risk organization [11]. This is all the more important since actors are generally assigned as risk owners, meaning that they have to manage risks. This includes monitoring their characteristics and implementing preventive or corrective actions. Whatever the criterion for dividing the list, there will always be a large amount of interdependencies between risks and thus risk owners' interdependencies that remain outside of official organizational boundaries. Due to the multiple dimensions a project has to consider (time, cost, quality, and more and more environmental and societal issues, health, safety, security, etc.), it is natural to have difficulties to break it down so that its organizational structure is aligned with actual interactions. In fact, it is even impossible. However, the behavior of a project strongly depends on its structure [12–15], and notably the way transverse interactions are managed. Classical organizations are generally based on decomposition into homogeneous elements, while our approach is based on interdependencies.

This is all the more important when two different actors own both risks. The main originality of this work is thus to differentiate interactions between two risks, depending on the fact that they are owned by one or two different actors. Both types of interactions do not have the same risks in terms of coordination, since a single actor owning two interdependent risks just has to coordinate with herself. Thus, the focus of this article is on proposing a plan for complementary project risk management organization to account for interdependencies between actors and mitigate risks due to the complex structure of the project. An organization is an adaptive and evolving system that must correspond to the complexity of the situation being managed [16].

To do this, clustering aims at maximizing the amount of interactions within clusters, in order to improve information exchange and coordination between actors within each cluster. The way the decisions may be collectively made depends on the way project actors are put together into meaningful clusters, clusters that help to capture current and possible future complexity of the project. Giannocaro and coworkers suggest that the resilience of a team depends on the density of its interactions [17], confirming our aim to cluster risk owners depending on the interdependencies they have. That means that clusters are interdependence-based, and then are likely to be heterogeneous, instead of being similarity-based. It naturally puts together actors who are initially assigned to different entities that may be managed as silos. This involves the following: (1) an improvement in how individual members respond to risk in their activities once they are grouped with interconnected people; (2) a higher level of coordination and collective behavior between multidomain and multitimeframe decisions.

The clustering methodology in this paper is tailored and applied to the specific context of a nuclear installation construction project. The remainder of the paper is as follows. Sections 2 and 3 introduce the strategy for formulating and solving the clustering problem. Section 4 presents the case study, with an analysis of existing situation and clustering results. Sections 5 and 6 present managerial implications of clusters and a global discussion about the results and their limits. Conclusions and perspectives are drawn in Section 7.

## 2. Reshuffling the Organization of Project Risk Owners

This section introduces first literature about clustering and then the problem formulation, consisting of description and formulation of objective function and constraints.

*2.1. Related Work.* Clustering consists of breaking down a set of elements down into smaller, more manageable groups, according to one or several parameters [18]. Clustering methods may use algorithms to attempt finding an optimum [19, 20], or heuristics for proposing good enough solutions [21–24], like, for instance, genetic algorithms [25–28]. Clusters can be proposed using top-down or bottom-up (respectively, descendant or ascendant) approach, which is our choice in this work. They can be built considering local (individual) or global indicators [29]:

(i) Locally, the methods take into account similarity between the elements (called vertices), and may focus on particular elements which are representative of the group, called centroids [30]. On the other side, clusters may be built according to dissimilarity or distance between elements [31–37], with elements which are least central (the opposite of centroids) or most between [38–41]. Different types of measures exist, like modularity [42–48], and eigenvalues/eigenvectors [15, 49–52].

(ii) Globally, the methods propose clusters and assess their performance (called cluster-based assessment, or cluster fitness measure). They can be more or less supervised, notably on the number of clusters k, which is required for instance in the k-means method [53–56]. Cluster density has been developed to partition the initial graph into smaller ones, depending on local density values of each cluster [57–61]. Cut size-based measures allow the quantification of the dependence of a subgraph to the rest of the graph [62, 63], with several indices, like for instance Dunn index [64], Davies-Boulding index [65], Xie and Beni's validity index [66], and Bezdek's partition coefficient and partition entropy [67, 68].

(iii) They can be based on crisp or uncertain values, using for instance fuzzy clustering [28, 69–72] and spectral clustering [28, 30, 73–75].

In terms of application, clustering has been and is still used in multiple engineering and design problems to group either product-related elements, processes or organizational elements [76, 77]. These elements are generally related to one of the main project domains, products, processes, or organizations. Product clustering is generally performed to determine and possibly increase product modularity because modular architectures are supposed to have many advantages [78–80]. In terms of process clustering, many studies have attempted to cluster activities, knowing that the activities may or may not be coupled [81–85]. Organizational clustering has also been examined in several studies, either as mitigating communication risks or seizing creativity opportunities [86–89]. The clustering of specific multidomain elements, like decisions, deliverables, and risks has also been developed by Marle and coworkers [90–95]. The originality is then twofold: first, we consider interdependencies between elements that may be of different nature (a risk may be related to project objectives, to time, cost, to a product component, to an actor, to a company, to a project task or to an activity related to product recycling 20 years later, etc.). Second, we consider differently an interaction between two risks depending on the fact that one or two actors manage this interaction. The first parameter changes the way we model and gather data, but they are inputs to clustering process. However, the second point involved modifying the objective function and the way clusters are appreciated *a posteriori* by the decision-maker. This is the object of the following paragraph to describe how the problem is formulated.

Interdependency strength is the main driver for reshuffling project organization using clustering. According to Worren, interdependencies exist when actions in one subunit of the organization affect important outcomes in another subunit [10]. They require frequent coordination and information exchange and have to be managed. In order to propose clusters of risks, interdependencies are modeled using an adjacency matrix approach, the properties of which being widely studied [96–99]. This matrix-based approach is justified by the existence of numerous developments for modeling, analyzing, and grouping elements in projects, notably engineering and design projects [100–102]. According to several authors, project elements may be [102, 103]

(i) dependent (sequential if temporality is a parameter of the relationship)

(ii) independent (or parallel)

(iii) coupled (or reciprocal)

(iv) conditionally connected (contingent relationship)

Another type of interdependence described by Thompson is the pooled interdependence, where each element renders a discrete contribution to the whole and is supported by the whole [103]. Worren introduces 5 types of interdependencies [10]: the commitment, the governance, the activity, the resource, and the social interdependencies. Marle and Vidal introduced 5 types of interdependencies [104, 105]:

(i) the hierarchical link, typically found in WBS or other trees

(ii) the contribution link meaning that one element contributes to the advancement of the other one

(iii) the sequential link if the output of one element is used as an input of the other one

(iv) the influence link if a decision or a change in element 1 may involve a change in element 2

(v) the exchange link if the two elements have an information flow, possibly without influence one upon another

In this work, in the context of risk interdependency, we choose to use an oriented cause-and-effect interdependence, meaning that the occurrence of a cause risk may influence the occurrence of the effect.

*2.2. Problem Formulation.* The problem is first described; then its objective function and constraints are presented.

*2.2.1. Problem Description and Nomenclature.* For reading convenience, matrix-related elements are in bold, and variables are in italics. As described in the Introduction, a project is composed of numerous and diverse elements X, owned by actors A, and characterized by numerous and diverse interactions connecting elements I (X, Y). Let's define here two types of elements, R as the set of risks identified for the project at the moment of the study, and G as the set of groups that break the existing project organization down into smaller pieces. There are NR risks {R} identified and managed and NG groups. A is the set of actors who are assigned to these risks as owners. A is a subset of the global set of project actors. NA is the number of actors in the set A, i.e., the number of risk owners.

The first assignment interaction I (A, G) is the affiliation of actors Ai to current groups Gj. This initial organization is modeled as a NA x NG matrix called **AG**, consisting of actors $\{A_i\}$ assigned to groups $\{G_j\}$.

The second type of interaction I (A, R) is defined as the assignment relationship between actor $A_i$ and risk $R_j$, meaning that $A_i$ owns $R_j$. Actors may be assigned to more than one risk; risks must have one and only one risk owner. This is modeled as a binary NA x NR matrix **AR**.

Last, the risk interaction I (R, R) is considered here as a potential cause-effect relationship. May $R_i$ occur, it has a nonnull probability to trigger the occurrence of $R_j$. This is modeled as I $(R_i, R_j)$, with an estimated value corresponding to a likelihood more than a pure mathematical probability. **RR** is an NR x NR matrix with each cell $\mathbf{RR_{j1,j2}}$ $(1 \leq j_1, j_2 \leq \text{NR})$ representing the interaction strength between risks $R_{j1}$ and $R_{j2}$, determined by expertise or less often by experience. These are inputs provided by the decision-maker, generally either project manager or risk manager.

The number of clusters is a variable, called *NC*. It may be defined by the decision-maker before the analysis. For instance, in [86], decision-maker tested a configuration with the same number of clusters than the initial number of groups NG. If the decision-maker cannot or does not want to influence the analysis, unsupervised clustering is useful to give an idea, an order of magnitude of a relevant number of clusters. The first output of clustering is the affiliation of risks to clusters, modeled as a binary NR x *NC* matrix **RC**. $\mathbf{RC_{j,k}}$ is equal to 1 if $R_j$ belongs to cluster $C_k$, zero otherwise.

*INTRA* indicator counts intracluster interactions only. Similarly, the *INTER* indicator is defined as the total value of interactions crossing clusters. **RC** is the decision variable. Details will be given further, but the main idea of clustering is to minimize *INTER* or maximize *INTRA*.

Knowing the assignments of actors $A_i$ to risks $R_j$, and the assignment of risks $R_j$ to clusters $C_k$, the affiliation of

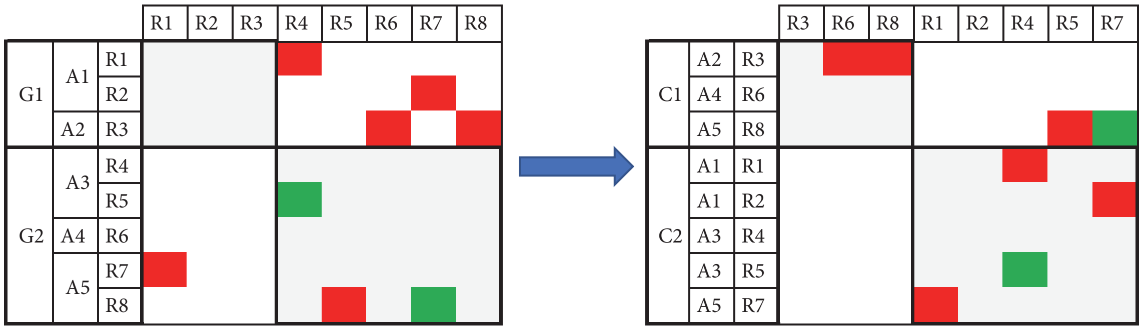


Figure 1: Illustration on a simple example of the difference between initial and clustered project organizations.

actors $A_i$ to clusters $C_k$ is then obtained by multiplying both matrices **AR** and **RC**. This gives the **AC** matrix, for assignment of actors $\{A_i\}$ to clusters $\{C_j\}$. This second and indirect output of the clustering process corresponds to the reshuffled organizational structure.

The main originality of this work is thus to make a difference between a risk interaction where risks are owned by two different actors (BAI for biactor interaction) and a risk interaction where risks are owned by the same actor (MAI for monoactor interaction). Both types of interactions do not have the same risks in terms of coordination, since a single actor owning two interdependent risks just has to coordinate with herself. Two parameters are then simultaneously considered, the *INTRA*/*INTER* nature of the risk interaction, and the MAI / BAI nature of actors' interaction. If two risks are in the same cluster, it counts as *INTRA*, otherwise *INTER*. If these two risks are managed by the same actor, it counts as MAI, otherwise BAI. There are thus 4 cases. For example, if risk 1 owned by actor 1 belongs to cluster 1 and risk 2 owned by actor 2 belongs to cluster 1, then the interdependency between risk 1 and risk 2 is counted as $INTRA|_{BAI}$ (*INTRA* since risks R1 and R2 belong to cluster 1, and BAI since risks are owned, respectively, by actor A1 and A2).

This means that the difference will be made, particularly for cross-clusters interactions (*INTER*), between biactor interactions ($INTER|_{BAI}$), the most dangerous ones, and monoactor interactions ($INTER|_{MAI}$), which appear less dangerous albeit cross-boundaries. MAI require less energy and present lower coordination risk than an interaction with another actor, within the same cluster or not [106].

To give an illustration of the potential interest of such a reconfiguration, a fictitious example is given with NR=8, NA=5 and NG=NC=2. Let us consider a fictitious project with a set of 8 risks $\{R_1..R_8\}$. Five actors manage these risks. $A_1$ owns $R_1$ and $R_2$, $A_2$ owns $R_3$, $A_3$ owns $R_4$ and $R_5$, $A_4$ owns $R_6$ only, and finally $A_5$ owns $R_7$ and $R_8$. Actors are currently affiliated to two groups, respectively, $A_1$ and $A_2$ in group $G_1$, and $A_3$, $A_4$, and $A_5$ in group $G_2$. This means that $G_1$ contains 3 risks, assigned to 2 actors. $G_2$ contains 5 risks and 3 actors. Eight risk interactions have been identified. As shown in Figure 1, 5 of them are outside group boundaries, meaning that they are counted as *INTER*. Moreover, they are between different actors, BAI (in red on Figure 1), so in the end we have 5 $INTER|_{BAI}$ interactions. There is no interaction between risks managed by actors affiliated to group $G_1$. The 3 last interactions are within $G_2$ boundaries, meaning that they are counted as *INTRA*. However, they do not have the same nature, since two are $INTER|_{MAI}$ (in green on Figure 1) and one is $INTER|_{BAI}$ (the $R_8$-$R_5$ interaction which connects $A_5$ and $A_3$).

A fictitious clustering is proposed with NC=NG=2. The same structure is proposed, to make results more comparable, with a 3-risk cluster $C_1$ and a 5-risk cluster $C_2$. Two elements illustrated in Figure 1 are important. First, only 2 interactions remain outside clusters boundaries. Second, one of these *INTER* interactions is between $R_7$ and $R_8$, which are owned by the same actor $A_5$. This means that this interaction is $INTER|_{MAI}$, which is considered as far less dangerous than an $INTER|_{BAI}$. The conclusion is that we started with a situation where 5 interactions (on a total of 8) were dangerous (in terms of possible bad communication and coordination) to a situation where only one interaction is dangerous, since the other *INTER* interaction is in fact $INTER|_{MAI}$. The originality of distinguishing MAI and BAI is that we can allow the algorithm to increase the number of $INTER|_{MAI}$ interactions.

In the end, interdependencies which are simultaneously *INTER* and BAI are considered as the main source of poor communication and coordination risks and will be the object of our minimization effort, as described as follows.

*2.2.2. Objective Function.* The *INTRA* function is defined as the sum of all risk interactions (from **RR** matrix) included within each cluster (from **RC** matrix), as described in

$$INTRA(\mathbf{RC}) = \sum_{1\le k\le NC} \sum_{1\le j1,j2\le NR} \mathbf{RC_{j1,k}} * \mathbf{RC_{j2,k}} * \mathbf{RR_{j1,j2}} \quad (1)$$

Defining TVI as the total value of interactions, *INTER* can be obtained as follows:

$$INTER(\mathbf{RC}) = TVI - INTRA(\mathbf{RC}) \quad (2)$$

Knowing the affiliation of risks to clusters, the **RR** matrix is decomposed as follows:

$$\mathbf{RR} = \mathbf{RR}|^{\mathbf{INTRA}} + \mathbf{RR}|^{\mathbf{INTER}} \quad (3)$$

With $\mathbf{RR}|^{\mathbf{INTRA}}{}_{i,j} = \mathbf{RR}_{\mathbf{i,j}}$ if $R_i$ and $R_j$ belong to the same cluster

= 0 otherwise.

And $(\mathbf{RR}|^{\mathbf{INTRA}}{}_{\mathbf{i,j}} = \mathbf{RR}_{\mathbf{i,j}}$ if $R_i$ and $R_j$ belong to different clusters

= 0 otherwise.

$\mathbf{AA}|^{\mathbf{INTER}}$ is thus obtained by considering only interdependencies which are outside the clusters in the clustered **AA** matrix.

$$\mathbf{AA}|^{\mathbf{INTER}} = \mathbf{AR} * \mathbf{RR}|^{\mathbf{INTER}} * \mathbf{RA} \quad (4)$$

Finally, the objective function is thus to minimize $INTER|_{\mathrm{BAI}}$, where the major coordination risks exist, introduced in

$$INTER|_{\mathrm{BAI}} = \sum_{(i \neq j)} \mathbf{RR}|^{\mathbf{INTRA}}{}_{\mathbf{i,j}} \quad (5)$$

*2.2.3. Problem Constraints.* Once the objective function is given, three constraints have been identified. The first one is the maximal number of risks per cluster $C_k$, called max($R \mid C_k$):

$$\forall k \in [1 \cdots NC], \quad NR(C_k) = \sum_{1 \leq j \leq NR} \mathbf{RC}_{\mathbf{j,k}} \leq \max(R \mid C_k) \quad (6)$$

where $NR(C_k)$ is the number of risks in the $k^{th}$ cluster.

Second, there are a maximal number of clusters a risk can be simultaneously assigned, called max (CR):

$$\forall j \in [1 \cdots NR], \quad NC(R_j) = \sum_{1 \leq k < NC} \mathbf{RC}_{\mathbf{j,k}} \leq \max(C \mid R) \quad (7)$$

where $NC(R_j)$ is the number of clusters to which risk $R_j$ is assigned. This constraint may simultaneously allow for some overlaps when they are justified, while keeping under control the number of assignments for the actors with multicluster risks. A reasonable value for max($C \mid R$) is 2. The justification of this constraint is given below.

By testing on multiple configurations (changing constraints), some risks were assigned exactly in 50% of cases to one cluster or another. We decided then to allow them to participate in both clusters, "participate" meaning that the actor who owns the risk will participate to both meetings. This means that interactions that were previously counted as *INTER* are now *INTRA* because this risk/actor belongs to the cluster, so it is normal and not a mistake. On the other side, overlapping should be kept under control; otherwise actors could participate to too many working groups. The relaxation of disjunction constraint should thus be accompanied by a limit on the maximal number of groups an actor can be assigned to. This is a tradeoff between mathematical ambition of minimizing *INTER* and managerial relevance while implementing clusters.

Third, it is possible to put constraints on *NC*:

$$NC_{min} \leq NC \leq NC_{max} \quad \text{or} \quad NC = NC_{required} \quad (8)$$

Finally, additional indicators may be considered to check the quality of proposed solutions. For instance, the concept of density is used, to compare proposed clusters with current groups, and also to compare clusters. Two types of density are used; both are based on the *INTRA* value of the cluster $C_k$; they are defined as follows (see (9) and (10)):

$$DENS \mid R(C_k) = \frac{INTRA(C_k)}{NR(C_k)} \quad (9)$$

Its meaning is to know whether the cluster is dense enough regarding the number of risks included within.

$$DENS \mid A(C_k) = \frac{INTRA(C_k)}{NA(C_k)} \quad (10)$$

Similarly, its meaning is to know whether the cluster is dense enough regarding the number of actors included within. It is all the more important that these actors will communicate and make meetings and decisions together. This means that if the cluster is not dense enough, they will have the perception of losing their time in meetings that do not often concern them, or not enough. This indicator is crucial to the success of practical implementation.

## 3. Clustering Process

Our 3-step approach aims at proposing the best possible solution adapted to the needs of the decision-maker. It is based on Jaber's PhD work, which had been developed in another context, both for problem specification and type of data [107].

*3.1. The Initialization.* The first step consists of gathering data and fixing decision parameters. About data gathering, we created a user-friendly interface to enter inputs and clustering parameters in our model. There are two different things, who and when clustering parameters are decided. The decision-maker is accountable for deciding; however, initial unsupervised clustering may help to give an idea, an order of magnitude of number of clusters for instance. This is why, if the decision-maker prefers this option, we propose to give an estimate of number and size constraints of clusters. Then, the strategy of simulating multiple runs allows for being not too precise at the beginning. We are running calculations with intervals. In other situations, we could give more precise constrains, like, for instance, in a previous work with Sosa [86], where decision-maker wanted to test a configuration similar to the existing one (in terms of number and size of clusters).

*3.2. The Solving.* The second step consists in running multiple scenarios using different algorithms and different configurations. The performance of several well-known graph-based clustering algorithms has been tested with real past case studies. Those have been chosen in the field of design problems, either on product or process or organizational point of view. Two aspects have been compared: the capacity to detect and form performant clusters, and the capacity to tailor the algorithm to specific parameters asked by the decision-maker. Four algorithms have been selected in our case study:

(1) The first one, developed by Leicht and Newman, searches for community structure in directed networks [41]. The modularity function has been generalized in order to incorporate the information contained in edge directions. This allows finding communities by maximizing the modularity over possible divisions of a network, using an eigenvector-based clustering algorithm. The number of clusters is not known in advance. The algorithm is dividing the network into two groups and then possibly dividing those groups and so forth. The process stops when a point at which further division does not increase the total modularity of the network is reached.

(2) The second one, proposed by Blondel and coauthors, develops an algorithm for fast unfolding of community hierarchies in large networks [42]. It is based on a two-phase process. First, a local search for aggregation with neighbors is done, starting from the situation where all clusters are singletons. The algorithm proposes to include a neighbor in the node community if it adds a gain of modularity. Then, the second phase consists in modeling a new network with the nodes being the communities previously built. Then, first phase is repeated with this compacted version of the network, and so on until no further gain of modularity is proposed. This is thus an unsupervised algorithm, using a heuristic which stops when predefined conditions exist.

(3) The third one is called IGTA, for Idicula-Gutierrez-Thebeau Algorithm, which considers maximal cluster size but not number of clusters [47, 48, 108]. It globally follows this 9-step process: (1) each element is initially placed in its own cluster; (2) Calculate the "Coordination Cost" of the Cluster Matrix; (3) randomly choose an element; (4) calculate bid from all clusters for the selected element; (5) randomly choose a number between 1 and rand-bid (algorithm parameter); (6) calculate the total Coordination Cost if the selected element becomes a member of the cluster with highest bid (use second highest bid if step (5) is equal to rand-bid); (7) randomly choose a number between 1 and rand-accept (algorithm parameter); (8) if new Coordination Cost is lower than the old Coordination Cost or the number chosen in step (7) is equal to rand-accept, make the change permanent otherwise make no changes; (9) go back to step (3) until repeated a set number of times. A refined version added a penalty (additional cost in the interaction matrix), to a solution that made an element a member of more than one cluster. That implies fewer multiple assignments for less elements.

(4) The fourth one is based on spectral clustering principles and has been developed by Bühler and Hein [75]. It uses spectral clustering based on the graph p-Laplacian. They prove that "in the limit as p tends to 1, the cut found by thresholding the second eigenvector of the graph p-Laplacian converges to the optimal Cheeger cut". As explained in the Introduction, the characterization of eigenvectors is strongly related to the structure of the matrix, and thus to its behavior. It takes into account edge direction and allows additionally to set cluster size parameter.

The experiments show that (1) the results found by these four algorithms are as good as, or even better than the other ones and (2) the algorithms do not have the same performance depending on the matrix structure (density, presence of loops, and number of eigenvalues). This justifies our choice to run them all in order to be more robust to the matrix structure.

Since it is difficult for decision-maker to fix parameters, multiple values for constraints have been tested:

(i) $NC_{required}$

(ii) max(R | C)

(iii) max(C | R)

(iv) disjoint or nondisjoint groups

(v) actors who must be put together or must be separated

*3.3. The Posttreatment.* We achieved automatic processing of all the solutions provided by the algorithms, which helps building a final recommendation by assembling one or several pieces of those solutions. The second originality of this work is thus to assemble a solution from the different solutions obtained in previous step. No generalized innovative assembling process is proposed; however we argue that this offers more flexibility to the decision-maker and that final solution meets better her expectations, since she is involved in the process.

## 4. Case Study: Analysis of Project Organization and Improvement by Interdependency-Based Clustering

This section introduces the case study at the CEA (*Commissariat à l'Energie Atomique*). The project data are presented with an analysis of the existing situation, and the clustering approach is applied for this specific case. Due to confidentiality reasons, all data are anonymized.

*4.1. The Project Data.* The project aims at designing and building a new nuclear installation (SYST), made of three interdependent subsystems ($SS_1$ to $SS_3$). They are interdependent for two reasons: first, outputs of a subsystem can be an input of another one. This means that there is a kind of sequence (notably for construction and installation phases), even if they are designed simultaneously. Second, there are some key drivers, like safety, which are transverse to the

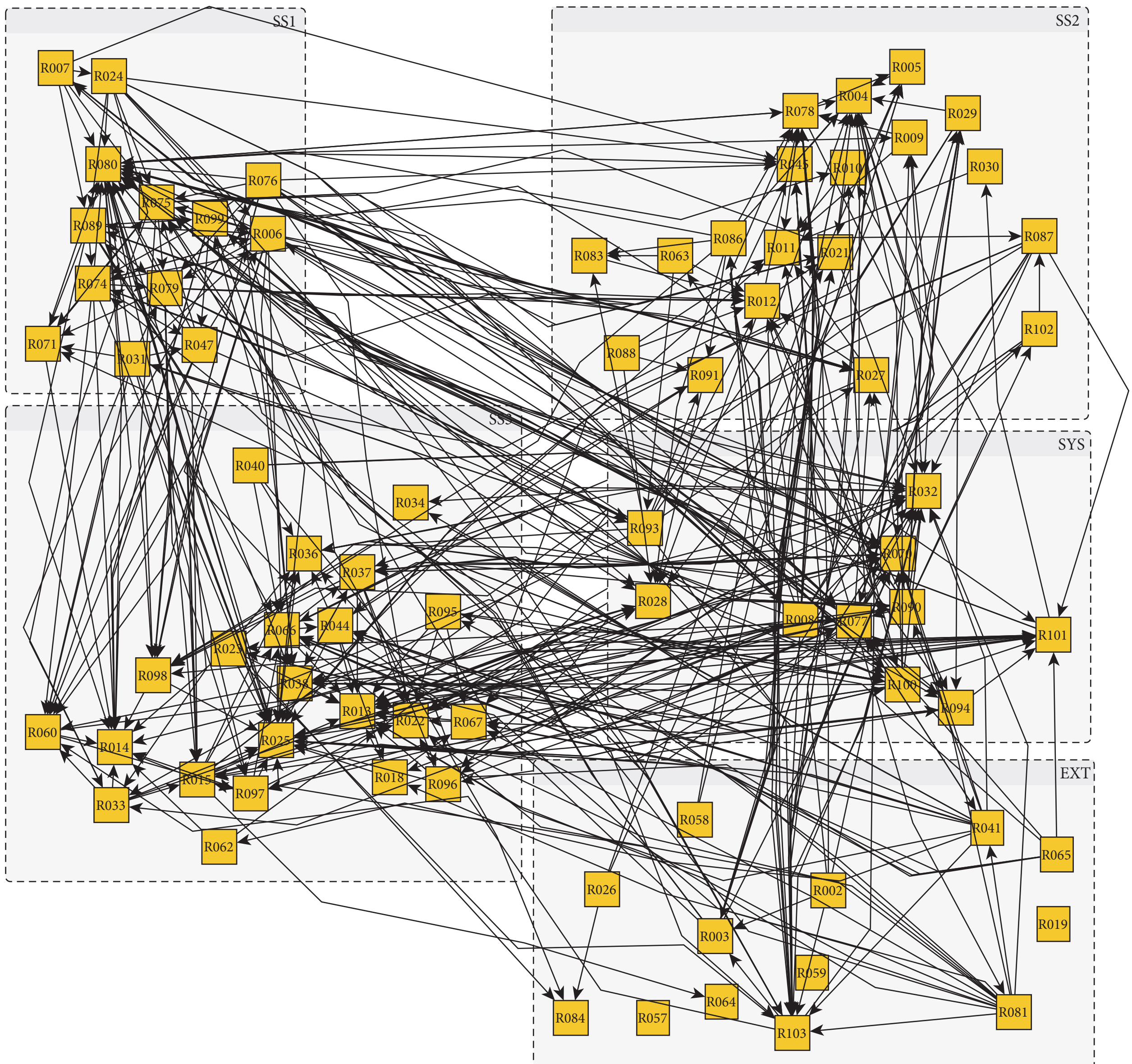


Figure 2: Representation of the existing risk network.

project and have to diffuse in every aspect of the designed subsystems. The organization is composed of 5 groups: 1 integration group at system level (SYST), 3 operational groups at subsystem level, and a fifth one corresponding to influence from the external environment (EXT).

There are 77 risks belonging to the 5 previous groups (**RG**), 21 risk owners (**AR**), and 495 interdependencies (**RR**). The risk network is presented in Figure 2 as a graph and in Figure 3 as a matrix for easier reading.

The graph version illustrates the density of interdependencies in this network and the potential difficulty to coordinate the different actors who make decisions.

Values between 8 and 10 are in red, values between 5 and 7 are in orange, and values inferior to 4 are in green (white if equal to 0).

*4.2. Analysis of the Existing Situation.* The next step consists in separating BAI and MAI. 90% of interdependencies are BAI, 100% of *INTER* interdependencies are $INTER|_{BAI}$, and *INTER* represents 66% of the total value of interdependencies TVI. The situation had been judged dangerous by the decision-maker, and this perception at the origin of the study has been confirmed by factual indicators.

*4.3. Clustering Process (Initialization, Solving, and Posttreatment).* Unsupervised algorithms have been run first, in order to have a preliminary idea of the structure of the network and establish more precisely problem constraints. It appeared that some risks were sometimes in one cluster and sometimes in another one. That justified the removal of disjunction constraint, in order to allow them to be simultaneously


FIGURE 3: Initial configuration with 5 groups of risks organized among the system decomposition.

TABLE 1: Comparison of interdependency type sharing between existing and proposed configurations.

| Interdependency type | Existing Groups | Proposed Clusters |
|---|---|---|
| $INTER\|_{BAI}$ | 2236 (66%) | 1032 (30%) |
| $INTER\|_{BAI}$ | 848 (25%) | 2038 (61%) |
| $INTER\|_{MAI}$ | 320 (9%) | 272 (8%) |
| $INTER\|_{MAI}$ | 0 | 48 (1%) |

TABLE 2: Comparison of performance indicators between existing groups and proposed clusters.

| Group_Id | *INTRA* | *NR* | *NA* | $DENS\|_R$=*INTRA*/*NR* | $DENS\|_A$=*INTRA*/*NA* |
|---|---|---|---|---|---|
| G1 | 316 | 13 | 4 | 24 | 79 |
| G2 | 206 | 19 | 6 | 11 | 34 |
| G3 | 438 | 22 | 6 | 20 | 73 |
| G4 | 142 | 10 | 3 | 14 | 47 |
| G5 | 66 | 13 | 3 | 5 | 22 |
| C0 | 404 | 3 | 2 | 135 | 202 |
| C1 | 378 | 15 | 9 | 25 | 42 |
| C2 | 116 | 7 | 4 | 17 | 29 |
| C3 | 624 | 18 | 9 | 35 | 69 |
| C4 | 576 | 16 | 9 | 36 | 64 |
| C5 | 332 | 12 | 6 | 28 | 55 |

assigned to 2 clusters (max(C | R) is equal to 2). The range interval for $NC_{required}$ is [4:7] and for max(R | C) is [12:18]. Clusters have been built by combination of several solutions proposed in different configurations. Results are presented in the following section.

*4.4. Results.* Organizational reshuffling in interdependency-based clusters is illustrated in Figure 4.

Three risks are declared as transverse. They are put together for convenience in a fictitious cluster called $C_0$. 60 risks are grouped into 5 clusters, from $C_1$ to $C_5$. 14 risks remain outside the clusters.

Table 1 compares the global indicators for initial and proposed configurations, with two highlighted elements:

(i) $INTER|_{BAI}$ decreases from 66% to 30% of total interdependencies (*TVI*).

(ii) *INTRA* increases from 34% to 69% of TVI (including biactor and monoactor interdependencies).

Table 2 summarizes and compares local information about groups and clusters. Except $C_2$, all clusters are more performant in terms of density *DENS* | *R*=*INTRA*/*NR* (see (9)) and *DENS* | *A*=*INTRA*/*NA* (see (10)).

Clusters naturally contain more actors than existing groups (Table 3). This is due to the fact that actors are affiliated to one and only one group but are allowed to be affiliated to more than one cluster. This remains under 2 simultaneous affiliations, except for $A_{16}$(5) and $A_{14}$(3).

In addition to these global changes, other local consequences are of interest. For example, $A_{19}$ is the only one of group EXT who has been assigned to $C_5$. This means that the way people were initially grouped together did not correspond to the reality of their interactions and their coordination needs.

Results show a significant decrease of $INTER|_{BAI}$ and increase of *INTRA*, with a slight increase of average cluster size (in terms of the number of affiliated actors). The following section discusses managerial implications of each cluster.

## 5. Managerial Relevance of Proposed Clusters

$C_0$ is not a cluster like others. This means that the actors declared as transverse have to exchange on a regular basis with all the clusters. For the rest, each cluster has been analyzed in terms of advantages and drawbacks, in order to decide whether it deserves to be implemented or not.

Cluster $C_1$ is made of 15 risks (8 from $SS_2$ and 6 from $SS_1$), owned by 9 actors (Figure 5).

Cluster $C_2$ is the smallest cluster, consisting of seven risks. This cluster is particularly homogeneous, with 6 risks from $SS_3$ and 1 risk from $SS_1$, common to clusters $C_2$ and $C_1$ ($R_{79}$). This cluster is centered on the design of $SS_3$ processes and related choices (Figure 6). The risk $R_{79}$ of $SS_1$ represents the object as an input for the design of other processes. This cluster has a practical meaning for the project, notably for linking various actors whose correct interfacing is extremely important for the proper functioning of this part of the future plant.

$C_3$ is the largest one (18 actors), with the highest *INTRA* value (624). Moreover, it has the rare distinction of fully integrating a 9-risk subcluster obtained from several algorithms with different maximum size constraints. As displayed in Figure 7, this subcluster is even denser than the cluster itself, acting like a kernel. It behaves like a steering committee inside $C_3$ because all identified risks in the kernel are strategic and

Table 3: Analysis of assignments of actors to clusters.

| | $G_1$ ($SS_1$) | $G_2$ ($SS_2$) | $G_3$ ($SS_3$) | $G_4$ (SYS) | $G_5$ (EXT) | $C_0$ | $C_1$ | $C_2$ | $C_3$ | $C_4$ | $C_5$ | $NC\|_A$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $A_{01}$ | 4 | | | | | | 1 | | | | | 1 |
| $A_{02}$ | 3 | | | | | | 1 | | 1 | | | 2 |
| $A_{03}$ | 3 | | | | | | 3 | 1 | | | | 2 |
| $A_{04}$ | 3 | | | | | 2 | 1 | | | | | 2 |
| $A_{05}$ | | 4 | | | | | 1 | | | | 2 | 2 |
| $A_{06}$ | | 5 | | | | | | | 2 | 1 | | 2 |
| $A_{07}$ | | 5 | | | | | 3 | | | | 1 | 2 |
| $A_{08}$ | | 3 | | | | | 3 | | | | | 1 |
| $A_{09}$ | | 1 | | | | | 1 | | | | | 1 |
| $A_{10}$ | | 1 | 1 | | | | | | 1 | | 1 | 2 |
| $A_{11}$ | | | 4 | | | | | 4 | | | | 1 |
| $A_{12}$ | | | 4 | | | | | | 3 | 2 | | 2 |
| $A_{13}$ | | | 3 | | | | | | 3 | | | 1 |
| $A_{14}$ | | | 9 | | | | | 1 | 3 | 4 | | 3 |
| $A_{15}$ | | | 1 | | | | | | | 1 | | 1 |
| $A_{16}$ | | | | 4 | | 1 | 1 | | 1 | 1 | 1 | 5 |
| $A_{17}$ | | | | 1 | | | | | | 1 | 1 | 2 |
| $A_{18}$ | | | | 5 | | | | | 3 | 2 | | 2 |
| $A_{19}$ | | | | | 6 | | | | | 2 | 6 | 2 |
| $A_{20}$ | | | | | 3 | | | 1 | | | | 1 |
| $A_{21}$ | | | | | 4 | | | | 1 | 2 | | 2 |

driven by the major contributors in the project. These risks are all related to fundamental decisions for the installation of $SS_3$. This cluster seems much more diverse than others because all domains of the project are concerned. However, when examining things deeper, we found that the cluster is centered once again on the $SS_3$, with a specific topic around the availability of the future nuclear installation $SS_3$. Once again, it is not a surprise to see connections between intermediary elements and the final outcome, which is the production by the plant. The diversity is not surprising. However, it was not intuitive to connect these specific elements, which was done by the clustering approach.

Cluster $C_4$ is characterized by two main elements: first, it is extremely diverse but mainly focused on $SS_3$ installation and associated risks in other categories ($SS_1$, $SS_2$, SYS, and EXT). Despite this diversity, the *INTRA* value is extremely high (576, the second-best cluster). Second, this 16-risk cluster is connected with two other clusters, with 3 common risks with $C_3$ and 4 common risks with $C_5$ (as shown in Figure 8). Once again, this is due to the mandatory diversity of points of view to address such complex issues as a subsystem design or installation. However, the number of assignments for risk owners is completely under control because only two actors have more than two assignments. This has been validated by the managers. Moreover, $C_4$ is more related to the financial aspects of the building, both during and after the project (construction costs and operations costs). This also explains why these risks should be included in two clusters.

Finally, cluster $C_5$ is a 12-risk cluster with an *INTRA* value of 332, which places it slightly lower than $C_3$ and $C_4$ and is equivalent to $C_1$. Surprisingly, this cluster groups 6 risks from the EXT category, 2 risks from SYS, and 4 from the subsystem $SS_2$. The decision-maker had not expected to see the presence of only one subsystem. As displayed in Figure 9, the EXT-related risks are relatively independent (the central part of the matrix is almost empty) but strongly connected with other categories: $SS_2$ and SYS, respectively.

$C_1$ reinforces the connection between subsystems $SS_1$ and $SS_2$. $C_2$ is focused on $SS_3$ design, just like $C_3$ (with a focus on exploitation). $C_3$' is used as an interface between $SS_3$ design and the rest of the project. $C_4$ is made of numerous cost-related risks about installation of subsystem $SS_3$. Finally, $C_5$ links $SS_2$ to SYS and EXT.

## 6. Discussion

Due to the fact that different algorithms were run using different problem configurations, the decision-maker recognized the validity of each cluster, both in terms of mathematical justification and of managerial relevance. Even cluster $C_3$, with its particularity to have a subcluster, has been validated. The only difference was to run two series of meetings, with different participants and different agendas.

Compared to the classical way risks are currently managed, the main difference is to formally connect actors outside of the traditional project organization boundaries. In this case, project risk list was classically broken into subsystems down, with a second categorization based upon risk nature (financial, technical, delay, safety, etc.). The importance of risk management is not always perceived as crucial by managers, mainly because of two reasons: the first one is the traditional


FIGURE 4: Proposed configuration with 3 transverse risks and 5 clusters.

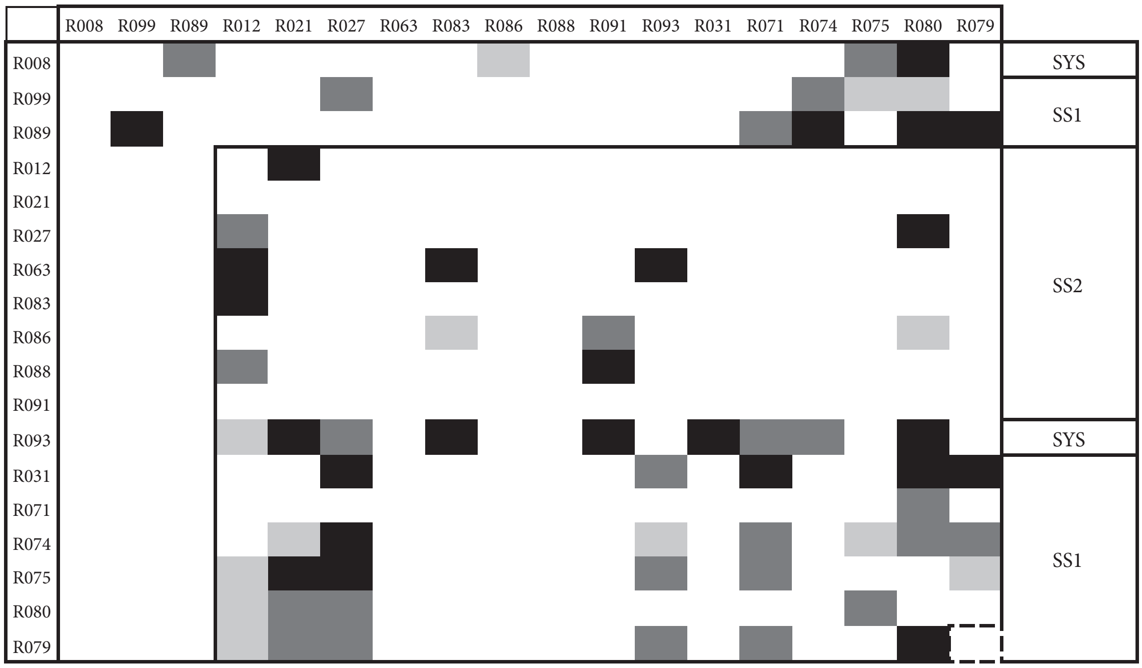


Figure 5: Display of cluster $C_1$ and the 3 transverse risks.

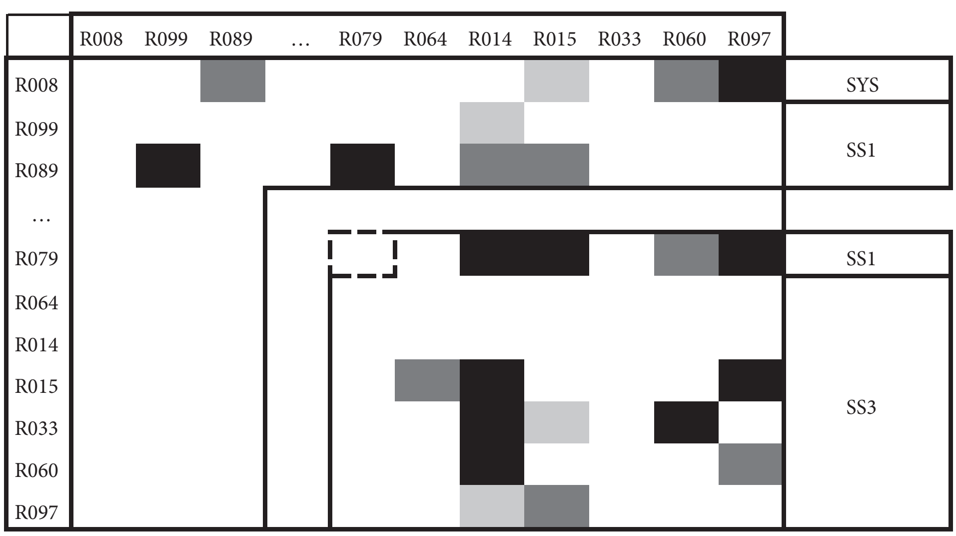


Figure 6: Illustration of the $SS_3$-centered cluster $C_2$ and its interdependencies with transverse risks.

technical focus of member of such innovative and technically complex projects; the second one is the unfortunately traditional reluctance to invest time and energy into an unreliable process. Namely, if risks are not properly managed, then risk management outcome is not good, meaning that project behavior is not correctly anticipated and mitigation actions are not correctly planned. This implies a negative perception of risk management, which is a negative loop. In this paper, the assumption is that we do not work on quality of risk data. We consider data as inputs, with their limits and potential lack of reliability (on assessments for instance, or on completeness of risk identification). However, our approach makes a difference in the use of these inputs, compared to classical approach where risks are considered as independent (management by Excel), or as dependent but with less advanced methodologies (trees or risk clustering without considering human resource assignment). So, increasing the perception of reliability and usefulness of risk management may also involve a better perception of investing time into proper and periodic risk identification and assessment.

Namely, risks are dynamic by essence, with their values evolving through time, and with new risks appearing or existing risks disappearing. This means that clustering analysis has to be updated when significant differences exist between

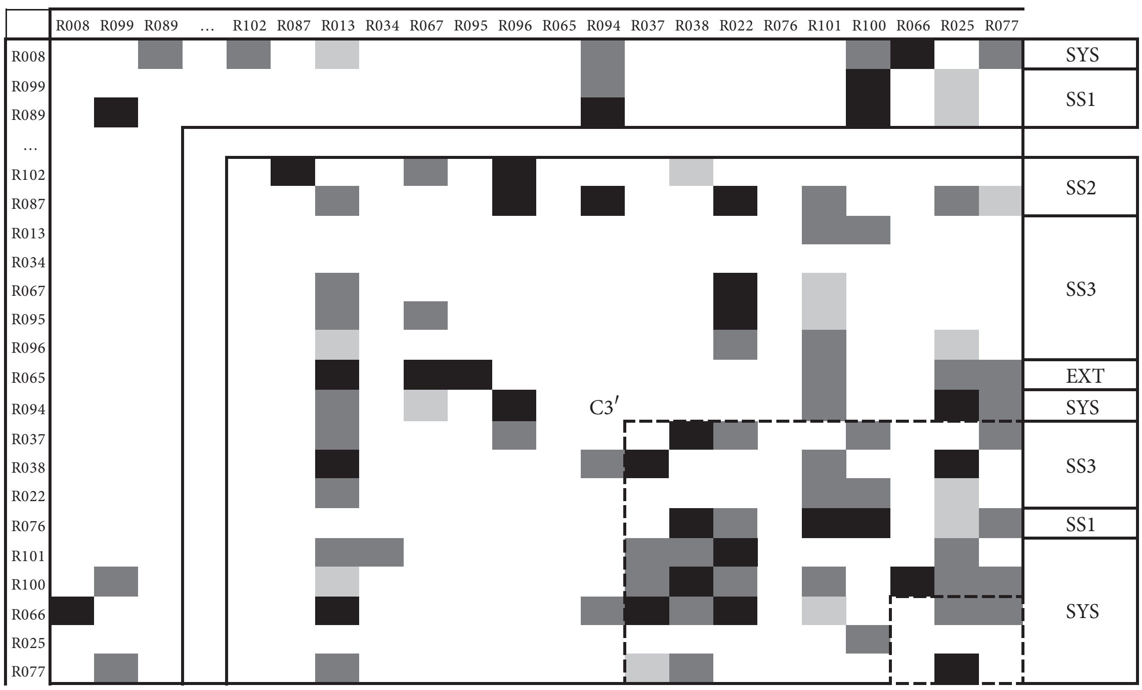


Figure 7: The cluster $C_3$ and its subcluster $C_3$' with connections with transverse risks.

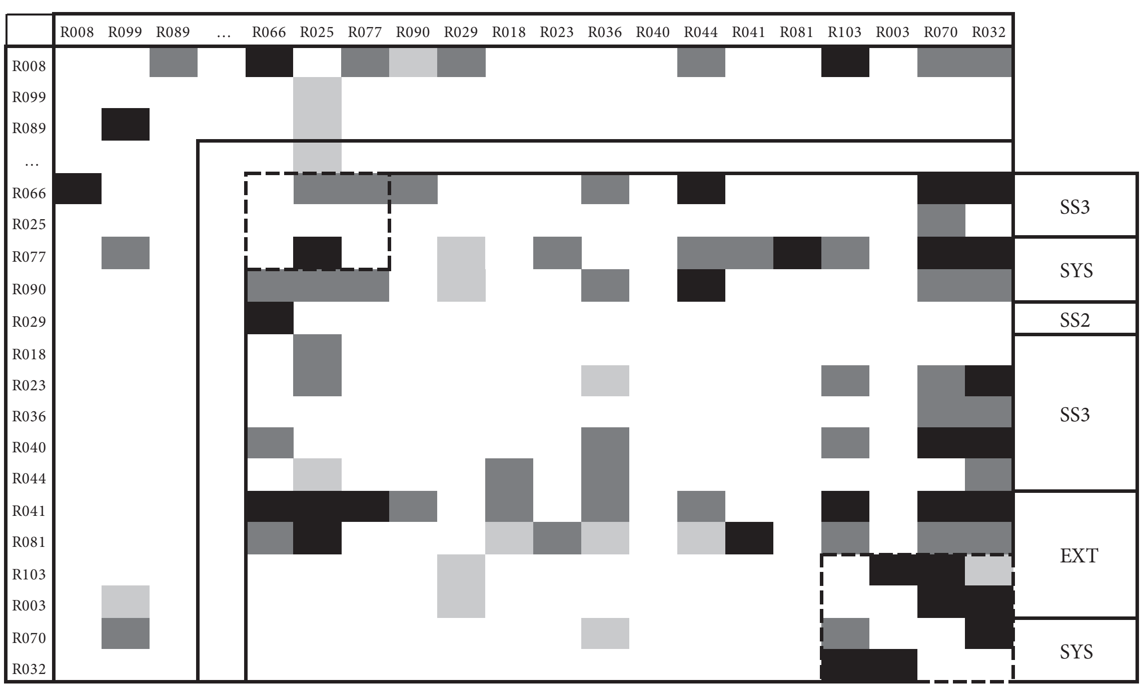


Figure 8: The cluster $C_4$ intertwined with $C_3$ (up-left) and $C_5$ (down-right).

two versions of the risk list. Based on our experience, it is not a problem to update the risk list and so the risk-based organization, since actors prefer to have an up to date version of the organization to work with. So, we work with a current version of the data, and we update the clusters when there are changes in the data, for instance on a monthly basis, which may classically correspond to project risk reviews frequency.

These complementary teams foster psychological safety and trust between members, which provides a supportive environment amenable to anticipation, collective problem-solving, and coordinated decision-making [109, 110]. They propose to work together in interdependency-based temporary working groups, which is not the same as if the manager of a subsystem invited people from another subsystem. This

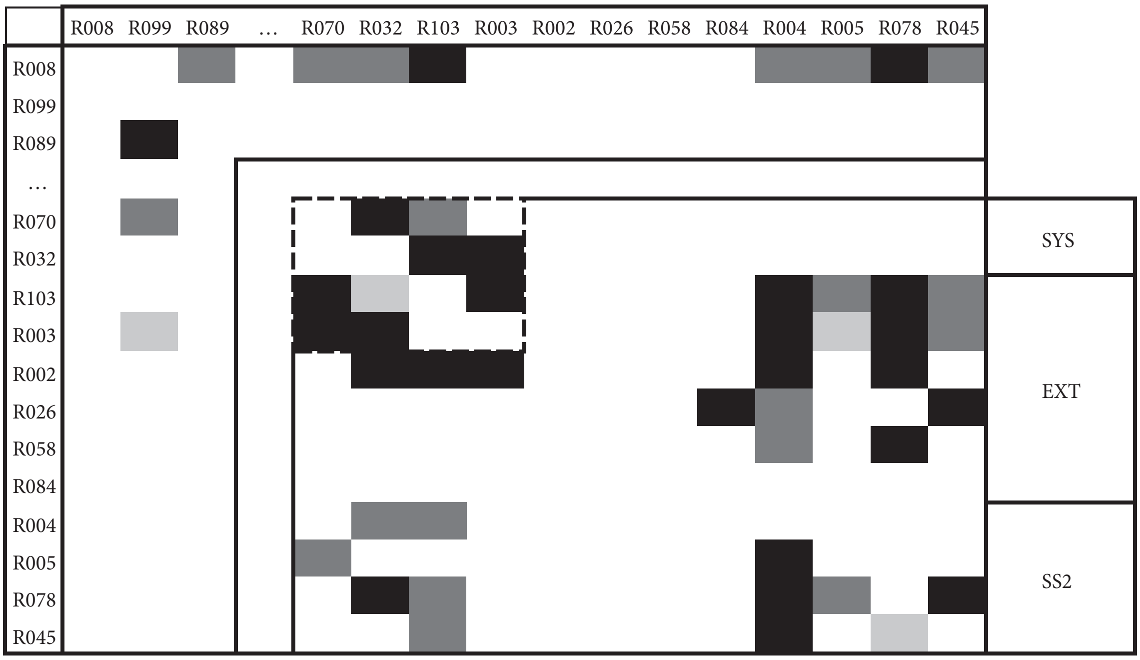


Figure 9: Cluster $C_5$ and its lower connections with the transverse risks.

is even more important than the way in which teams are assembled seems to have an influence on their success [111]. One additional important point is that clusters of actors are indirectly proposed based on risk interdependencies, which has two positive and one negative implications: (1) the focus is on cause-effect interdependencies between nonhuman elements (risks), which has not the same implication as direct identification of interaction between two actors, especially when it is not correctly managed; (2) the data about risk interdependencies are easier to assess with a neutral, factual way, without a priori interference depending of who is involved in the interaction, what their personalities are and so on; (3) the counterpoint of this indirect consideration of groups of actors is that the calculation of a risk interdependency-based solution may be disturbed by the possibly negative consequences on actors groups. For instance, an optimal solution considering risk interdependencies only may be rejected because it does not respect an actor-based constraint (maximal size of the group).

The will to involve the decision-maker in tailoring the clustering methodology has the following implication: the performance can be a bit lower since the decision-maker may prefer a suboptimal solution, from the pure calculation point of view, in order to implement it more easily and have more warranty to get a collective behavior within and between human clusters.

There are some limits to this work. First, it is based on an initial version of the list and a network of elements, which is given by the decision-maker. We did not test the consequences of possible mistakes made in this initial input. However, we will be able to update the initial network once the project continues and the situation changes. New risks appear or disappear, and new interdependencies appear or disappear or simply see their values change. The effort is reduced because the largest part of the work has already initially been completed, and updating an existing network is far less demanding than building it from scratch. The calculation time is not a problem, so the limiting factor is the data gathering effort. The decision-maker was ready to invest time at the beginning but wanted updates to be given very quickly. The second limit concerns the interdependencies assessments. Because of the clustering algorithm groups risks with the highest interdependency levels, it is a priori enough to have orders of magnitude of assessments with relative gaps that are significant enough to justify a preference for placing this risk into a certain cluster rather than a different one, which is why we tested the sensitivity of the proposed clusters for the uncertainty on input in other studies. We tested the sensitivity of the chosen algorithm and made proposals corresponding to robust solutions; however, further research could more deeply analyze the importance of precise assessment.

On a managerial point of view, some managers are attached to hierarchical power (or the impression or illusion of it). The main downside for them is that they (seem to) lose a part of this power. But we argue that this is more aligned with the actual nature of complexity of the project, which is not correctly taken into account by classical, hierarchical organizations based on services and departments. So, even for managers, we think that removing problematic situations or crisis could be better for them. Second, it apparently adds some work and particularly meetings since we add a complementary organizational structure which needs to undertake meetings series (calling them working groups, task forces, or whatever). But we argue that the investment is profitable, both in terms of time and on other parameters like cost. Indeed, these meetings have a chance to avoid far bigger troubles in downstream phases, where amounts at stakes are multiplied by 1000 in such projects. It costs several tens of hours, but may save hundreds of crisis meetings hours, and several millions/tens of millions of overcost/wasted money. Last, some people could argue that a complementary way of seeing and managing things would add more complexity to a situation that does not need it. However, once again, we argue that this way is considering the complexity to align at best organization to it, so we think that it is exactly the opposite of this natural fear.

## 7. Conclusion

This research work proposes a clustering-based approach to form teams to make collective decisions about interdependent risks in an evolving environment. This challenge is nontrivial because of the interdependencies between project risks and thus between the actors owning these risks. Our approach proposes complementary organizational clusters based on the interdependencies between the risks that the actors own, meaning that it avoids the classical criteria based on similarity or diversity. More specifically, we capture and use the information about the fact that risk interdependency is managed by one or two different actors. Forming alternative teams based on interdependencies between project elements, which is complementary to the classical project breakdown structure organization, is an emerging and vital topic to the performance of projects. Some promising perspectives arise from this work, like the dynamics of the model, and the robustness of proposed clusters to data changes, or the consideration of specific complex phenomena, like propagation chains and loops, in building complexity-oriented project organizations. Moreover, this work is a step between pure algorithmic-based organization reshuffling and putting the organization on a different management mode, more based on lateral interactions, distribution of authority, and incitation to coordination (more than collaboration). New ways of managing projects and organizations, like agile management or holacracy, will be developed in further work in order to use interdependence-based algorithms to serve such management modes.

## Data Availability

Data which are not included in the paper are not available, due to confidentiality reasons.

## Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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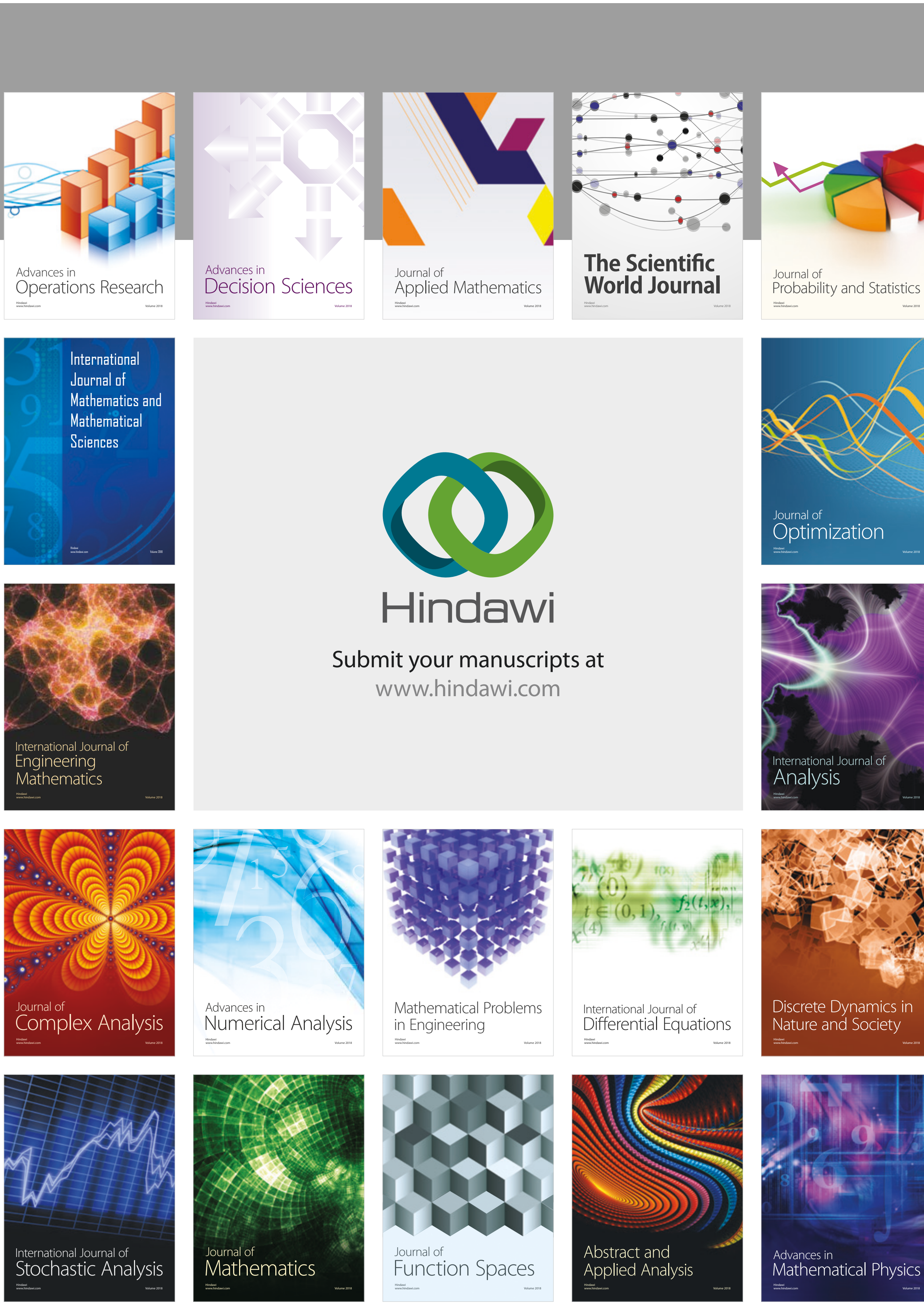
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