Thinking project management in the age of complexity: particular implications on project risk management

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Ludovic-Alexandre VIDAL

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Prologue

Overall introduction of this work

A project is a temporary and unique endeavour undertaken to deliver a result. This result is always a change in the organization, whatever it is in its processes, performance, products or services. This transformation consists then in a gap between a start and a final state. Time and resources are consumed to produce results, which may be deliverables and/or performance improvement and/or resource improvement (skills, knowledge). Each project is unique because there is always at least one of the following parameters that changes: targets, resources and environment. As projects became more and more present into organizations, and as they had bigger and bigger amounts at stake, it became impossible to let them live without specific and rigorous methodology. As a consequence, project management was created as a formalized and structured methodology. It is usually admitted than modern project management appeared during World War II and was initially dedicated to big military and construction projects.

For all practical purposes, lots of studies have been done, based on statistical calculations or surveys. Limits and lacks have been detected in research as well as in industry about the project predictability, since usual parameters (time, cost and quality) are clearly not sufficient to describe properly the complete situation at a given time. As a whole, the conclusion of these studies is that current methods have shown their limits, since they cannot face anymore the stakes of ever growing project complexity. For instance, as noted during discussions with consulting practitioners, in the case of oil industry, it is clear that engineering projects today are larger, involve more sophisticated technology and are organised with a higher number of contractors and partners compared to 40 years ago. As a whole, project complexity results in damages or failures for the projects. In other words, project ever growing complexity is an ever growing source of project risks.

This Ph.D. thesis thus aims at addressing this issue by answering the following principal research questions (which will find their justifications thanks to the states of the art which was performed throughout the different chapters).

- What is project complexity? What are its characteristics and sources? How can it be described?
- In order to manage, one needs to measure. The question is then how can project complexity be measured to assist decision-making in complex project management?

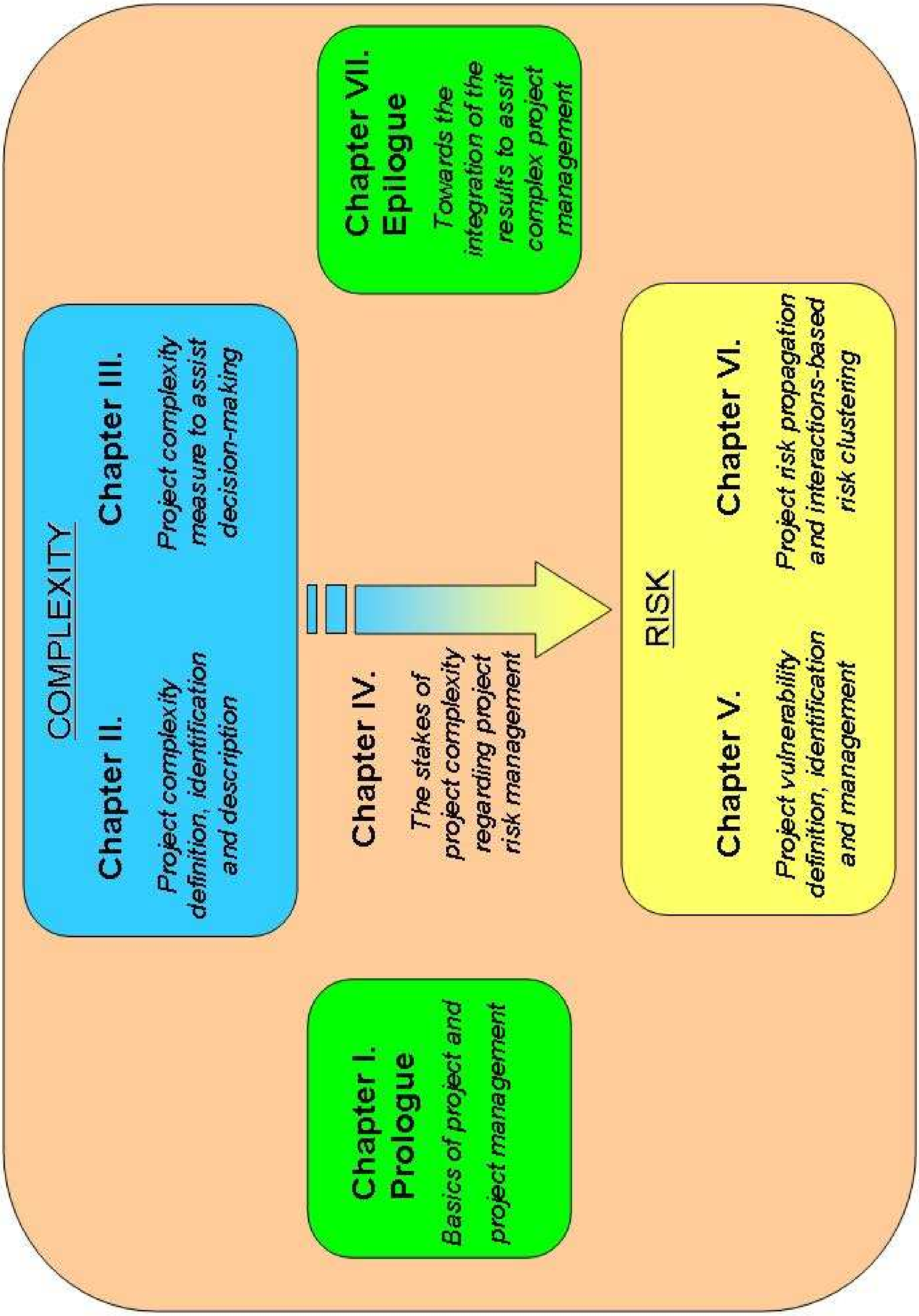

Figure 1. Overall structure of this Ph.D. thesis

- What are the stakes of project complexity? What are its implications on project risk creation? What are the lacks of traditional project risk management methodologies regarding the integration of complexity?
- Can innovative methodologies and tools be developed to integrate better complexity related aspects into project risk management? Can these innovative approaches, whether systemic or analytical, permit to assist complex project risk management?

In order to answer these questions, this Ph.D. thesis is structured as seen before (Figure 1). This structure corresponds to a way to explore the different aspects of this thesis and tries to bring clarity in how to understand and handle project complexity.

Each chapter makes the point of a specific introduction to a more detailed problem setting which permits to explicit better the overall research questions of this Ph.D. work.

Chapter 1 – Basics about project and project management through systems thinking

Chapter 1 permits to explore the basics of project management in order to set up definitions, describe what a project is and underlines the specificities of project so that no confusion is made throughout the Ph.D. thesis. It also underlines how projects can be considered as complex systems.

Chapter 2 – Building up a project complexity framework

Chapter 2 proposes the construction of a standard project complexity framework as a basis for the identification of project complexity sources. An international Delphi study permits to draw some conclusions on project complexity and refine the framework for future use. Application is proposed to former vehicle development projects at Renault.

Chapter 3 – Assessing project complexity

Chapter 3 claims for the use of a multi-criteria approach to evaluate project complexity. An AHP hierarchical structure is built up thanks to the refined framework which is elaborated in Chapter 2. The practical use of such a measure is discussed. Application is proposed to a project portfolio in a start-up firm within the stage musicals production industry.

Chapter 4 – Understanding the stakes of project complexity. Implications on project risk management.

Chapter 4 permits to underline the consequences of project complexity in terms of ambiguity, uncertainty, propagation and chaos. Implications on project risks are underlined and limits of conventional project risk management methodologies are exposed.

Chapter 5 – Systemic approach. From project risk management to project vulnerability management.

Chapter 5 proposes a systems thinking- based approach around the concept of project vulnerability. It depicts the process of project vulnerability management around several steps and shows how vulnerability can help to highlight the existing weaknesses of a project system. Application is proposed to a software development project within the healthcare industry.

Chapter 6 – Analytical approach. Interactions-based clustering and other tools to assist project risk management

Chapter 6 proposes an analytical approach to permit a better integration of complexity in project risk management processes. By introducing risk interactions and building up a project risk network, risk propagation is studied thanks to matrix representation and its associated indicators. An innovative approach to cluster risks according to their possible interactions is finally proposed as a tool to assist complex project risk management. Application is proposed to a project in the stage musicals production industry and to a large infrastructure project (a tramway infrastructure).

Epilogue

This Ph.D. thesis then draws a brief synthesis of this research work. It highlights how this work proposes some answers to the research questions which have been raised. It finally proposes a possible integration of all results and possible research perspectives.

Chapter I -

Basics about project and project management through systems thinking

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Abstract

The overall ambition of this chapter is to be a prologue for this Ph.D. thesis thanks to the introduction of the main, though sometimes basic, concepts about projects and project management which are likely to be used throughout this thesis.

In order to present them, we however propose to use an innovative approach to highlight them. By following a systems thinking-based approach, we aim at being complete about the description of projects, underlining what a project is, what it is composed of, what it performs during its execution, what its objectives are,

This chapter also underlines project specificities (notably compared to other organisational systems), mainly in terms of uniqueness and temporariness, and what this implies on project management and its complexity.

This chapter is thus to be the necessary basis to explore projects as complex systems.

Chapter Keywords

Project, Project Management, Systems, Systems Thinking, Uniqueness, Temporariness.

I.1. The increasing share of projects

Broadly, the activity of an organisation (a firm, an association, a non-profit organisation, etc…) can be divided into two main categories: operations and projects. Operations involve repetitive and ongoing activities, such as production, whereas projects are in essence unique and one-shot initiatives. As for them, as highlighted by (Schneider, 2008), "projects are the microcosm where different functions, management levels, and professional backgrounds, with their respective worldviews, collide". Examples of projects can be the following ones:

- Developing and launching new products (product development projects).
- Designing new organisations (organisation projects).
- Improving existing processes within a firm (process improvement projects).
- Staging a play (event project).
- Searching for an innovative process, product, or material (R&D projects).
- Developing a new software (IT projects).
- Constructing a building (construction projects).

As Shenhar and Dvir underline it (Shenhar and Dvir, 2007), "with high demand for growth and innovation, the share of operations in most organizations is declining and the share of projects is on the rise", as shown on Figure 2. As they explain it, this trend is present in almost every organization and industry since "the only way organizations can change, implement a strategy, innovate, or gain competitive advantage is through projects".

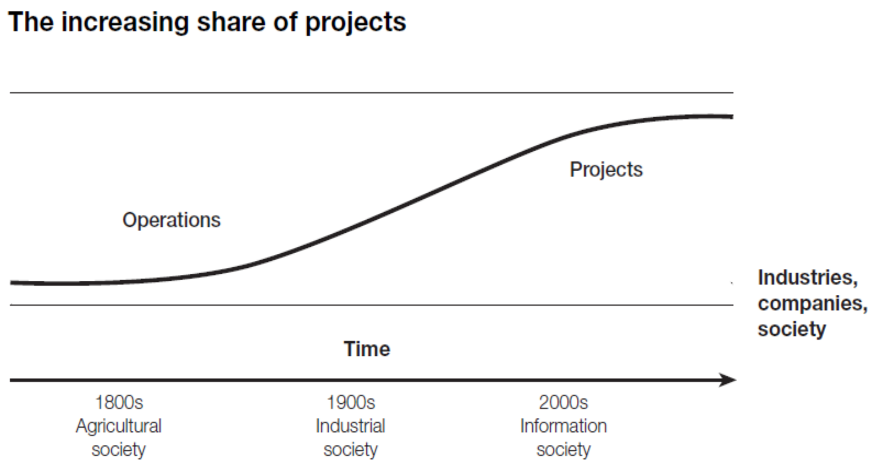

Figure 2. The increasing share of projects (Shenhar and Dvir, 2007)

However, when most of firms or organisations have kept on improving their operations (through theories and concepts such as lean manufacturing or six sigma), despite the fact that projects have been encountered everywhere, few organisations have been paying as great attention to their projects. But, "no business enterprise can survive if it is focused only on improving its operations" (Shenhar and Dvir, 2007). As a consequence, focusing on projects, focusing on innovative, efficient and effective approaches to manage them is to create great value for modern organisations.

That is why this Ph.D. thesis concentrates on projects and project management, particularly focusing on the phenomenon of project complexity and its implications on project management and project risk management. Before carrying out any pertinent research on the subject, one is first to define properly what a project is (and also what project management is). Basically, a lot of definitions do exist, as highlighted in (AFNOR, 2004), (Marle, 2002), (Gautier, 2004) for instance. This work is based on the Project Management Institute (PMI) definition (PMI, 2004):

Definition – adapted from (PMI, 2004)

A project in an organisation is a temporary endeavour undertaken to deliver a result.

As mentioned before, this result is always a change in the organization, whatever it is in its processes, performance, products or services. This transformation consists then in a gap between a start and a final state. Time and resources are consumed to produce results, which may be deliverables and/or performance improvement and/or resource improvement (skills, knowldege). Each project is unique because there is always at least one of the following parameters that changes: targets, resources and environment. As projects became more and more present into organizations, and as they had bigger and bigger amounts at stake, it became impossible to let them live without specific and rigorous methodology. As a consequence, project management was created as a formalized and structured methodology. It is usually admitted than modern project management appeared during World War II and was initially dedicated to big military and construction projects, when the first principles of organization, planning, and overall management were proposed. Project management has then grown up and spread around the world to become what it is today, that is to say a set of theories, principles, methodologies and practices (WBS -Work Breakdown Structure, PERT -Progamme Evaluation and Review Technique- networks, etc…), sometimes included in a standard body of knowledge such as PMI (PMI, 2004) and IPMA (IPMA, 2006). However, there can still be some lack of consensus on the definition and description of projects as well as their objectives, processes and elements.

PROBLEM SETTING OF THIS CHAPTER

As a consequence, this chapter proposes to use a systems thinking-based approach to describe projects. This description is not innovative in its content as it is notably based on a state of the art on traditional project management standards (notably (PMI,2004)), but it permits a reorganization of information which is driven by project final objectives in terms of values creation. The ambition of this prologue chapter is thus to

- Describe project systems and their main subsystems (activity system, management system).
- Underline the specificities of projects (uniqueness and temporariness) and their implications on project management.

These points are going to be the basic concepts which are references for this Ph.D. thesis.

I.2. Systems thinking

In order to do so, this Ph.D. thesis claims for the use of systems thinking to explore the description of projects. Basically, our systems thinking-based approach is notably based on or at least consistent with the works of (Boulding, 1956), (Simon, 1968), (Von Bertalanffy, 1972), (Le Moigne, 1990), (Penalva, 1997), (Heylighen and al., 2006), (Bocquet and al., 2007), (Schindler and al., 2007) or (Vidal and al. 2007). This Ph.D. work considers the following definition of a system.

Definition - adapted from (Vidal and al., 2007)

A system can be defined as an object, which, in a given environment, aims at reaching some objectives (teleological aspect) by doing an activity (functional aspect) while its internal structure (ontological aspect) evolves through time (genetic aspect) without losing its own identity.

According to this definition, a project can be undoubtedly considered as a system. Indeed, it possesses the four aspects listed above. A project exists within a specific environment and aims at reaching objectives given this context (teleological aspect). A project has to accomplish a network of activities using some methods and methodologies (functional aspect). A project has an internal structure composed of resources, deliverables, tools, workers, etc… (ontological aspect). Finally, a project evolves through time, via resource consumption, product delivery, members' changes and gain of experience, without losing its own identity (genetic aspect). In the systems thinking vision, the project system evolution is to be considered with the assumption that future is under perpetual construction (Prigogine, 1996), which excludes the use of analytical tools. In order to provide innovative practical tools for complex project management, this Ph.D. work is to claim for the use of a shared epistemology which permits to define, when necessary, methods and tools based on analytical decompositions, but which use or are at least compatible with the systems thinking-based vision of projects as four aspect entities.

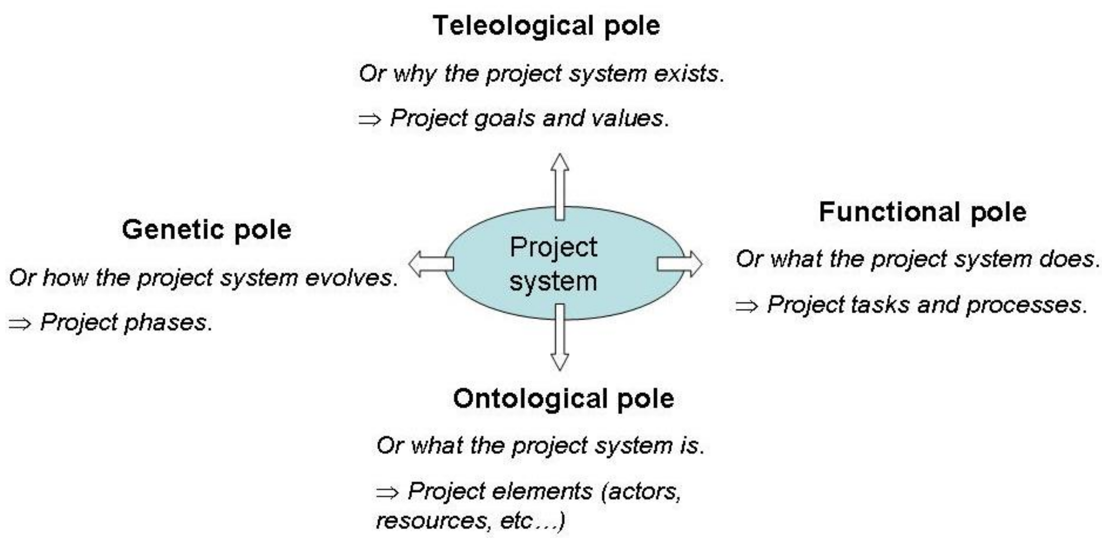

Figure 3. A systems thinking-based approach to describe projects

We firstly do so in this chapter as it claims for the use of a systems thinking-based organisation design methodology, SCOS'D (Bocquet and al., 2007), (Schindler and al., 2007), meaning Systemics for Complex Organisational Systems Design, in order to describe project systems. In essence, this method calls for the description or design of organisational systems thanks to a four step process which consists in:

- The identification of the system's phases. (Genetic pole)
- In each phase, the identification of its goals and targets in terms of value creation (due to the expectations and constraints of the project environment, clients and stakeholders) (Teleological pole).
- For each value, the identification of the tasks and processes which are to be performed in order to reach the project objectives in terms of values creation (Functional pole).
- For each task or process, the identification of the elements which are needed to perform them, that is to say actors, resources, and any other inputs. (Ontological pole)
- A feedback loop can be performed in order to check that the supposed phases of the project system are consistent with the evolution of the obtained system. This is notably to ensure the robustness of the whole approach.

We claim for the use of these principles to describe project systems in order to ensure the robustness of their description. These principles (which are in essence at the edge of systems thinking and analytical decompositions) will also be used in other parts of this Ph.D. thesis, especially in Chapters 2 and 5.

I.3. Describing projects

I.3.1. First level of description: project systems and their subsystems

Basically, traditional approaches of project management consider that a project system evolves over time according to five principal phases (genetic aspect), which are:

- Project initiation (including pre-contract and contract elaboration processes).
- Project planning (in terms of budget, resource allocation, time planning, etc…)
- Project execution (to create project deliverables)
- Project monitoring and control (to watch over the project correct execution)
- Project closure (to end the project correctly after completion)

In order to describe the entire reality of projects, a systems approach should be carried out for any of these phases. In this paragraph, we propose to concentrate only on the phases of project execution and project monitoring and control in order to highlight the existence of two subsystems: the project management system and the project activity system. Another system, the project information system, though existing (as in the canonical decomposition of Le Moigne (Le Moigne, 1990), is not highlighted here (and it will not be addressed in this Ph.D. work). This is consistent with other systems thinking oriented ones (Gourc, 1997), (Stal Le Cardinal, 2000), (Marle, 2002), (Jankovic, 2006). We now propose to apply the SCOS'D process for project systems.

During these phases, the targeted values (teleological pole) of the project system are to be notably:

- The quality of project deliverables.
- The cost of the project (keeping it under a certain value), and thus the profit obtained from the project.
- The time to complete the project (target is to close the project at a certain date D).
- The quality of project management processes.
- Other performance values such as societal or environmental values.

The three first proposed values (Giard, 1991) constitute the so-called triple constraint or iron triangle (Atkinson, 1999). Deviations from this triangle are undoubtedly seen as a negative sign, which must be prevented or corrected. The organisation's management board (which is part of a more global governance system) is to require high standard project management processes in order to guarantee as much as possible the success of their projects. Modern projects also tend to include other performance values to judge of the success of a project such as societal or environmental values as mentioned hereinbefore. That is why the former bulleted list of project values is proposed.

So that it can reach the objectives of values creation, a project is to perform a lot of activities during these phases. The identification of theses activities permits to underline the existence of two sub-systems within a project system: the project activity system and the project management system.

The two next sections explore respectively the description of the project activity system and the project management system. The ambition of this description is not to be exhaustive, but to be set up in all minds what a project within an organisation is.

I.3.2. Second level of description: the project activity system

The project activity system is expected to:

- Deliver a final product, service, deliverable which corresponds to the expectations of the project's client(s).
- More generally, create performance values (particularly industrial, societal and environmental) as expected by the project management system and the organisation's management.
- Deliver a regular activity reports and results (regarding the targeted project objectives) to the project management system.
- Share a vision of the project which is consistent with its objectives and with the strategic objectives announced by the organisation's management.

The project activity system must work, knowing that:

- The project management system gives information, previsions and objectives to it.
- The organisation's management gives to it a set of values and a strategic vision to cling to.

- The other project activity systems existing within the organisation may be compared to it, notably in terms of performances and outcomes.

As a whole, the project activity system must therefore perform efficient and effective processes in order to meet the achieve these seven last points. These ones are to be performed thanks to project resources (material, machines, etc…), project actors and other inputs (information, etc…), which constitute the core elements of the project activity system.

I.3.3. Second level of description: the project management system

As for it, the project management system is expected to:

- Define the project objectives over time as the project activity system needs them.
- Make decisions to reach these objectives as the project activity system needs them.
- Measure and monitor regularly the project, notably in terms of advancement reaching its final performances targets regarding values creation.
- Communicate regularly with the organisation's management on the project advancement thanks to the delivery of regular project reports and reviews.
- Be consistent with the strategic vision of the organisation's management.
- Deliver regular project management reports and indicators.

The project management system must work, knowing that:

- The activity system gives to it regular project activity reports and results.
- The organisation's management gives to it a strategic vision and objectives to communicate to the project activity system.
- The other project management systems existing within the organisation may be compared to it, notably in terms of performances and outcomes.

As a whole, the project activity system must therefore perform efficient and effective processes in order to achieve these nine last points. These ones are to be performed thanks to project resources, project actors and other inputs which are often gathered into a project steering committee. The reader should note that actors may be present into the activity and management subsystems.

I.4. Underlining project specificities and their implications

I.4.1. Projects facing their temporariness

In essence, a project is temporary, which means that is expected to have a start date and a finish date. This implies that projects have a temporary existence within organisations. As highlighted by several research works (Lundin, 1995), (Packendorff, 1995), (Turner and Müller, 2003), this results in several implications:

- First, the projects which exist in an organisation are themselves forms of temporary organisation which have to coexist with the permanent entities of the organisation in which it is executed. This coexistence may imply difficulties in managing the interdependencies between projects and permanent entities, such as when dealing with the question of scheduling or resource attribution.

- Moreover, temporariness implies that objectives are to be met under a certain constraint of time, which is to add pressure in a project. There is consciousness of a short, or at least, limited duration / lifetime of the project system, which means that project member are aware of the future termination of their coexistence within the system. Depending on one's culture or character, this notably often results in lower or higher implication in the structure. This also often implies a longer time for people to feel they belong to a same project team / system.
- Finally, temporariness evokes therefore a non-routine process and/or a non-routine product/service. This non-routine aspect, which makes project management even more complex, is even more highlighted by the project uniqueness.

I.4.2. Projects facing their uniqueness

Indeed, a project is in essence unique. This means that, due to their own characteristics and context, projects are all different. Two projects with the same objectives, processes and resources, but which do not start at the same date can for instance be very different because of their own specific context.

The implication of this uniqueness is that, contrary to operations (which are in essence repetitive), no standard methodology or calculation can be handled without paying particularly great attention to the specific context and characteristics of the project. Projects are thus more difficult to manage and project performance is all the more difficult to optimise since this absence of repetition implies that no lessons learned can be directly reused in an absolute manner for the future.

The value of lessons learned in project management is an issue the importance of which has been highlighted by several researchers, such as (Pritchard, 1997), (Schindler and Eppler, 2003), (Aiyer and al., 2005) or (Besner and Hobbs, 2006). Shenhar (Shenhar, 2007) stresses that no "one size fits all" which would consist in the use (though correct) of standard project management tools can be applied to project management due to the core uniqueness of any project. Actually, the systematic application of such standard tools, if not adapted to a specific project context, may lead to project failure. But the fact is that projects need to use lessons learned so the organisation does not reinvent the wheel at each new project start (Newell, 2004). That is why, even though not addressing this issue deeper in this Ph.D. thesis, it claims for efficient and proactive learning processes as well as clear project governance and management systems support in order to learn lessons and use them in the future to assist complex project management (Trevino and Anantatmula, 2008).

I.5. Conclusion

Project systems are as a whole temporary and unique organisations within larger organisations which aim at creating business results and other values thanks to their execution. The use of systems thinking to describe project proves us that projects are composed of many diverse elements which interact along processes in order to deliver these targeted created values. Project systems in the end appear to be technological and organisational systems, the characteristics of which (notably temporariness and uniqueness which have been underlined as project definition-driven characteristics) make it all the more complex to manage.

This issue of the complexity of project systems is therefore to be addressed in this Ph.D. thesis. That is why, keeping in mind the principles of systems thinking, the two following chapters concentrate on the two following issues:

- Project complexity definition, identification and categorization into a framework thanks to the conduction of a broad state of the art and an international Delphi study (Chapter 2).
- Project complexity measure in order to highlight particularly complex projects within a portfolio, or project zones within a project (Chapter 3).

Chapter II.

Building up a project complexity framework

Abstract

The overall ambition of this chapter is to define and understand what project complexity is, despite the lack of consensus on this issue in the literature. In addition to the traditional project management methodologies, we argue for a conjoint paradigm shift which claims for project management through a complex system-oriented view. Identifying project complexity sources is then all the more interesting since it can have direct implications on project management. Understanding better the manifestation of project complexity is understanding better how complex projects can be managed.

This chapter permits to describe better what project complexity is thanks to the elaboration of a standardized framework, which consists in a 2×4 table. First, two kinds of project complexity are considered: organisational complexity and technological complexity. Moreover, four groups of project complexity factors are studied: project size factors, project variety factors, project interdependency factors and project context-related factors. This first version illustrates that organisational complexity is likely to be the greatest source of complexity in projects (given the number of identified sources). In order to illustrate the direct application and benefits of this framework to highlight industrial project complexity sources in fieldwork, the multi-purpose vehicle development projects within the firm Renault (Espace, Twingo, Scenic, Modus) are partly analysed regarding this framework. Such analysis permits to claim for the use of this complexity factors framework as a check-list when executing a project.

However, due to the quite large size of this framework, an international Delphi study has been conducted over 38 international academics and industrials. This survey permitted us not only to refine the framework but also to draw interesting conclusions both on project complexity and on the perception of this concept within the interrogated population.

Chapter Keywords

Project, Complexity, Framework, Delphi methodology, Expert judgement.

II.1. Introduction – The lack of consensus on complexity and project complexity

Complexity is everywhere and is continuously growing. Research works on the concept of complexity have been conducted for years and have produced some interesting results and notions. There are historically two main scientific approaches of complexity (Schlindwein and Ison, 2005). The first one, usually known as the field of descriptive complexity, considers complexity as an intrinsic property of a system, a vision which incited researchers to try to quantify or measure complexity. An example of this vision is the work of Baccarini (Baccarini, 1996). He considers project complexity through the concepts of technological complexity and organisational complexity. He regards them as the core components of project complexity which he tries to describe exhaustively. The other one, usually known as the field of perceived complexity, considers complexity as subjective, since the complexity of a system is improperly understood through the perception of an observer. Both approaches can apply to project complexity and project management complexity. For all practical purposes, a project manager deals with perceived complexity as he cannot understand and deal with the whole reality and complexity of the project. We do aim at creating a link between those two traditional visions of complexity. Knowing that one tries to cope with perceived complexity, this research work aims at bridging the gap between perceived complexity and real complexity by defining, describing and modelling better real project complexity. The definition and identification of a list of project complexity factors which could be used as a check-list for instance may then permit to complement one's perception and intuition when analysing the complexity of a given project. This new frame of reference would then enable anyone who shares this representation to talk about project complexity with less ambiguity (due to their own perception).

The difficulty is that there is actually a lack of consensus on what project complexity really is. As Sinha and al. (Sinha and al., 2001) underline it, "there is no single concept of complexity that can adequately capture our intuitive notion of what the word ought to mean". Complexity can be understood in different ways, not only in different fields but has also different connotations within the same field (Morel & Ramanujam, 1999). However, Edmonds (Edmonds, 1999) proposes an overview of the concept of complexity within different fields and finally tries to give a generic definition of what complexity is: "Complexity is that property of a model which makes it difficult to formulate its overall behaviour in a given language, even when given reasonably complete information about its atomic components and their inter-relations". This definition, which is quite appropriate to encompass all the aspects of project complexity, emphasises that complexity is generally related to the way the project system is modelled. To some extent, the model is the first layer of project perception, the second layer being the perception when understanding the project model.

Other attempts to describe and define complexity exist in the literature. Karsky (Karsky, 1997) considers three kinds of complexity:

- The first one, spatial complexity, is the structural complexity of a system, in terms of the number and variety of elements and their interrelations.
- The second one, unpredictable complexity, refers partially to chaos, fluctuations and bifurcations, considering that the behaviour of a system is in essence unpredictable since it is characterized by non-trivial non-linearity, an aspect emphasized by Prigogine (Prigogine, 1996).
- Finally, the third one, dynamic complexity, considers that no one is able to analyse, understand and assess efficiently the evolution of a system, due to the presence of interrelations and positive or negative feedback loops.

These three kinds of complexity do exist in project management. Spatial complexity is created by the number and variety of project resources, actors, tasks, processes, etc… and can notably be shown through simple models (such as the Work Breakdown Structure which permits to define and group a project's tasks in order to help to define the project scope). Unpredictable complexity is notably due to the fact that a project is an organisation including people: by their actions, decisions and behaviours, they involve non-trivial non-linearity in the system. Finally, dynamic complexity can be shown for instance through models of a projects such as PERT (Project Evaluation and Review Technique) networks (including interrelations and loops) which permit to analyse and represent the tasks that must be completed to achieve a given project.

On his side, Biggiero (Biggiero, 2001) analyses the sources of complexity in human systems and is thus relevant for projects. He identifies six classes of complexity:

- The first one is the logical complexity referring to the non-simultaneity of the properties of coherence and completeness of any formal system: for all practical purposes, it means that the understanding of a coherent system is to remain incomplete.
- The second one is relational complexity when interactions occur between observers and shape their communication.
- The third one is gnosiological complexity which underlines the fact that no observer can completely perceive all the information a system and its environment contain.
- The fourth one is semiotic complexity, this one referring to the ambiguity of information due to subjectivity.
- The fifth one is chaotic complexity, which is related to disorder, emergence, bifurcations and unpredictability as very small errors at the beginning can largely amplify until the final outcomes are produced.
- Finally, the sixth and last one is the computational complexity, which is very similar to the complexity of the algorithms.

Each of these classes of complexity can once again apply to projects and project management. Indeed, logical complexity is to be faced when working on any project model since the coherence of this model implies the incompleteness of its understanding. A project faces relational complexity between team members, shareholders, steering committee members and whatnot. Gnosiological and semiotic complexity are very close to the considerations around perceived complexity, i.e. inability to perceive the whole reality and ambiguity of the perceived information. Chaotic complexity is also present in projects since very small errors for inputs can give very large errors for outputs. Finally, computational complexity is found when formulating some project issues such as the scheduling problem.

As for him, Genelot (Genelot, 2001) considers complexity as one of the greatest stakes of today's management, and thinks it should be understood at three different levels:

- The first level, real complexity, consists of internal characteristic of a system.
- The second level, perceived complexity, consists of one's representation and model of the system.
- The third level is the feedback on the real system of the actions decided thanks to the system's representation.

In this case, real project complexity is very close to the notion of structural project complexity and is an absolute property of the project system. Perceived complexity is what we have already discussed before. The third aspect of retroaction on reality is present in the case of project management since a project manager uses for instance some models to make some decisions for the project.

Genelot defines a complex phenomenon as a phenomenon that cannot be understood and totally kept under control, emphasizing that complexity manifests itself at the three above-cited levels. In the end, he insists on the fact that anyone should keep in mind that being complex is in essence different from being complicated and that confusion must be avoided between these two different notions: a complicated phenomenon can always be understood and kept under control thanks to work, expertise and computation.

On the contrary, when some aspects of complexity tend to be understood and controlled by an observer, then other aspects of complexity do appear, so that it can never be neither understood nor controlled. Ulrich and Probst (Ulrich and Probst, 1988) also insist on the difference between the terms complicated and complex, categorizing systems in four families in terms of structural complexity: simple systems, complicated systems, complex systems and very complex systems (see Figure 4). According to this classification, projects are to be considered as very complex systems since they are composed of a large number of differentiated elements that are non-trivially interrelated.

According to Marle and Bocquet (Marle and Bocquet, 2001), who notably follows the concepts of Genelot, it must be emphasized that complexity is the property of a system that causes on one hand the emergence of new properties that none of the elements of the system owns, and on the other hand the apparition of phenomena that could not be predicted thanks to the sole knowing, even complete, of the behaviour and interactions of the elements of the system. As a matter of fact, complexity can have both a negative aspect (in terms of difficulty to be understood or controlled) and a positive one on the project system (thanks to the emergence of opportunities).

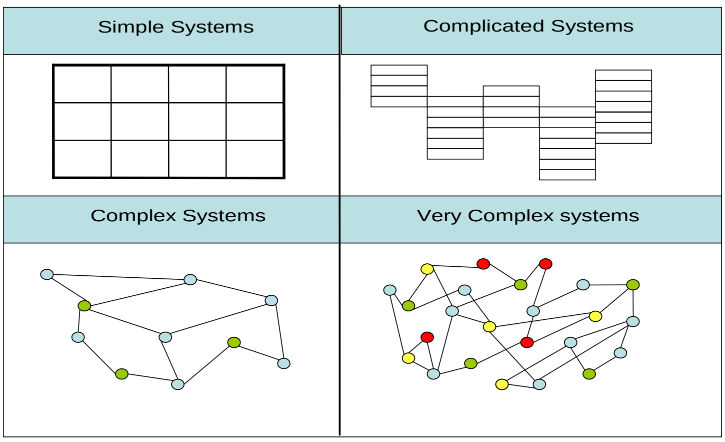

Figure 4. The structural nature of systems: simplicity, complication and complexity.

As a whole, whatever the vision of complexity one has, project systems can be considered as (very) complex systems. Understanding project complexity to improve project management (and therefore project success rate) has thus become an even more strategic issue for organisations. Still, some work has to be done to clarify the notion of project complexity in order to cope with it more efficiently (Vidal and al., 2007). Due to the lack of consensus between the different visions and definitions of complexity, even though the manipulated concepts are sometimes very near, many research works tried to define and identify some key factors and drivers of project complexity. However, there is no standardized and commonly-agreed list of project complexity drivers in the literature either.

PROBLEM SETTING OF THIS CHAPTER

As a consequence, the aim of this chapter is to **build up a project complexity framework** which could help in the end **complexity understanding and analysis** in terms of project complexity sources definition and identification. Through this definition and identification process, we hope to create an assistance to future complex project management. First, this framework is to encompass all the aspects of project complexity and bridge the gap between the existing visions of project complexity. Then, the aim of this framework is to concentrate on the **specific factors** of project complexity.

To build this framework properly, the points which need to be addressed to answer this issue are:

- The **identification** and **classification** of a list of major project complexity factors.
- The **description** of the direct **implications** of these factors on project complexity and project management, and how they can assist project management for all practical purposes.
- The proposal of a new **definition** of project complexity.
- The identification of **major sources** of complexity in order to highlight project managers and project teams where they should pay particular attention thanks to an international Delphi study.

II.2. Identifying project complexity factors

First, a literature review on project management and project complexity factors was carried out. The ambition of this literature review is to be relevant, and illustrative of what complexity is in fieldwork (as the final framework is to encompass all the aspects of project complexity). However, it must be underlined that some factors may be absent from this version of the framework, and that this one is likely to be evolving. This state of the art was performed, keeping in mind the definition of Edmonds which underlines complexity as the property which makes it difficult to formulate the behaviour of the project system (both in terms of diagnostic and prediction). We chose this approach in order to draw the state of the art by the consequences of project complexity, so that implications on project management processes are more direct. As a consequence, an important work hypothesis is the following one.

Hypothesis H1: Project ambiguities and uncertainties are to be considered as manifestations of the difficulty to formulate the project behaviour. This means they are considered here as a consequence (and as crucial stakes) of project complexity. Therefore, uncertainty or ambiguity-related factors are not present in the framework, although sometimes cited as project complexity sources in the literature.

Note that a deeper look at the relationships between the concepts of complexity, ambiguity, uncertainty, propagation and chaos will however be addressed in Chapter 4. This chapter is to highlight that this hypothesis is to be particularly underlined, since feedback contributions undoubtedly exist between these concepts.

This work hypothesis being stated, the methodology which was followed to identify these factors was the following:

- Step 1 – Identification of the aspects of project complexity which should be encompassed in the framework.
- Step 2 – Constitution of a first list of factors thanks to a state of the art based on:
    - Some project management academic standards (PMI, 2004), (IPMA, 2006a), (IMPA, 2006b).
    - Some project management industrial standards (ISO, 2003), (AFNOR, 2004), (AFNOR, 2007)
    - Some publications focusing on complexity and project complexity aspects (Baccarini, 1996), (Calinescu and al., 19998), (Edmonds, 1999), (Williams, 1999), (Laurikkala and al., 2001), (Sinha and al., 2001), (Bellut, 2002), (Corbett and al., 2002), (Jaafari, 2003), (Koivu and al., 2004), (Sherwood Jones and Anderson, 2005)
- Step 3 – Gathering of some complexity factors under a same common denomination and obtaining as a consequence a refined list of factors.

- Step 4 – Gathering of factors into several groups thanks to the analysis of the factors list and the identification done during Step 1.
- Step 5 – Final construction of the first version framework

Step 1 is a direct following of the piece of information given in Chapter 1. In order to structure the literature review in the best possible way in terms of robustness and exhaustiveness (even though exhaustiveness can never be reached, particularly when dealing with complexity, which means that new aspects may be added), we indeed argue that the manifestations of project complexity are to be seen in every aspect of systems thinking, which completely describes a project system. As a consequence, a first structure around the aspects of systems thinking is proposed here: teleological and genetic aspects, functional aspects and ontological aspects of project complexity are thus to be identified. Paragraphs II.2.1 to II.2.3 are a synthesis of steps 2 and 3 of the methodology which has just been presented. Paragraph II.2.4 proposes a synthesis thanks to the construction of an innovative project complexity framework. Paragraph II.2.5 details how this framework can be helpful to propose a standard definition for project complexity and to assist directly project management under complex situations at different project phases. Finally, paragraph II.2.6. illustrates on a case study how project complexity analysis (in this case, retrospective analysis for lessons learned) can be performed thanks to the framework.

II.2.1. Project complexity teleological and genetic aspects

As exposed in Chapter 1, the genetic aspect of a project system describes its evolution (i.e. the phases it evolves in). As for it, the teleological aspect of a project system addresses the issue of project values creation by identifying the expected target values (objectives) of a project (thanks to the identification of the project stakeholders and environment). Project complexity teleological and genetic aspects are to be mainly related to these aspects of the project system.

During the steps 2 and 3, several project complexity factors regarding project teleological and genetic aspects were identified and gathered under a common denomination. These factors are:

- **Competition**

  A competitive context is a more demanding and complex one since the targeted business is to choose the best products, processes, etc… in terms of expected values. Competition can be either technological or organisational.
- **Cultural configuration and variety**

  A project with a variety of cultures (social, technological, organisational,…) which need to be managed altogether appears to be more complex. Cultural configuration and variety can appear within the project or in its environment.
- **Environment complexity (networked environment)**

  Environment complexity in terms of network (networked environment) is to increase project complexity and make its management harder. Indeed, the management of the relationships with the project environment is one of the core activities of project management. Performing this activity in a networked environment is more complex since the impact of any relationship or decision is to propagate through this network.

- **Institutional configuration**
  The more complex is the institutional configuration and organisation, the more complex the project is, since one is likely to cope with higher coordination difficulties.
- **Local laws and regulations**
  Local laws and regulations (in both organisational and technological aspects) can increase project complexity since they may impact notably some differentiation in the project processes/outcomes according to the geographical zone where they are performed/created.
- **New laws and regulations**
  New laws and regulations (in both organisational and technological aspects) can increase project complexity since they may result in the need for changes in the processes/outcomes, given the requirements of new laws and regulations (such as security norms for instance).
- **Degree of innovation**
  Degree of innovation (organisational or technological) is to have an influence on project complexity. For instance, the lack of experience (due to innovation requirements) makes it more difficult to formulate the behaviour of the project, and is thus part of project complexity.
- **Demand of creativity**
  Demand of creativity is very similar to degree innovation in the way it can influence project complexity, since it implies new processes or elements, the behaviour of which is harder to formulate.
- **Scope for development**
  The larger the scope for development of a project is, the more complex the project is. Indeed, large scope for development imply more pressure, more long-term strategies and long-term aspects which make the project more complex.
- **Significance on public agenda**
  Significance on public agenda increases project complexity since overall pressure increases (due to necessary delay respect and possible impacts of a project failure), making the behaviour of the project system more complex to analyse, manage and predict.
- **Number of deliverables**
  When project deliverables are more numerous, then the project is likely to be more complex, since more aspects are to be controlled and achieved properly, which makes the project more complex.
- **Number of objectives**
  When project objectives are more numerous, then more aspects must be controlled, which make it more difficult to control and predict the whole behaviour of the project.
- **Variety of the interests of the stakeholders**

When the stakeholders' interests are varied, then project coordination and control is more complex because conflicting interests are likely to appear during the project definition and execution.

II.2.2. Project complexity functional aspects

As exposed in Chapter 1, the functional aspect of a project system focuses on what the project system executes in terms of tasks and processes. This functional aspect is the principal cause of interactions and interrelationships within the project system since resources, actors, information systems, etc… interact when project tasks are executed. Project complexity functional aspects are thus to be mainly related to these aspects of the project system.

During the steps 2 and 3, several project complexity factors regarding project functional aspects were identified and gathered under a common denomination. These factors are:

- **Availability of people, material and of any resources due to sharing**

  Projects may share their people, material and all their resources within the firm. Moreover, within a given project some resources may be shared between people, tasks, etc… Such a non-availability of resources during a project make it in essence more complex.

- **Combined transportation**

  Combined transportation of project inputs and outputs imply more project complexity since the project transportation plans are intertwined with other transportation plans.

- **Dependencies between schedules**

  Dependencies between schedules make it all the more complex to manage people within a project. Indeed, for instance, if a change happens in a project team member schedule, then other project team members schedules may change. But, these schedules are constrained (notably by permanent organizations). As a consequence, the needed changes may not be possible, which make project management processes even more complex.

- **Relations with permanent organizations**

  In most cases, within a firm, several projects have to coexist with several permanent organisations. Any project team member is to be involved in one or several projects and in one or several permanent organisations. Relations with permanent organizations make it more complex to manage a given project since these permanent structures may exert constraints on the project. For instance, the dependencies between the corresponding schedules generate complexity when trying to accommodate them and meet the requirements of each of them.

- **Level of interrelations between phases**

  The level of interrelations between phases is a project complexity factor. Indeed, the more project phases are interrelated, the more decisions made during a phase may impact the following ones, and the more a failure occurring during a phase is to be cured by rework in other phases. As a whole, predicting the project evolution is therefore more difficult.

- **Dependencies with the environment**

  During the execution phase of the project, dependencies with the environment make it all the more complex to manage the project since a constant look is to be given to changes within the environment as they may impact the project evolution and outcomes.

- **Dynamic and evolving team structure**

  The project team structure is to be evolving during its execution. Changes in the team structure over time imply difficulty to analyse, predict and control the behaviour of the whole project system.

- **Interconnectivity and feedback loops in the task and project networks**

  Such loops in the task network and other project networks (information networks, etc…) make it impossible to analyse the recursive phenomena which exist, making the project more complex.

- **Interdependence between actors**

  Interdependence between actors which execute the project, whatever their nature (information exchange, hierarchical interdependence, social relationship, etc…), make it all the more complex to coordinate the project efficiently.

- **Interdependence between sites, departments and companies**

  Similarly, interdependence between sites, departments and companies which are involved in the project make it more complex to manage, since other constraints due to their relationships may notably influence the project evolution.

- **Interdependence of information systems**

  In the same way, interdependence of information systems make the project more complex since any failure or dysfunction in any information system may impact dramatically the whole information systems architecture of the project.

- **Interdependence of objectives**

  The interdependence of project objectives make the project evolution more difficult to formulate since any change in any project objective may involve changes for the other project objectives, which may make project outcomes inconsistent with the new objectives.

- **Specifications interdependence, Interdependence between the components of the product and Resource and raw material interdependencies.**

  Similarly, in terms of outcomes specifications, product components, and raw material (3 distinct factors), interdependencies are to generate more project complexity.

- **Stakeholders interrelations**

  Stakeholders interrelations make it difficult to predict the evolution of a project since project objectives may for instance be redefined by stakeholders because of their relationships. Managing the relations with stakeholders thus appears to be crucial.

- **Processes interdependence**

Similarly, project processes (organisational or technological) interdependence, resulting in failure propagation for instance, make it all the more complex to manage a project.

- **Number of interfaces in the project organization**
  Interfaces in the project organization are potential sources of project complexity. Indeed, interfaces are information or material exchange zones which need to be coordinated under some pressure conditions (coming from each part of the interface). These coordination activities, often based on compromise and adaptation, are difficult to analyse and foresee.
- **Team cooperation and communication**
  Low team cooperation and communication make it all the more complex to manage the project since project strategies, decisions, objectives and processes may for instance be shared less effectively by the project team.
- **Duration of the project**
  The impact of duration of the project on complexity is difficult to assess, even though this criteria is often cited in the literature. The longer a project lasts, the more project complexity sources are to influence the project and the more difficult it is to predict the project evolution. But the shorter a project lasts, the more it is constrained, resulting in higher pressure and difficulties to manage the project. A good compromise might thus be found when defining the duration of a project.
- **Number of activities**
  When project activities (or tasks) are numerous, then the project is more complex since numerous activities require higher coordination and finer analysis to formulate the whole behaviour of the project.
- **Number of decisions to be made**
  The more decisions are to be made, the more the coordination of the project and the prevision of the impact of these decisions is difficult to tell.

II.2.3. Project complexity ontological aspects

As exposed in Chapter 1, the ontological aspect of a project system focuses on what the project system is in terms of its constituting elements which permit the execution of tasks and processes (resources, actors, information systems, etc…). Project complexity ontological aspects are thus to be mainly related to these aspects of the project system.

During the steps 2 and 3, several project complexity factors regarding project ontological aspects were identified and gathered under a common denomination. Two main aspects do appear: number or size of project elements and variety of project elements. These factors are:

- **Staff quantity**
  When the project staff is more numerous, then project coordination (and thus the project) is more complex.

- **Number of companies / projects sharing their resources, Largeness of capital investment, Number of departments involved, Number of hierarchical levels, Number of information systems, Number of investors, Number of stakeholders, Number of structures / groups / teams to be coordinated, Number and quantity of resources, Largeness of scope (number of components, etc…)**

  We choose to talk about these criteria together since they are very similar. Basically, when these elements are more numerous, then more aspects must be controlled, which make it more difficult to control and predict the whole behaviour of the project.
- **Diversity of staff (experience, social span …).**

  When the staff is varied, notably in terms of work experience, social span or culture, then the project coordination and control appear to be more complex.
- **Geographic location of the stakeholders (and their mutual disaffection)**

  When stakeholders of the project are far from one another in terms of geographic location, then the project analysis, coordination and prediction are harder because of numerous effects (loss of information during information exchange, lack of information sharing due to their mutual disaffection, variety of local contexts of the stakeholders, etc…).
- **Variety of resources to be manipulated**

  Manipulating more resources during the project requires more project coordination and control (stocks and availability of resources, compatibility of resources, etc…), which makes projects more complex.
- **Variety of the stakeholders' status**

  When the stakeholders' statuses are diverse, then it is more complex to coordinate the project since the control of the relationships with the stakeholders may imply varied procedures or behaviours for instance.
- **Variety of information systems to be combined**

  When information systems are varied, then the compatibility and conjoint use of these information systems appear to be complexity sources for project management.
- **Variety of skills needed**

  The more diverse the needed project skills are (whether organisational or technical), the harder the project is to analyse, predict and control, which makes it more complex.
- **Variety of interdependencies, Variety of the product components, Variety of the technologies used during the project, Variety of financial resources, Variety of hierarchical levels within the organisation, Variety of project management methods and tools applied, Variety of the resources to be manipulated**

  Similarly, these seven other factors appear to make the project more complex.

II.2.4. First version of the project complexity framework

The point is that speaking in terms of teleological, genetic, functional and ontological aspects of project complex is not the easiest manner to communicate about complexity in real projects and see what are the concrete phenomena behind these notions. We thus claim for a gathering of these factors into four more intuitive groups (see Figure 5). These groups, which are closely linked to the four aspects of systems thinking, are all necessary but non-sufficient conditions for project complexity. The first group gathers the factors that are relative to the size of the project system. The second one gathers those that are relative to the variety of the project system. These two first groups globally correspond to the ontological aspect of the project system. The third one gathers those that are relative to the interdependencies and interrelations within the project system, which corresponds to some extent to the functional pole of the project system. Finally, the fourth one deals with the context-dependence of project complexity, which mainly corresponds to the teleological and genetic poles of the project system.

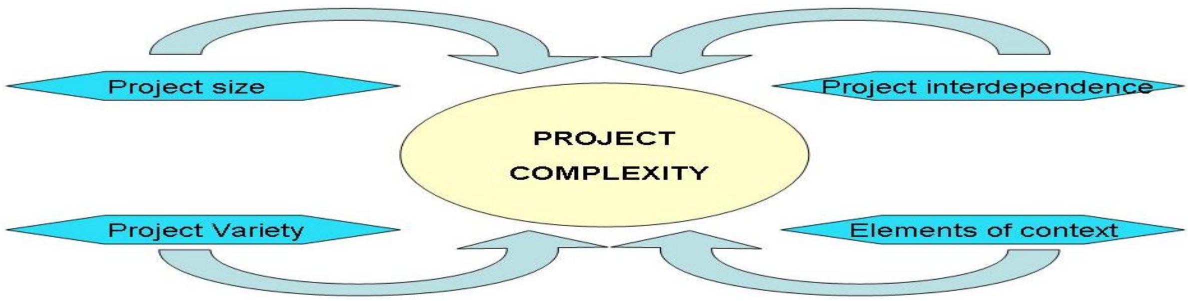

Figure 5. Drivers of project complexity

The gathering of the identified project complexity factors into these four distinct groups makes more meaning both for direct industrial use (as these denominations make more sense for fieldwork) and for academic establishment (since these denominations have widely been used in research articles for instance). Indeed:

- Project size is to be defined as a whole as the sizes of elementary objects which exist within the project system. These sizes are likely to be assessed thanks to appropriate quantitative measure (for instance time scale, cardinal scale, etc…). This aspect of project size (which is somewhat close to the ontological aspect of project complexity in terms of number of identified elements) then appears to be a necessary condition for project complexity which makes sense. Indeed, recent papers notably state that any organisational system should be over a minimum critical size to be considered as a complex system (Corbett and al.,2002).
- Project variety is to be defined as a whole as the diversity of elementary objects which exist within the project system. This aspect of project variety (which is somewhat close to the ontological aspect of project complexity in terms of diversity of identified elements) indeed appears to be a group which makes sense. Indeed, as mentioned by Sherwood and Anderson (Sherwood Jones and Anderson, 2005) , "diversity relates closely to the number of emergent properties". Moreover, as underlined by Corbett and al. (Corbett and

al.,2002), "the one thing that comes through loud and clear is that complexity is tied up with variety, be it in the world of biology, physics or manufacturing".

- Project interdependence is to be defined as the existence of relationships between elementary objects within the project system. This aspect of project interdependence (which is somewhat close to the functional aspect of project complexity in terms of interactions between elements to execute the project) indeed appears to be another category which makes sense. As underlined by several authors, interdependencies (and all the notions related with them such as interactions, interrelationships or interfaces) are even likely to be the greatest drivers of project complexity. Besides, Rodrigues and Bowers (Rodrigues and Bowers, 1996) explain that "experience suggests that the interrelationships between the project's components are more complex than is suggested by the traditional work breakdown structure of project network", suggesting that traditional project management tools cannot be sufficient to catch the reality of interdependence. This seems all the more problematic since "there is a complete interdependence between the components of the complexity: each element will depend and influence on the others" (Calinescu and al., 1998).
- Project context is defined here as what refers to the environment within which a project is undertaken. This aspect of project context-dependence (which is somewhat close to the teleological and genetic aspects of project complexity) indeed appears to be another category which makes sense. First, Chu and al. (Chu and al., 2003) underline that contextuality is an essential feature of complexity, considering it as a common denominator of any complex system. The context-dependence of project complexity is also stressed by Koivu and al. (Koivu and al., 2004) who notably insist on the fact that "the context and practices that apply to one project are not directly transferable to other projects with different institutional and cultural configurations, which have to be taken into account in the processes of project management and leadership". Note that this point is also underlined in Chapter 1, when addressing the question of the value of lessons learned in project management.

As a whole, this literature review and proposed classification permits to build a project complexity framework which aims at being a reference for any project manager to identify and characterize some aspects of its project complexity, so that he can understand more efficiently the stakes of its project complexity management. Once again, even though we had the ambition to be quite exhaustive, some others project complexity factors are likely to be added to this framework. Knowing that, we insist on the fact that this project complexity framework is a descriptive vision of complexity: for all practical purposes, the perceived complexity of the real system throughout this framework is finally the one that is being managed. Moreover, one should keep in mind that this framework is a form of consensus on project complexity and that complexity cannot in essence be managed and handled through a generic consensus. This framework should as a consequence be considered as a basis to understand better complex projects and particularly identify the principal sources of complexity within a given project (Vidal and al., 2008), (Vidal and Marle, 2008).

Family	Organisational complexity (Org)	Technological complexity (Tech)
Project System **Size**	Number of stakeholders	Largeness of scope (number of components, etc...)
	Number of information systems	Number and quantity of resources
	Number of structures / groups / teams to be coordinated	
	Number of companies / projects sharing their resources	
	Number of departments involved	
	Number of deliverables	
	Number of objectives	
	Largeness of scope (number of components, etc...)	
	Number and quantity of resources	
	Number of hierarchical levels	
	Number of investors	
	Number of activities	
	Largeness of capital investment	
	Staff quantity	
	Number of decisions to be made	
	Duration of the project	
Project System **Variety**	Variety of information systems to be combined	Variety of the technologies used during the project
	Geographic location of the stakeholders (and their mutual disaffection)	Variety of the product components
	Variety of the interests of the stakeholders	Variety of resources to be manipulated
	Diversity of staff (experience, social span ...)	Variety of technological dependencies
	Variety of the stakeholders' status	Variety of technological skills needed
	Variety of hierarchical levels within the organisation	
	Variety of financial resources	
	Variety of organisational interdependencies	
	Variety of organisational skills needed	
	Variety of project management methods and tools applied	
Interdependence within the Project System	Dependencies with the environment	Specifications interdependence
	Availability of people, material and of any resources due to sharing	Interdependence between the components of the product
	Interdependence between sites, departments and companies	Technological processes dependencies
	Interconnectivity and feedback loops in the task and project networks	Resource and raw material interdependencies
	Team cooperation and communication	
	Dependencies between schedules	
	Interdependence of information systems	
	Interdependence of objectives	
	Level of interrelations between phases	
	Processes interdependence	
	Stakeholders interrelations	
	Combined transportation	
	Interdependence between actors	
	Number of interfaces in the project organization	
	Dynamic and evolving team structure	
	Relations with permanent organizations	
Elements of **Context**	Cultural configuration and variety	Environment complexity (networked environment)
	Environment complexity (networked environment)	Technological degree of innovation
	Organisational degree of innovation	Cultural configuration and variety
	New laws and regulations	New laws and regulations
	Institutional configuration	Demand of creativity
	Local laws and regulations	Local laws and regulations
	Competition	Scope for development
		Institutional configuration
		Significance on public agenda
		Competition

Figure 6. First version of the project complexity framework

Hereinbefore, on Figure 6, the completed project complexity framework we have built thanks to this research is exposed. It has to be noticed that approximately 70% of the identified complexity factors are related to organizational aspect, not technical. Principal sources of project complexity are thus likely to be organisational factors, as underlined by some former works on this issue (Shenhar, 2007). Moreover, even though the factors belonging to the family of interdependencies within the project system are hardly more numerous that the others, this group appears to be in the literature as the most important for project complexity and day-to-day project management (Marle,2001). Interactions management is likely to be both one of the causes of greatest value creation during the project and one of the riskiest parts of the project.

II.2.5. Applications of this framework

This state of the art being made, this framework being elaborated and the concepts being discussed, we now propose a refined definition of project complexity. We state that:

<u>Definition</u>

Project complexity is the property of a project which makes it difficult to understand, foresee and keep under control its overall behaviour, even when given reasonably complete information about the project system. Its drivers are factors related to project size, project variety, project interdependence and project context.

Every aspect of systems thinking is part of the overall behaviour of the project system, which means that, according to this definition, project complexity is the property which makes it difficult to understand, foresee and keep under control any of these aspects. The reader is to keep in mind this definition until the end of this Ph.D. thesis.

In the end, many complexity-related phenomena can explain the difficulties to understand, foresee and keep under control the behaviour of a project, due to its complexity. These reasons and their links with project management will be addressed in Chapter 4. But, before detailing these phenomena and stakes linked with project complexity, applications of the framework (direct applications, refinements, definition of a project complexity measure, etc…) are to be developed in this chapter and in Chapter 3.

As a whole, as noticed by Ivan and Sandu (Ivan and Sandu, 2008), there are three types of project complexity (as in the case of the majority of project characteristics): estimated, planned and actual. According to them, "Estimated complexity is based mostly on expertise gathered from of similar past projects. Planned complexity is a refinement of the estimated complexity, as some corrections are applied in order to adapt to the distinct project context. Actual complexity is finally measured after the project has been implemented." This classification permits us to insist on three direct possible uses of the project complexity framework which is proposed here:

- **Predictive project complexity analysis.**

  This application consists in the a priori project complexity evaluation. This finds direct implications in the management of the pre-project period and the project start processes. As underlined in (Gareis, 2000) "the project start is the most important project management subprocess, because in it the bases for the other project management subprocesses, such as the project plans, the project communication structures, the relationships to relevant environments, are established". As for them, (Dvir and al., 1998) also note that "pre-contract activities […] are highly influential in all types of projects". Predictive project complexity analysis is thus a crucial issue to achieve properly the pre-contract and project start phases. Using the project complexity framework as a checklist is to ensure a better identification of possible complexity sources within the project. It may also influence decisions which are directly made during these phases. For instance, project team constitution should be addressed in terms of possible complexity sources by focusing on the factors "staff quantity", "diversity of staff (experience, social span,…)", etc… By paying attention to such phenomena when making decisions during the pre-contract and start phases, one is to avoid some unnecessary or undesired complexity sources.

- **Diagnostic project complexity analysis.**

  Diagnostic project complexity analysis is to be performed during the execution phase of the project. This analysis permits to assist project management processes during the execution phase, such as planning and re-planning, monitoring and control, decision-making, etc… The identification of existing project complexity sources during the project permits to stand back on some issues of the execution phase. We claim for the conjoint use of traditional project management tools as a basis and a more holistic approach which can permit to analyse more properly project complex situations. This approach is facilitated by the project complexity framework which is proposed here. Generally, people have a tendency to focus on some detail which appear to them as existing crucial problems in a project. But focusing on detail does not permit them to solve the problem, which causes some project failures (Shenhar and Dvir, 20007). Looking at these problems through the glass of complexity permits to have a holistic vision of the tackled issue and thus to make more influent decisions. Having a better vision of interdependencies for instance permits to understand better propagation phenomena and change implications on a whole project. In the case of design engineering for example, such understanding of change propagation is to avoid unnecessary and costly rework during the project (Austin and al., 2002), (Clarkson and al., 2004), (Steffens and al., 2007). Adaptive management practices should thus be employed when facing complex situations (Shenhar, 2007), (Lindkvist, 2008).

- **Retrospective project complexity analysis.**

  Retrospective project complexity analysis thanks to the project complexity framework is to assist project closure and return on experience processes. Indeed, the a posteriori identification of complexity sources which existed during the project permits to assess what happened and thus draw some lessons for the future. The overall processes of lessons identification and lessons learned future use is to give some precious experience to the firm. As underlined by Williams (Williams, 2003), "management's role in facilitating and encouraging learning from projects is vital", and particularly in the context of complex projects. Learning finally improves project maturity and future project complexity management within the firm. Indeed, building up databases on possible complexity sources of a firm's projects for instance is to facilitate future predictive and diagnostic project complexity analysis.

That is why the goal of this chapter is notably to permit greater consensus on project complexity. Even though this first version of the framework already permits to make things clear about project complexity, it is suggested to carry out a international Delphi study to reach more consensus on this framework. The objective of this study is to underline principal project complexity sources, thanks to the participation of industrial and academic experts. This study and its results make the point of section II.3. But before addressing this issue, a case study is proposed in II.2.6. to highlight the possible uses of the project complexity framework.

II.2.6. Case study: Renault Multi-Purpose Vehicle (MPV) development projects

II.2.6.i Introduction

In order to illustrate this framework and show how it can be useful to identify possible complexity sources within a project, the case of several Renault Multi-Purpose Vehicle (MPV) development projects are explored. This case study corresponds to the third utilisation of the framework which was stated before, that is to say retrospective project complexity analysis.

As an introduction, general description of MPVs is the following. The engine appears to be mounted close to the front edge of the car, and its elements are generally grouped higher than in other cars, which minimizes front overhang length. Generally, seats are located higher than in lower cars, leaving more space for the legs. Larger minivans usually feature three seat rows, with two or three seats each. Smaller minivans tend to have two seat rows, with a traditional 2-3 configuration. Most current minivans are front-wheel drive. The main advantage is better traction than rear-wheel drive cars under slippery driving conditions. This configuration also permits to have more inner area along the floor, due to the absence of the driveshaft hump. Most modern MPVs feature unibody architecture (this is notably the case of the two projects which are to be studied), which offers better crashworthiness and a much more comfortable ride than a body-on-frame chassis.

Two MPV development projects are the main basis of this study: the Renault Espace development project and the Renault Twingo development project. Some forewords about these two projects are given hereunder in order to appreciate the scope and context of these two projects. Special acknowledgements are addressed to Jean-Louis Giordano, who worked as a project manager at Renault for several years.

- **The Renault Espace development project**

The Renault Espace development followed this timeline:

- 1979: Emergence of the idea of the project but no direct industrial following.

- 1982-1983: Cooperation agreement between Matra and Renault. The project is launched.
- 1984: The Renault Espace I is commercialised.
- Successive developments: New versions of the Renault Espace (II, III, and IV) appeared successively in 1988, 1996 and 2002.

The Renault Espace was a very innovative concept, which was originally based on Volkswagen minibus. The aim was to develop a familial vehicle, with a large internal volume, with a large trunk for luggage and take-down seats. Moreover, the Renault Espace was the first Renault vehicle with a composite main body and a tinned frame. At the time of development of the first Espace, the firm was not very mature for project management, which was a somewhat new discipline within the organization. In the end, this project appeared to be very crucial in the firm development. It was highly symbolic (new brand image of Renault), and strategic (since Renault was the first European firm to work on MPVs). The project required also many technical and creative skills (as this was a very innovative project) and implied complex managerial aspects, due to the cooperation with Matra.

Figure 7. The Renault ESPACE VI

- **The Renault Twingo development project**

The description of this project is also permitted thanks to the works of Midler (Midler, 2004). The Renault Twingo development project follows this timeline:

- 1986-1987: Emergence of the idea of the project but no direct industrial following.
- 1989-1992: Emergence of the project. Design and execution of the project.
- Sept. 1992: The Renault Twingo is presented to the auto show in Paris.
- Spring 1993: The Renault Twingo is commercialised.

- Successive developments: The Renault Twingo II appeared in 2007.

Figure 8. The Renault TWINGO

The first motivation of the Renault Twingo development project was the financial difficulties that Renault was having in the mid 1980s. Indeed, some former vehicle development projects appeared to be relative failures, the sales of the Renault Clio and Super 5 were in decline and the firm of Billancourt had just closed. Then, the aim of the Renault Twingo development project was to help Renault come back to its financial balance. In order to do so, Renault wanted to develop a new multi-purpose vehicle which would be original, innovative and non-costly. The project thus followed a Design-to-Cost approach, which implied a higher level of competition between the project suppliers.

II.2.6.ii Application for retrospective complexity analysis

The project complexity framework which is proposed permits to perform a retrospective project complexity analysis of these two projects. The ambition of this sub-paragraph is not to be exhaustive on all the complexity sources which occurred during these two vehicle development projects. The aim is to highlight how the use of this framework as a checklist permits to identify specific possibly important complexity sources in MPVs development project, which can assist future project management of such projects. Examples of retrospectively identified project complexity sources of these two projects are the following ones. The synthetic denominations correspond to the organisation of the framework (Size, Variety, Interdependency and Context-dependence crossing Organisational and Technological).

- **Example of SIZE-ORG factors**

  Number of stakeholders can affect project complexity. For instance, in the case of the Renault Espace development project, the coordination between the employees, cultures, processes, etc… of Renault and Matra due to the cooperation of these two firms implied greater managerial and organisational complexity.

- **Example of VAR-ORG factor**

  Diversity of staff (experience, social span,…) appeared to be a critical complexity factor in the Renault Espace development project. Indeed, some professional cultures needed to be coordinated, which cause some managerial difficulties. The specific cases of the different visions and cultures of the workers from the Engineering and design department and the ones from Marketing department were interesting in that case. Ideal definitions of a familial car were viewed by the marketing department and conflicting technical views could often be objected. Managing the projects with compromise and adaptation around such visions which emerge due to the diversity of the staff made the project more complex. We do insist on the fact that these different visions were indeed a source of difficulties, but also a great source of opportunities for the project.

- **Example of INT-ORG factors**

  Level of interrelation between phases appear to be very critical in these two projects. For instance, in the Renault Twingo project, some specifications (notably technical with the door handles) which had been validated during the project first phases appeared to be meaningless and or impossible while performing the project execution. This implied to redefine these specifications, which implied even more changes because of project specifications interdependence (INT-TECH factor).

- **Examples of INT-TECH factors**

  Interdependence of the components of the product appeared to be a critical complexity factor in the Renault Espace development project. The technological innovation due to the MPV format implied changes in the windscreen inclination. Even though they had not been predicted, because of the component interdependence, this implied changes in the front windscreen wipers and also in the engine position.

  As for the Renault Twingo development project, resource and raw material interdependence made the project more complex regarding the same components. Indeed, a new kind of glass was used to elaborate the windscreen. But it had not been seen that this new material which was used was not compatible with the glue which was formerly used to fix the windscreen wipers. This implied some changes and rework in the end.

- **Examples of CONT-ORG factors**

  Local laws and regulations appeared to make these two projects more complex when trying to extend the commercialisation and production of these vehicles into different European countries. For instance, new local laws and norms appeared in the mid 1980s in Germany. These ones were not all compatible with the Renault Espace technical specifications and production processes, which implied major changes in order to keep the possibility for the Renault Espace to exist in Germany.

Project complexity Factors	Renault Espace Development Project	Renaul Twingo Development Project
SIZE-ORG FACTORS		
Number of stakeholders	3	Negligible
Number of information systems	Negligible	Negligible
Number of structures / groups / teams to be coordinated	3	1
Number of companies / projects sharing their resources	2	Negligible
Number of departments involved	2	2
Number of deliverables	1	1
Number of objectives	2	2
Largeness of scope (number of components, etc…)	2	2
Number of hierarchical levels	Negligible	Negligible
Number of investors	1	Negligible
Number of activities	2	2
Largeness of capital investment	2	2
Staff quantity	1	1
Number of decisions to be made	2	1
Duration of the project	2	2
SIZE-TECH FACTORS		
Largeness of scope (number of components, etc…)	1	1
Number and quantity of resources	1	1
VAR-ORG FACTORS		
Variety of information systems to be combined	Negligible	Negligible
Geographic location of the stakeholders (and their mutual disaffection)	2	1
Variety of the interests of the stakeholders	3	Negligible
Diversity of staff (experience, social span,…)	3	2
Variety of the stakeholders' status	1	Negligible
Variety of hierarchical levels within the organisation	Negligible	Negligible
Variety of financial resources	Negligible	Negligible
Varierty of organisational interdependencies	Negligible	Negligible
Variety of organisational skills needed	1	Negligible
Variety of project management methods and tools applied	1	3
VAR-TECH FACTORS		
Variety of the technologies used during the project	2	1
Variety of the product components	Negligible	Negligible
Variety of resources to be manipulated	2	1
Variety of technological dependencies	1	1
Variety of technological skills needed	1	Negligible
INT-ORG FACTORS		
Dependencies with the environment	2	1
Availability of people, material and of any resources due to sharing	2	1
Interdependence between sites, departments and companies	2	1
Interconnectivity and feedback loops in the task and project networks	1	1
Team cooperation and communication	3	1
Dependencies between schedules	3	1
Interdependence of information systems	Negligible	Negligible
Interdependence of objectives	1	2
Level of interrelations between phases	2	2
Processes interdependence	Negligible	Negligible
Stakeholders interrelations	2	2
Combined transportation	Negligible	Negligible
Interdependence between actors	2	2
Number of interfaces in the project organization	Negligible	Negligible
Dynamic and evolving team structure	1	Negligible
Relations with permanent organizations	1	1
INT-TECH FACTORS		
Specifications interdependence	1	1
Interdependence between the components of the product	3	3
Technological processes dependencies	3	2
Resource and raw material interdependencies	2	2
CONT-ORG FACTORS		
Cultural configuration and variety	3	1
Environment complexity (networked environment)	2	1
Organisational degree of innovation	1	3
New laws and regulations	1	1
Institutional configuration	Negligible	Negligible
Local laws and regulations	2	1
Competition	2	2
CONT-TECH FACTORS		
Environment complexity (networked environment)	1	1
Technological degree of innovation	3	1
Cultural configuration and variety	2	1
New laws and regulations	1	1
Demand of creativity	3	2
Local laws and regulations	1	1

Figure 9. Synthesis of the retrospective project complexity analysis

Furthermore, the significance on public agenda appeared to be a very important factor in the case of the Renault Twingo development project. As mentioned in the introduction, the Renault Twingo was a very strategic project for the firm, which implied higher levels of stress and pressure when executing this project.

- **Examples of CONT-TECH factors**
  This cited local laws in the case of the Renault Espace implied higher technical competition with German firms, such as Volkswagen, which tried to use this needed rework for Renault as a possibility to bridge the technical gap about MPVs. Higher pressure thus existed because of this competition. Moreover, in these two cases, the technological degree of innovation was very high and there was an important demand of creativity. These two projects were thus even more complex to manage due to the constant emergence of new ideas or situations which had not been experienced in the past. For instance, thinking about the creation of a large internal volume and unibody car in the case of the Renault Espace development project was a very new situation.

These were examples of project complexity factors which can be identified thanks to the use of the project complexity framework. As a whole, a synthesis of identified project complexity factors in these two projects thanks to this retrospective analysis is proposed in Figure 9, where expert judgments attributed some importance (from negligible to 3) to possible project complexity factors. Still, if this list of factors permit to have a closer look on projects in terms of complexity, the factors are still very numerous and no a priori classification of these factors (in terms of the importance of their average contribution to project complexity) is proposed. That is why we carried out an international Delphi study to refine this framework.

II.3. Conducting a Delphi study to refine the framework

II.3.1. The Delphi methodology

As stated in II.2.5., refining our results thanks to an international Delphi study is indeed to permit to have a more reliable definition and understanding of the project complexity framework we have built. The Delphi methodology (Linstone and al., 2002), which was originally developed in the 1950's, is a systematic and interactive method which relies on a panel of independent experts. It is a very flexible tool which permits to reach a consensus, through the collection of experts' opinions on a given issue during successive stages of questionnaire and feedback. Direct confrontation of the experts, whose anonymity is kept at every stage of the study, is avoided (Okoli and Pawlowski, 2004). As mentioned in (Skulmoski and al., 2007), " the Delphi method is well suited as a research instrument when there is incomplete knowledge about a problem or phenomenon". It has proven over the years to be a very popular tool for framework building, forecasting, issues prioritizing, decision-making, etc… It has been used for several studies in the field of industrial engineering and project management, which encouraged us in our research work. For instance, Schmidt and al. used the Delphi method in order to build up a list of common risk factors in software projects (Schmidt and al., 2001). Our research methodology is based on a two-round Delphi process (see Figure 10):

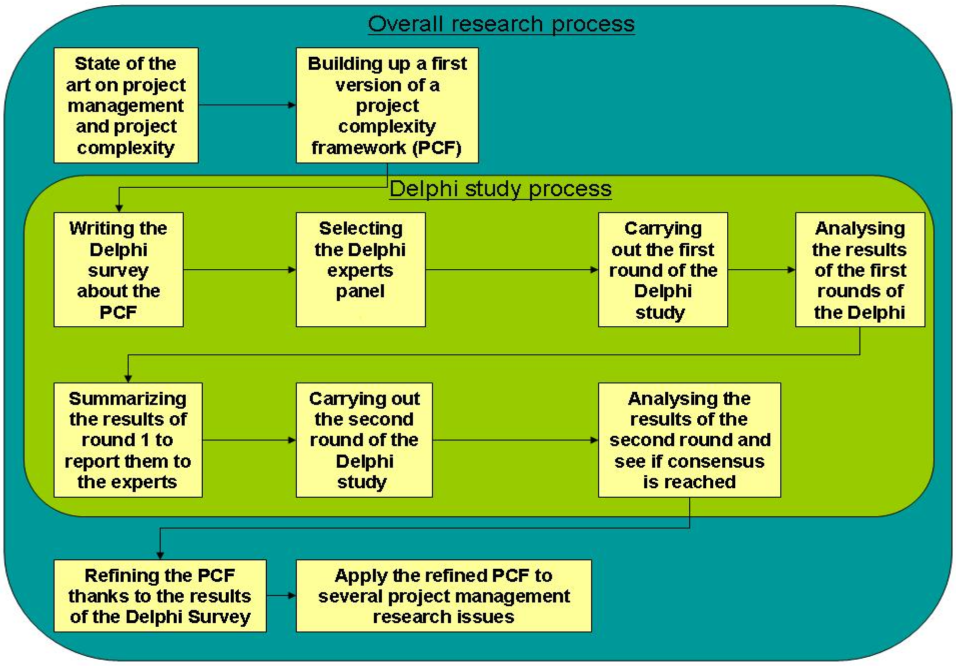

Figure 10. Conduction of the Delphi study according to a two-round process.

The Delphi survey was conducted thanks to blind copy electronic mail sending to international academic and industrial experts in project management in order to save time and expenses for both the surveyor and the experts. The questionnaire was introduced by a page explaining, such as in (Bryant and Abkowitz, 2007), the overall purpose and structure of the survey as well as the experts anonymity conditions at each stage of the study. The questionnaire was divided into eight sections, following the structure of the first version of the project complexity framework: SIZE-ORG, SIZE-TECH, VAR-ORG, VAR-TECH, INT-ORG, INT-TECH, CONT-ORG, CONT-TECH.

The questions were formulated thanks to a 5-level Likert scale, in order to express the importance of the contribution of a given factor to project complexity (from no contribution -1- to essential contribution -5-, leaving the possibility to answer "do not know" and "do not want to answer"). Furthermore, participants could leave commentaries and questions at any moment on any point of the Delphi questionnaire in order to generate some discussions about it or to suggest other potential project complexity factors. At each round, a little more than three weeks were left to the panelists to answer the survey. The statistical analyses of round 1 and round 2 correspond to the results expressed in the discussions paragraph. It must be noted that the results of round 1 and round 2 are the same since the synthesis and proposition which was done after round 1 satisfied all experts, reaching global consensus at this stage. No change was as a consequence done between the answers of round 1 and round 2. Only some commentaries and suggestions appeared during round 2.

II.3.2. Panel selection and survey scales definition

The Delphi survey group size appears to be very different in the literature. However, it is often recommended to have a group between 9 and 18 participants in order to draw some relevant conclusions and avoid at the same time difficulty to reach consensus among experts. We argue, such as in (Okoli and Pawlowski, 2004), that an experts categorization should be made properly before undertaking the Delphi survey in order to build up the most representative panel. As for them, Skulmoski and al. require different aspects for the participants to be selected in the Delphi survey panel (Skulmoski and al. 2007):

- Sufficient knowledge and experience about the survey issues,
- Capacity, willingness and time to participate,
- Good communication skills.

Our prospective panel was constituted of 38 experts, 19 of them being industrial practitioners and 19 being academics, and at the same time 19 being men, 19 being women. Of those 38 solicited experts, 18 actually participated to the study from the beginning to the end, 10 of them being academics and 8 being industrials, and at the same time 10 of them being women, and 8 being men. Academics were notably identified thanks to their publications regarding project complexity in the Web of Science and specialized conferences or revues (International Journal of Project Management, PMI Research Conference, etc…). Industrial practitioners were identified thanks to the browsing of some professional social networks (Linkedln), the identification of some project managers of large firms websites, and the identification of project managers whose education was followed in some high standard schools, universities and institutions. We thus consider that the overall results are going to be relevant since the interrogation of 18 experts permits to trust them. In order to do comparisons and generate discussions during the next section, we also study separately men, women, academics and industrials. Even though the suggested minimum quota of 9 experts is not reached for men and industrials (8 for each category instead of 9), we will consider the results as relevant.

II.3.3. Results and discussions

II.3.3.i. Global results

Our discussion starts with the overall analysis of the panelists' answers to our survey. A synthesis of their reached consensus can be seen after in Figure 11 and in Figure 12.

	Org		Tech		Global	
	Average	Standard deviation	Average	Standard deviation	Average	Standard deviation
Size	3,854	0,717	4,167	0,726	4,010	0,722
Variety	3,978	0,708	3,989	0,773	3,983	0,741
Interdependence	4,319	0,605	4,375	0,610	4,347	0,608
Context	3,817	0,642	3,667	0,670	3,742	0,656
Global	3,992	0,668	4,049	0,695	4,021	0,682

Figure 11. Global Delphi results for each factor family

Average scores and mean deviations were calculated to perform the analysis of this questionnaire. Mean standard deviation of the answers, as shown in Figure 11, is 0.682, which makes it a satisfying consensus for (also notice that all standard deviations are less than 1). Figure 12 shows the statistical results of the survey. Average values lie between 2.278 and 4.889. When having a closer look at the answer of the panel, some points are to be noticed about project complexity:

- First, of the first 18 identified project complexity drivers after the panelists' evaluation (the mean value of which is over 4.500), only 2 of them are of a technological type (11.1%), as shown in figure 4. Organizational complexity thus seems to be the greatest source of complexity for projects and project management today. Project managers should thus focus on organizational issues when tackling and dealing with complexity. This also appears to be legitimate when discussing with industrials facing their project day-to-day life.
- Second, of these first 18 project complexity drivers, 11 of them belong to the family of project interdependencies (61.1%), making it the most contributive family of project complexity drivers, before context-dependence and variety (both 16,7%) and size (5.6%). This also appears to be consistent with former works of the academic literature and with the industrials' feelings about complexity when discussing with me. This is also enlightened by the number of tools and works that have been developed to try to better catch project interactions and interdependencies, such as interactions model (Marle, 2002), or Design Structure Matrices (Steward, 1981).
- However, when analyzing Figure 12, we can express (according to average values) that

$$Interdependence \succ Size \approx Variety \succ Context-dependence$$
$$Technological \approx Organizational$$

We must notice here that this average value classification is to be taken with caution, for two reasons. First, the number of factors coming from each category are not the same. Indeed, in our first version of the framework, organizational complexity factors are much more numerous than technological ones (44 compared to 26). The multiplicity of sources of complexity of a drivers' category is to increase real project complexity and the relative importance of this category, which thus highlights the influence of organizational factors. Moreover, if organizational factors represent 63% of the number of identified project complexity factors, they represent 89% of the factors among the 18 first factors (those over the score of 4.500), which underlines even more their crucial importance.

Criterion	Family	Compl. Type	Average	Std Dev
Dependencies with the environment	Int	Org	4,889	0,323
Cultural configuration and variety	Cont	Org	4,833	0,514
Availability of people, material and of any resources due to sharing	Int	Org	4,722	0,461
Interdependence between sites, departments and companies	Int	Org	4,722	0,461
Environment complexity (networked environment)	Cont	Tech	4,722	0,575
Variety of information systems to be combined	Var	Org	4,667	0,594
Interconnectivity and feedback loops in the task and project networks	Int	Org	4,667	0,594
Specifications interdependence	Int	Tech	4,667	0,485
Environment complexity (networked environment)	Cont	Org	4,667	0,594
Team cooperation and communication	Int	Org	4,611	0,502
Number of stakeholders	Size	Org	4,556	0,511
Dependencies between schedules	Int	Org	4,556	0,511
Interdependence of information systems	Int	Org	4,556	0,705
Interdependence of objectives	Int	Org	4,556	0,922
Geographic location of the stakeholders (and their mutual disaffection)	Var	Org	4,500	0,707
Variety of the interests of the stakeholders	Var	Org	4,500	0,514
Level of interrelations between phases	Int	Org	4,500	0,618
Processes interdependence	Int	Org	4,500	0,514
Number of information systems	Size	Org	4,444	0,784
Number of structures / groups / teams to be coordinated	Size	Org	4,444	0,511
Diversity of staff (experience, social span ...)	Var	Org	4,444	0,856
Stakeholders interrelations	Int	Org	4,444	0,705
Interdependence between the components of the product	Int	Tech	4,444	0,616
Technological processes dependencies	Int	Tech	4,444	0,616
Number of companies / projects sharing their resources	Size	Org	4,389	0,698
Combined transportation	Int	Org	4,389	0,698
Largeness of scope (number of components, etc...)	Size	Tech	4,333	0,686
Interdependence between actors	Int	Org	4,333	0,594
Technological degree of innovation	Cont	Tech	4,333	0,686
Variety of the technologies used during the project	Var	Tech	4,278	0,895
Organisational degree of innovation	Cont	Org	4,278	0,826
Number of departments involved	Size	Org	4,222	0,647
Variety of the product components	Var	Tech	4,222	0,878
Cultural configuration and variety	Cont	Tech	4,222	0,732
Number of deliverables	Size	Org	4,167	0,985
Number of objectives	Size	Org	4,167	0,707
Variety of the stakeholders' status	Var	Org	4,167	0,618
Largeness of scope (number of components, etc...)	Size	Org	4,056	0,725
Variety of resources to be manipulated	Var	Tech	4,056	0,802
Number and quantity of resources	Size	Tech	4,000	0,767
Number of interfaces in the project organization	Int	Org	4,000	0,707
Number and quantity of resources	Size	Org	3,944	0,802
Variety of hierarchical levels within the organisation	Var	Org	3,944	0,639
Resource and raw material interdependencies	Int	Tech	3,944	0,725
Variety of financial resources	Var	Org	3,889	0,758
Variety of technological dependencies	Var	Tech	3,889	0,583
New laws and regulations	Cont	Tech	3,889	0,471
Number of hierarchical levels	Size	Org	3,833	0,707
Number of investors	Size	Org	3,833	0,618
New laws and regulations	Cont	Org	3,833	0,618
Demand of creativity	Cont	Tech	3,778	0,808
Number of activities	Size	Org	3,722	0,752
Variety of organisational interdependencies	Var	Org	3,556	0,922
Variety of organisational skills needed	Var	Org	3,556	0,856
Largeness of capital investment	Size	Org	3,500	0,786
Variety of technological skills needed	Var	Tech	3,500	0,707
Institutional configuration	Cont	Org	3,444	0,616
Local laws and regulations	Cont	Tech	3,444	0,511
Scope for development	Cont	Tech	3,444	0,511
Local laws and regulations	Cont	Org	3,389	0,502
Institutional configuration	Cont	Tech	3,389	0,698
Staff quantity	Size	Org	3,167	0,707
Dynamic and evolving team structure	Int	Org	3,000	0,594
Significance on public agenda	Cont	Tech	2,833	0,857
Number of decisions to be made	Size	Org	2,722	0,752
Relations with permanent organizations	Int	Org	2,667	0,767
Competition	Cont	Tech	2,611	0,850
Variety of project management methods and tools applied	Var	Org	2,556	0,616
Duration of the project	Size	Org	2,500	0,786
Competition	Cont	Org	2,278	0,826

Figure 12. Synthesis of Delphi results for each criterion, sorted by decreasing average

- The issues are in essence complex when dealing with project complexity. But surprisingly, the convergence of the experts was fast, even though they were of different origins and backgrounds. Although none of the experts changed their answers at this stage, they all accepted the consensus proposal at second round. Another iteration of the evaluation process was not required.
- It must finally be noted that the factors which appear earlier in the Delphi questionnaire do not receive significantly higher or lower scores than the factors which appear in the end of the Delphi questionnaire. This implies that there is no direct correlation between the order of the questions and the scores of the factors. This was notably observed when alternating the orders of the tabs in the Delphi questionnaire without observing a change in the average scores of each group of factors.

II.3.3.ii. Position comparison

Results of the comparisons between academic and industrial experts can be seen hereinafter in Figure 13. Two aspects are to be enlightened to compare those two populations:

	Org				Tech			
	Academics		Industrials		Academics		Industrials	
	Average	Standard deviation	Average	Standard deviation	Average	Standard deviation	Average	Standard deviation
Size	3,825	0,717	3,891	0,723	4,350	0,542	3,938	0,873
Variety	4,030	0,674	3,913	0,742	4,040	0,723	3,925	0,817
Interdependence	4,362	0,556	4,266	0,631	4,425	0,524	4,313	0,726
Context	3,914	0,551	3,696	0,692	3,790	0,631	3,513	0,698
Global	4,033	0,624	3,941	0,697	4,151	0,605	3,922	0,779

Figure 13. Professional comparison of the Delphi study

- First, mean standard deviations appear to be different between populations since academics mean standard deviation on the survey is 0.615 and industrials' one is 0.738. This difference can express the fact that, even though there are very conscious of and interested in the concept of project complexity, they might not all understand it the same proper way. This observation is also enlightened by some commentaries during the Delphi survey, since some industrials wanted to have some details on some criteria, not understanding them, or not seeing them first as complexity sources.
- Slight differences can be observed in the judgments of the two populations. First, SIZE-TECH complexity factors appear to be judged more important by academics than industrials (4.350 VS 3.938). Similarly, CONT-ORG and CONT-TECH are judged more important by academics than industrials (3.914 VS 3.696 and 3.790 VS 3.513). This is to be related with some commentaries and questions of industrials during the survey, as some of

them did not understand or catch globally the concept of context-dependence and the factors belonging to this category. To some extent, this lower maturity around the conceptual vision of project complexity is to explicit the lower assessments of these factors by industrials. However, some work should be carried out to clarify those relative divergence zones, which remain quite isolated, the whole survey showing a relative common vision of project complexity between academics and industrials.

II.3.3.iii. Gender comparison

One of the ambitions of this research work was also to compare two other populations, men and women, in order to see if their perception of project complexity, whether they are industrial practitioners or academics, was the same or not. Others works had indeed shown that no difference was observed between men and women when dealing with managerial tasks (Toren and al., 1998). The results synthesized in Figure 14 give us a part of answer, since the results obtained for those two populations are impressively similar. Mean standard deviation is 0.699 for men and 0.734 for women. Mean evaluations of organizational and technological complexity appear to be the same (3.963 VS 3.990 and 4.045 VS 4.028). Gender does not thus seem to be a source of different project complexity perception.

	Org				Tech			
	Male		Female		Male		Female	
	Average	Standard deviation	Average	Standard deviation	Average	Standard deviation	Average	Standard deviation
Size	3,743	0,796	3,925	0,736	4,154	0,507	4,150	0,883
Variety	4,065	0,798	3,930	0,738	4,000	0,795	3,960	0,800
Interdependence	4,306	0,663	4,332	0,619	4,471	0,510	4,300	0,676
Context	3,739	0,730	3,771	0,709	3,556	0,791	3,700	0,709
Global	3,963	0,747	3,990	0,701	4,045	0,651	4,028	0,767

Figure 14. Gender comparison of the Delphi study

II.3.4. Refining the project complexity framework

Thanks to the Delphi survey, we propose a refined project complexity framework (Figure 15) with the most important complexity drivers according to the panellists (factors evaluated essential, i.e. over 4.500). This framework is to be handled more easily than the original framework with 68 factors. However, for all practical purposes, this simplified version of the framework is to be accompanied by a version of the framework with 41 drivers (those over 4.000) and the original one.

However, one should notice that the criteria cuts (above 4.000 and 4.500) are quite absolute and arbitrary criteria. We do insist of the fact that these refinements should be taken with caution and that, in any case, any user of the framework or the refined framework should always feel free to incorporate lower scores factors or even new factors.

Family	Organisational complexity (Org)	Technological complexity (Tech)
Project System **Size**	Number of stakeholders	
Project System **Variety**	Variety of information systems to be combined	
	Geographic location of the stakeholders (and their mutual disaffection)	
	Variety of the interests of the stakeholders	
Interdependence within the Project System	Dependencies with the environment	Specifications interdependence
	Availability of people, material and of any resources due to sharing	
	Interdependence between sites, departments and companies	
	Interconnectivity and feedback loops in the task and project networks	
	Team cooperation and communication	
	Dependencies between schedules	
	Interdependence of information systems	
	Interdependence of objectives	
	Level of interrelations between phases	
Elements of **Context**	Cultural configuration and variety	Environment complexity (networked environment)
	Environment complexity (networked environment)	

Figure 15. Refined project complexity framework

II.4. Conclusions and perspectives

As a whole, this chapter proposes an approach to define and describe with greater consensus the concept of project complexity. It answers the problem setting of this chapter since it permitted

- The **identification** and **classification** of a list of major project complexity factors.
- A short **description** of the direct **implications** of these factors on project complexity and project management.
- The proposal of a new **definition** of project complexity.
- The identification of **major sources** of complexity.

Indeed, the standard framework of identified and classified project complexity factors which is proposed on the basis of four distinct groups (size, variety, interdependency and context-dependence) and of the traditional dichotomy of Baccarini (project organisational and technological aspects) is trying to make things clear on project complexity. These factors and their links to project complexity are also underlined. Finally, an international Delphi study (the participants of which are academic and industrial practitioners) is carried out to reach more consensus and identify crucial project complexity factors. Moreover, some important trends were underlined as this study calls for the highlight of organisational complexity factors, and more precisely (as shown by the refined framework) of factors belonging to the INT-ORG part of the matrix.

However, some limitations and perspectives do appear

- First, the size of the sample used during the Delphi study could appear to be a limitation for the validation of the results. Even though the size appears to be enough for validation when performing a Delphi process, and even though the experts were carefully selected, we aim at confirming the results of this Delphi study, notably through the possible interview of non-respondents. Incorporating their results and remarks regarding the results of the Delphi study should indeed be of great interest in order to validate even more the standard framework. Another perspective would be to explore other kinds of respondents. Indeed, for the moment, the panellists have been expert project managers or researchers in project management: incorporating the visions of other project team members / practitioners could be of high interest in order to refine this study.

- Another perspective of this work makes the point of ongoing research. It consists in a deep correlation analysis of the factors with the answers of the panellists. Kruskall-Wallis tests are presently being performed in order to identify correlations. Identified correlations are to make the point of deeper interviews with project management experts.
- Moreover, we do insist on the fact that exhaustiveness remains in essence an utopia when trying to describe project complexity. Indeed, even though the ambition was to be exhaustive, and even though the state of the art process was carried out with a methodology including both industrial and academic works on the issue of project complexity definition and description, the obtained list of factors is to be the basis for a check-list when identifying and handling project complexity. New factors are likely to be added in the future.
- Furthermore, one should remember that if this work aims at reaching greater consensus around the concept of project complexity, consensus is not meaningful when managing complex projects. This could even be counterproductive. Indeed, one should always remain that in essence, project complexity is specific to any project or firm context. As a consequence, this is another reason why this proposal of standard project complexity framework should be a basis for project complexity analysis. As a whole, this framework is to be adaptive.
- Finally, new applications and case studies are to be performed, notably on projects which are to be in their execution, start or pre-contract phases, in order to study examples of predictive and diagnostic project complexity analysis.

A final perspective should be the definition of measures or scales (or at least a procedure to define them) to quantify the level of each project complexity factor which is in the framework. Indeed, as stated by David Packard, the founder of Hewlett Packard, “You can’t manage what you can’t measure”. Measuring project complexity and these factors is thus to be very helpful for modern project management (this aspect is also underlined in several articles (Edmonds, 1999), (Laurikkala and al., 2001)). That is why in the next chapter of this Ph.D. thesis, we aim at proposing a relative measure of project complexity in order to assist decision-making. This measure is to be founded on the project complexity framework we have built, but it can easily be extended to any hierarchical structure / framework of project complexity factors.

Chapter III.

Assessing project complexity

Abstract

The overall ambition of this chapter is to define a measure of project complexity in order to assist decision-making (notably when analysing several projects existing in a portfolio, or when studying different areas of a project in terms of complexity). A synthesised literature review on existing project complexity and complexity measures is proposed in order to highlight the limitations of existing measures. We then propose a multi-criteria approach to project complexity evaluation, underlining the benefits of such an approach.

In order to solve properly this multi-criteria problem, we first conduct a critical state of the art on multi-criteria methodologies. We then argue for the use of the Analytic Hierarchy Process in order to assess project complexity, in multi-project environments or in mono-project cases when dealing with possible future project scenarios. The hierarchical structure which is used in order to perform this process corresponds to the refined project complexity framework which is built in the former chapter.

In the end, this tool permits to define a relative project complexity measure, which can notably assist decision-making. Complexity scales and subscales are defined in order to highlight the most complex alternatives and their principal sources of complexity within the set of criteria and sub-criteria which exist in the hierarchical structure.

Finally, a case study within a start-up firm in the entertainment industry (musicals production) is finally performed. Conclusions, limitations and perspectives of research are given in the end.

Chapter Keywords

Project, Complexity, Measure, Evaluation, Multi-criteria methodologies, Analytic Hierarchy Process (AHP).

III.1. Introduction – The limits of existing project complexity measures

As an introduction to this chapter, this paragraph aims at giving a brief review on the literature on complexity measures defined within the field of project management or that can be extended to the field of project management. As shown on Figure 16, two different approaches mainly exist when dealing with the issue of project complexity. The first one consists in a twisted approach: these works focus on some issues of project management (such as the project scheduling problem) and consider the complexity of the processes to obtain a solution regarding these issues as an assessment of project complexity. The second one focuses on the project system structure: researchers intend to assess project complexity thanks to a better understanding of the project structure model complexity. As seen in the former chapters, this research work, which is notably based on the principles of systems thinking, follows this approach.

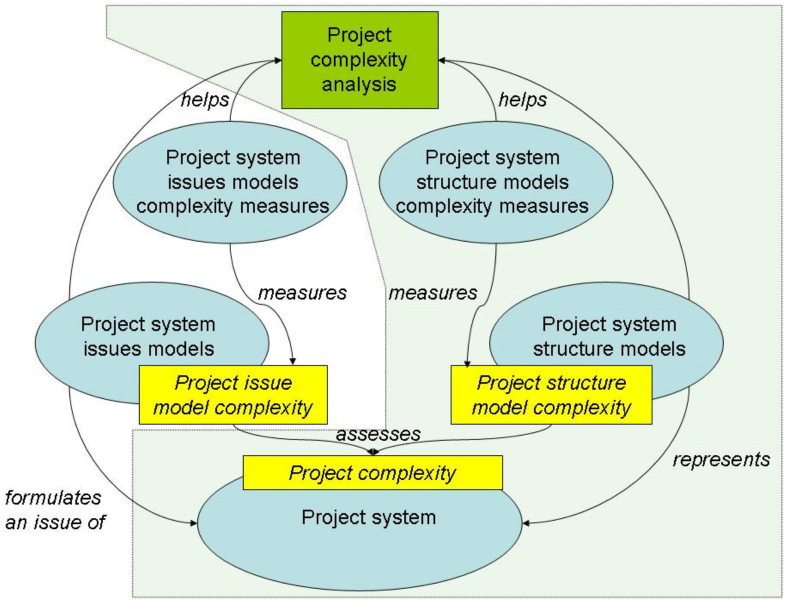

Figure 16. Project complexity modelling through project structure or project issues

Several authors in the literature tried to define complexity measures in order to explain project failures, to identify intricate situations, to understand better project complex phenomena and to help decision-making. Indeed, such a measure is notably to assist decision-makers before engaging their projects / portfolios into too complex situations since too early decisions when facing complex and uncertain situations often fail to deliver the targeted performance. But before choosing a suitable project complexity measure, one must be able to define a list of criteria that can be used to assess if it is good or not. Latva-Koivisto (Latva-Koivisto, 2001) proposes a first list in a research report which includes parameters such as reliability, ease of implementation and intuitiveness for instance. As far as this research work is concerned, a literature review on existing project complexity measures (or complexity measures which could be adapted to project management) was performed. Once again, as explained on Figure 16, a focus was made on project complexity in terms of systemic complexity (right side of the figure) and not of algorithmic complexity when solving some issues about project management (such as the sequencing and scheduling problem (Akileswaran and al., 1983)). The works of Edmonds (Edmonds, 1999), Latva-Koivisto (Latva-Koivisto, 2001) and Nassar and Hegab (Nassar and Hegab, 2006) were crucial sources to generate this list of indicators (about fourty complexity measures globally listed). For instance, in his Ph.D. thesis, Edmonds (Edmonds, 1999) identified formulations and measures of complexity, working on a large scope of fields and applications. As for him, Latva-Koivisto (Latva-Koivisto, 2001) reviewed complexity measures to assess the structural complexity of business processes. He argued that the complexity of business processes could be assessed through the conversion of process charts (composed of activities, dependencies, information flows, material flows and control flows) to graphs, giving the example of the resource-constrained project scheduling problem. If interested, one should directly refer to these three references for more information on complexity measures and formulations. Then, the obtained list of possible complexity measures was refined thanks to the criteria. Four specific complexity measures are given here since among the most appropriate ones for a use in project management.

- The coefficient of network complexity (CNC) defined by Kaimann (Kaimann, 1974) applies to both PERT and precedence networks. In the case of PERT networks, the CNC is equal to the quotient of activities squared divided by events. The CNC, thanks to an intuitive definition is a good complexity measure to catch the structural complexity of systems that are modelled thanks to graphs. However they take redundant arcs into account.
- The cyclomatic number defined by Temperley (Temperley, 1981) gives the number of independent cycles in a graph. The equation calculation of the cyclomatic number is equation (1). S is the cyclomatic number, A is the number of arcs, N is the number of nodes.

$$S = A - N + 1 \quad (1)$$

- The traditional static entropic measurement of complexity by the Shannon information (Shannon, 1948) is based on the probability of receiving a message, as shown by equation (2) where $p(n_i)$ is the probability of receiving a message n_i. The Shannon information is also a complexity measure since information and disorder are strongly related.

$$Sha = - \Sigma \log_2 (p(n_i)) \quad (2)$$

- Arguing that complexity measures such as CNC are imperfect since they take redundant arcs into account and therefore show that the system is more complex than it actually is, Nassar and Hegab (Nassar and Hegab, 2006) define a measure for project schedules. This measure gives the degree of interrelationships between the activities in a schedule. This complexity measure is the following equation (3) for an Activity On Node project network.

$$Cn = 100 \times (Log(a/(n-1))/Log[(n^2-1)/4(n-1)])\% \text{ if } n \text{ is odd}$$

$$Cn = 100 \times (Log(a/(n-1))/Log[n^2/4(n-1)])\% \text{ if } n \text{ is even} \quad (3)$$

The point is that existing measures have shown their limits for several reasons:

- First, some limits have been highlighted about the reliability of such measures. For instance, some counterexamples were found: indeed, some graphs and networks were sharing the same CNC but were very different considering their easiness to be managed. One of the main reasons for this lack of reliability is that those measures mainly refer to a single aspect of (project) complexity, mainly in terms of interdependencies.
- Second, these measures are often non intuitive for the final users and thus give results which are difficult to communicate on. Indeed, these mathematical formulations do not permit a reference to real project complexity factors: both the identification of important complexity sources and possible actions for complexity handling/reduction are not facilitated. Moreover, such measures are sometimes difficult to calculate for non-skilled users, which make it all the more complex to perform and analyse them. For instance, in the case of the Shannon number, both difficulties are encountered for all practical purposes.
- Finally, these measures mainly refer to a model of the project system. Indeed, measures such as the CNC, the cyclomatic number or the one proposed by Nassar and Hegab refer in essence to an existing network or graph. Such graphs are specific models of the project system, which restrict the view and understanding of project complexity. For instance, a project can be modelled thanks to different WBS, PERT networks or Gantt charts, depending on the detail level, willingness of the project manager, etc… Applying such measures to these kinds of elementary models of the project systems cannot properly account for a measure of project complexity since they are in essence relative to the model.

<u>PROBLEM SETTING OF THIS CHAPTER</u>

As a consequence, the aim of this chapter is to **define a project complexity measure** which could help **decision-making**. This measure is notably to be used:

- When selecting projects within project portfolios (as one of the criteria used for selection)
- When opting for a specific project scenario in the case of project management
- When analysing a project and understanding what are its principal areas of complexity.

To **overcome the limits** of existing measures, we are to define an index which is as far as possible:

- **Reliable**, meaning the user can be confident with the measure.
- **Intuitive** and **user-friendly**, meaning it should be easily computed and implemented, and that users must understand why it assesses project complexity.
- **Independent of the project models**, so that the measure is an evaluation of project complexity and not an evaluation of the complexity of a given project model.
- Able to **highlight project complexity sources** when building up the measure, so that the user can analyse more properly project complexity and thus make his decisions with a better vision of the problem.

III.2. Exploring the evaluation of project complexity as a multi-criteria problem

III.2.1. Introduction

Chapter 2 underlined the different aspects of project complexity through the elaboration of the project complexity framework proposed in this Ph.D. thesis. As a consequence, project complexity appears to be a multi-attribute characteristic of a project. We do argue that one of the reasons of the limitations of existing (project) complexity measures is that they do not take properly into account the multiple aspects of project complexity. The following paragraphs thus propose the construction of a project complexity relative measure on a multi-criteria approach. This measure is to be obtained thanks to this five-step methodology:

- Step 1 – Identifying the requirements of such a method.
- Step 2 – Carrying out a state of the art of existing multi-criteria decision-making methods.
- Step 3 –Identifying the most suitable or one of the most suitable multi-criteria method(s) for project complexity evaluation.
- Step 4 – Applying the selected multi-criteria method and defining the project complexity measure.
- Step 5 – Testing the whole on a case study in order both to give a first validation of the reliability, intuitiveness and user-friendliness of the measure, and to underline how this measure can be used as an assistance to some decision-making issues.

III.2.2. Requirements for a multi-criteria method to evaluate project complexity

Before the emergence of multi-criteria analysis, a major part of problems were solved by optimizing a unique economic function, notably through the method of cost-benefit analysis. However, the point is that some aspects are difficult to be expressed in terms of a monetary value, which limits the application of such methodologies in complex problems. Indeed, in problems of choice and decision-making, there is always a large number of aspects to consider (multiple criteria which can be contradictory and whom impact on the final decision can be difficult to quantify). Methods to support multi-criteria decision-making should take into consideration not only the quantitative or objective criteria but also the ones that appear to be more qualitative or subjective. Such methods are mainly designed to evaluate and compare alternatives, are independent of the project models that are used (since they are mainly based on expert judgement), and therefore represent a practical tool to assist managers' choices. In order to cope with the issue considered in our study, we reviewed the literature on multi-criteria decision-making methods in order to select the most appropriate one in the context of our study.

In general, decision-making is the study of identifying and choosing alternatives based on the values and preferences of the decision-maker. Making a decision implies that some alternative are to be considered, and that one chooses the alternative(s) that possibly best fits with the goals, objectives, desires and values of the problem. According to Baker and al. (Baker and al., 2001), the decision-making process should start with the identification of the decision-maker(s) and stakeholder(s) in the decision (which can be addressed through systems thinking as exposed in Chapter 1), reducing the possible disagreement about the issue. Then, as they underline it, a global decision-making process can be divided into the eight following steps: define the problem, determine requirements, establish goals, identify alternatives, define criteria, select a decision-making tool, evaluate alternatives against criteria, validate solutions against problem statement.

Requirements	Description of requirements
Multi-Criteria	The method should be capable to encompass different aspects and compare alternatives regarding multiple criteria of different nature.
Handle qualitative criteria	The method should be able to handle qualitative criteria in addition to quantitative ones.
Prioritise criteria	The method should enable the user to prioritise the criteria, since they are likely to have different influences on the final choice.
Evaluate a discrete set of alternatives	The method should be able to search for the best alternative among an initial discrete set of known alternatives.
Rank alternatives	The method should not only give the most complex project within the portfolio but also prioritise the projects functions of their complexity level
Rank alternatives according to a cardinal scale	The method should rank alternatives according to a cardinal scale. This cardinal scale is to be used afterwards to build up the relative complexity measure we propose.
Reliable	The method should give a reliable result to be eligible for decision-making support.
Computable	The method is to be computable to enable quick calculations on computers
Show great user-friendliness	The method should be user-friendly: this notably includes both the facts that no special/demanding skills should be necessary to perform the process and that results should be understood and handled easily.
Give autonomy	Users (mainly project managers) should be autonomous and should possibly suggest or do modifications.
Evolving	Modifications (new criteria, etc..) need to be easily implemented.
Adapted to project environment	The method should be adapted to project environment decision processes (Stal Le Cardinal, 2000), (Jankovic, 2006) and characteristics (constraints, skills, information systems, need for reactivity, …)

Figure 17. Requirements for a multicriteria method to be used for project complexity evaluation

A deeper look at the literature reveals that the problem of selecting the appropriate method (Step 6) appears itself to be a multi-criteria problem. We do not use any of existing methods to solve it, but we follow the forthcoming methodology to select the method used in our study: we first conducted a literature review in order to define the requirements of the method that could enable us to develop a good tool for project complexity evaluation. This literature review is notably based on the works of Gershon (Gershon, 1981), Deason (Deason, 1984) and Tecle (Tecle, 1988). It permits to build up Figure 18 in the end.

III.2.3. Critical state of the art of multi-criteria decision-making methods

The list of requirements being established, a literature review was carried out and permitted to identify a large number of multi-criteria methods. They can mostly be grouped into one of the three main families (multi-criteria optimization methods, outranking methods, multi-criteria decision-making methods) described by Roy (Roy, 1985). As a consequence, after describing some first elementary methods, these three families indeed permit a global classification of the critical state of the art which is proposed hereinafter. A global synthesis is finally proposed in a table in III.2.3.v.

III.2.3.i. Elementary methods

Such methods are mainly based on basic mathematics, logics and rules. Such examples of methods are for instance:

- The lexicographic method which consists in
    - Ranking the criteria qualitatively
    - Ranking the alternatives regarding their score on the first criterion
- The weighted sum methodology
- The traditional Minmax and Maxmin methods.

III.2.3.ii. Multi-criteria optimization methods

This family corresponds to mathematical methods which aim at optimizing a certain objective function. This objective function is defined according to the multiple criteria which exist in the addressed problem. Examples of such methods are for instance:

- Goal Programming (Charmes and Cooper, 1961)

  Goal programming can be viewed as an extension/generalisation of linear programming to handle multiple and possibly conflicting objective measures. Each of these measures is given a target value to be achieved. Unwanted deviations from this set of objective values are then minimised in an achievement function, which depends on the goal programming variant used.
- Compromise Programming

III.2.3.iii. Outranking methods

These methods first aim at building binary relations in order to take into consideration the user's preferences. Then, these relations are used to formulate a recommendation (thanks to the one-to-one comparison of the different alternatives). Some of these methods are for instance:

- ELECTRE (Roy, 1968), (Roy, 1978)
  - The first step is the construction of one or several outranking relations, which aim at comparing in a comprehensive way each pair of actions
  - The second step corresponds to the exploitation procedure which elaborates on the recommendations obtained in the first phase. The nature of the recommendation depends on the problem being addressed: choosing, ranking or sorting.
  - For instance, ELECTRE I aims at finding the best solution among an initial set of alternatives.
  - Note that the criteria in the ELECTRE methods have two distinct sets of parameters: the importance coefficients and the veto thresholds
- PROMETHEE (Brans and Vincke, 1985)
  - The first step calls for the user to fix for each criterion the curve and parameters which describe it best (true criterion, quasi criterion, pre criterion, pseudo criterion, Gaussian criterion)
  - For each pair of alternatives, global preference is calculated (degree of outranking).
  - Flows are then calculated and permit to rank the alternatives.

III.2.3.iv. Single-criterion synthesis approach methods

Finally, the third one corresponds to the methods which use the approach of the single synthesis criterion. These methods are seeking for a synthetic answer thanks to performances and values aggregation. They use a single criterion which corresponds to the aggregation of all the criteria which are considered in the problem. Examples of these methods are

- Multiple Attribute Value Theory – MAVT (Keeney and Raifa, 1976)
  - The first step corresponds to the construction of a matrix which gathers the evaluation of each alternative on each criterion.
  - Partial value functions are then built for each criterion. (Farquhar, 1984).
  - Criteria weights are then determined.
  - Final evaluation of all the alternatives is then permitted thanks to the definition of a final utility function which corresponds to the aggregation of former values (weighted sum, weighted product, etc…).
- Simple Multi-Attribute Rating Technique – SMART (Edwards, 1971)
  - The first step corresponds to the classification of criteria in descending order.
  - The second step permits to determine the weights of criteria.
  - Weights are normalized in order to be between 0 and 1.

- Alternatives are then assessed on each criterion on a scale between 0 and 100.
- The final value of each alternative is then determined thanks to a weighted sum.
- Alternatives are then ranked in descending order.

- The Analytic Hierarchy Process – AHP

III.2.3.v. Critical synthesis of the methods

Identified multi-criteria methods are assessed regarding the requirements which were identified, as shown on Figure 18 next page. The five first criteria are evaluated on a Boolean scale which permits to say if these criteria are respected by the method. These criteria are required for the goal which is pursued in this study. As a consequence, when a method is assessed 0 on one of these criteria, further evaluation of the method is not performed and the method is rejected. Then, the set of the six last criteria are evaluated on a 5-level Likert scale. Evaluations of the five first criteria of this set are mainly performed thanks to a state of the art which is notably based on (Gershon, 1981), (Deason, 1984), (Tecle, 1988) and (Al-Shemmeri and al., 1997). Evaluation of the sixth criteria (adapted to project environment) is notably based on a survey of scientific databases (ISI, etc…) to identify the use of these methods in the project management literature. A distance is then defined as a comparison in absolute value with the ideal method which would be noted 5 on every criterion of this set. The two best scores are obtained for the Analytic Hierarchy Process (AHP) and the PROMETHEE methodologies.

It is to be noted that the evaluation of these methods corresponds to our personal analysis of the literature about decision-making methodologies and their applications within the field of project management. For instance, some methods (such as MACBETH) are not present in this analysis since not taken in consideration at the time it was performed. As a whole, this means that Figure 18 is notably to be confronted to a panel of experts and discussed in the future in order to explore the possible suitability of other methods for the issue project complexity evaluation.

This point being underlined, regarding the issue of project complexity evaluation, preference is notably finally given to the AHP, because of its numerous applications in the project management context which were found in the literature (Al-Harbi, 2001). For instance, in (Ahmand and Laplante, 2006), the AHP is used to select the most appropriate software project management tool. The authors argue that "the AHP provides a flexible, systematic, and repeatable evaluation procedure that can easily be understood by the decision maker in selecting the appropriate software project management tool". Other applications particularly consider the issue of project evaluation or selection in the case of project outsourcing (Bea and Lloveras, 2007) or project portfolio management (Liang, 2003). Indeed, in (Alhazmi and McCaffer, 2000), the development of the project procurement system selection model (PPSSM) thanks to the AHP is presented. Another example can be found in the works of Simpson and Cochran for construction project prioritisation (Simpson and Cochran, 1987), who however argue that 'the AHP methodology is applicable to problem sizes from order 2 to about order 15 [and that] if a large number of projects is to be considered, some means is required to reduce the number of candidate alternatives".

	Handle qualitative criteria	Prioritise criteria	Discrete alternatives	Ranking alternatives	Cardinal scale	Reliable	Computable	User-friendliness	Give Autonomy	Evolving	Adapted to projects	DISTANCE
IDEAL METHOD	1 (necessary)	1 (necessary)	1 (necessary)	1 (necessary)	1 (necessary)	5	5	5	5	5	5	0
AHP	1	1	1	1	1	4	5	4	5	5	5	2
Categorical method	1	0										
Composite Programming	1	1	1	0								
Compromise programming	1	1	1	0								
Conjunctive method	1	0										
Cooperative Game Theory	1	1	1	0								
Cost-ratio method	0											
Disjunctive method	1	0										
Displaced Ideal	1	1	1	1	1	5	4	3	4	4	3	7
ELECTRE	1	1	1	1	1	4	5	3	5	5	4	4
Evaluation & Sensitivity Anal. Pro.	1	1	1	1	1	4	3	3	4	4	3	9
Goal programming	0											
JAS	1	1	1	1	1	4	4	4	5	5	3	5
Lexicographic method	1	1	1	1	0							
MAUT	1	1	1	1	1	5	4	3	5	4	4	5
MAVT	1	1	1	1	1	4	5	3	5	5	4	4
Maxmin / Minmax	1	1	1	0								
Multi-criteria Q-analysis	1	1	1	1	1	3	3	3	4	3	3	11
ORESTE	1	1	1	1	1	4	5	3	5	5	3	5
Probabilistic Trade-Off Dev. Met.	0											
PROMETHEE	1	1	1	1	1	4	5	3	5	5	5	3
PROTRADE	0											
QUALIFLEX	1	1	1	1	1	3	5	4	5	5	3	5
SMART	1	1	1	1	1	3	5	4	5	5	3	5
STEM	0											
STEP	0											
Surrogate Worth Trade-Off	0											
TOPSIS	1	1	1	1	1	4	4	3	4	4	4	7
UTA	1	1	1	1	1	4	5	3	5	5	3	5
Weighted product method	1	1	1	1	1	2	5	5	5	5	4	4
Weighted sum method	1	1	1	1	1	2	5	5	5	5	4	4
Zionts-Wallnius Method	0											

Figure 18. Critical analysis of multicriteria methods

Last but not least, another example in the field of project management is the works of Gourc (Gourc, 2006) which use the AHP for project risk analysis and assessment, under the assumption that project risks have multiple aspects. Finally, the reader should note that the AHP also has many applications in different contexts which all underline the user-friendliness and intuitiveness of the methodology (Lin and al., 2008), (Gerdsri and Kocaoglu, 2007), (Chiu and Chen, 2007) which makes it both a very generic and project context-friendly method.

III.3. Using the Analytic Hierarchy Process (AHP) to assess project complexity

III.3.1. The AHP methodology

The Analytic Hierarchy Process (AHP) was developed by Thomas Saaty (Saaty, 1977), (Saaty, 1980), (Saaty, 1990). It is a multi-criteria decision-making method which permits the relative assessment and prioritization of alternatives. As underlined by Saaty (Saaty, 1981) and exposed in Fumey (Fumey, 2001), the AHP permits to integrate both quantitative and qualitative aspects of decision –making, which makes it an efficient and effective method under complex contexts, as synthesized in Figure 19.

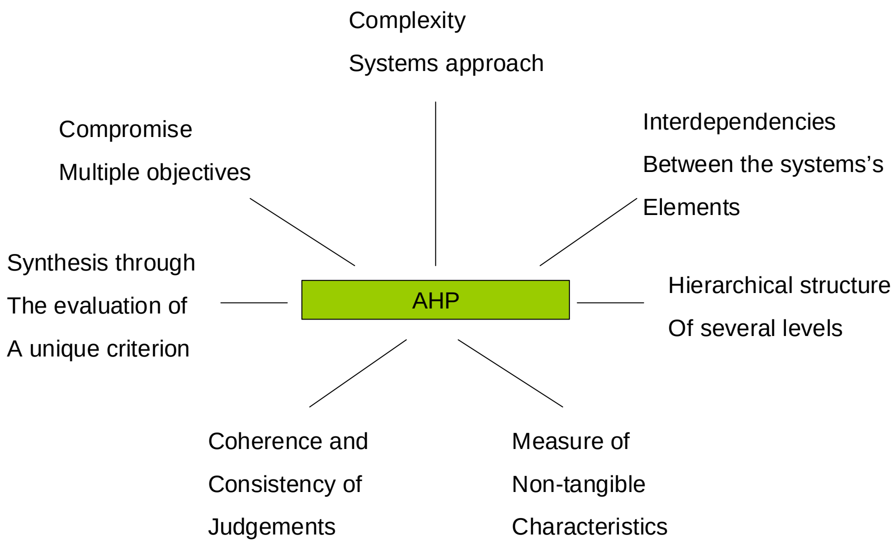

Figure 19. Using the AHP under complex contexts (Fumey, 2001) adapted from (Saaty, 1981)

The AHP is based on the use of pairwise comparisons, which lead to the elaboration of a ratio scale. The AHP uses a model of the decision problem as a hierarchy, consisting of an overall goal, a group of alternatives, and a group of criteria which link the alternatives to the goal. Pairwise comparisons are classically carried out by asking how more valuable an alternative A is to criterion *c* than another alternative B. Saaty scales can transform these judgements into numerical values. As shown hereinafter on Figure 20, pairwise comparisons constitute in the end square matrices, the values of which are between 1/9 and 9, and the diagonal elements of which are equal to 1 while the other elements verify two conditions:

- The i-jth element is equal to the comparison between element i and element j regarding the considered criterion.
- For i different from j, the i-jth element is equal to the inverse of the j-ith element

$$\begin{bmatrix} 1 & a_{12} & \dots & a_{1i} & \dots & a_{1j} & \dots & a_{1n} \\ 1/a_{12} & 1 & \dots & a_{2i} & \dots & a_{2j} & \dots & a_{2n} \\ \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots \\ 1/a_{1i} & 1/a_{2i} & \dots & 1 & \dots & a_{ij} & \dots & a_{in} \\ \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots \\ 1/a_{1j} & 1/a_{2j} & \dots & 1/a_{ij} & \dots & 1 & \dots & a_{jn} \\ \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots \\ 1/a_{1n} & 1/a_{2n} & \dots & 1/a_{in} & \dots & 1/a_{jn} & \dots & 1 \end{bmatrix}$$

Figure 20. AHP pairwise positive reciprocal comparison matrices

This piece of information is processed mathematically, in order to transform user information, objective or subjective, into mathematical one. Priorities are then determined thanks to these matrices and a global consistency test can be performed to evaluate the coherence of the user's judgements. The final result is a table which gives a global evaluation of each alternative for the objective, as well as for each criterion. The reader should note at this stage that the fact that the AHP allows inconsistencies to a certain extent (being under a certain level for the consistency index) is one of the specific strengths of this method. Indeed the AHP "does not expect perfect consistency from imperfect humans" (Erkut and Tarmicilar, 1991). Actually, the priority of each criteria and the final score of the alternatives can be calculated thanks to the maximal eigenvalues and eigenvectors of the matrices. Indeed, if following (Saaty, 2003) and the famous Perron-Frobenius theorem (Horn and Johnson, 1990), then the following assumption can be proved. For a given positive matrix A, the only positive vector x and only positive constant c that satisfy Ax = cx, is a vector x that is a positive multiple of the Perron vector (principal eigenvector) of A, and the only such c is the Perron value (principal eigenvalue) of A. For strongly consistent matrices (which means that rows are multiples of each other), then the rank of the matrix is 1, and there is only one eigenvalue, which is in essence the maximal one. In the general case, principal eigenvectors and values can be calculated thanks to the power iteration algorithm. This algorithm does not compute a matrix decomposition, and hence it can be used on very large sparse matrix. However, it can find only one eigenvalue (the one with the greatest absolute value) but since the objective here is to find exactly this eigenvalue, we argue for the use of this algorithm to facilitate calculations. The reader should note however that this algorithm may converge slowly.

III.3.2. Building up the hierarchical structure

According to Baker and al. (Baker and al., 2001), criteria used in multi-criteria decision making methods should be:

- able to discriminate among the alternatives and to support the comparison of the performance of the alternatives
- complete to include all goals,
- operational and meaningful,
- non-redundant,
- few in number.

With the refined project complexity framework, an AHP hierarchical structure is to be built according to Figure 21. The overall goal (objective) is the ranking of alternatives. First level criteria (intermediary goals) correspond to the four groups of project complexity factors, that is to say project size, project variety, project interdependencies and project context-dependence.

Sub-criteria then correspond to the factors which exist in the refined framework. Default values for the criteria weights can be kept (relative weights coming from the Delphi study) but we want to leave the users the possibility to assess by themselves the criteria and sub-criteria weights thanks to the whole AHP process. Moreover, the opportunity to add the complexity criteria which were eliminated between the original and the refined version of the framework should also be left. New criteria or new values should also be possibly added in order to be more consistent with the project context the user is working in.

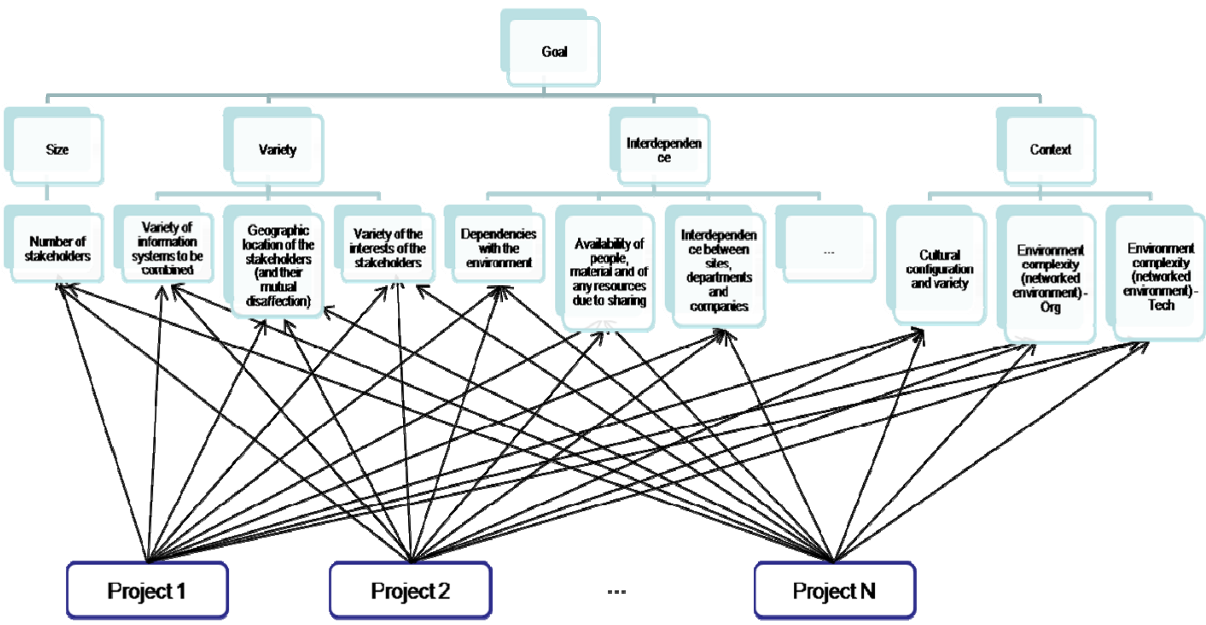

Figure 21. AHP hierarchical structure to assess project complexity

The hierarchical structure we propose here meets the requirements exposed at the beginning of this paragraph. Indeed, criteria in the structure are:

- able to support the comparison of the performance of the alternatives, since Saaty scales can easily be built to permit pair-wise comparisons of alternatives regarding each criterion
- complete to include all goals, since they address any aspect of project complexity as they correspond to the project complexity framework that was built
- operational and meaningful, since they were generated from a state of the art of industrial and academic works
- non-redundant, since the construction of the framework included a step of gathering similar factors under a same common denomination to avoid repetition
- few in number, since there are only 17 sub-criteria for the evaluation of a characteristic which is in essence complex

III.3.3. Proposing a relative measure for project complexity

Given the ranking obtained thanks to the AHP calculations on the set of alternatives, a relative measure of project complexity is proposed. Once again, we insist on the fact that alternatives can be projects in a multi-project environment, possible future projects compared to former ones, areas of a given project or project possible future scenarios in a mono-project environment, etc…
Let S_i be the priority score of alternative A_i obtained thanks to AHP calculations ($0 \leq S_i \leq 1$). We propose that the relative complexity of alternative A_i, given the specific context of the set of alternatives, can be expressed as the following ratio

$$CI_i = \frac{S_i}{\max(S_i)} \rightarrow 0 \leq CI_i \leq 1$$

A relative project complexity scale between 0 and 1 can thus be built thanks to this method (this index indeed permits to classify projects / project scenarios / project areas according to their global score regarding the main project complexity sources). This scale thus permits to give a relative indicator of project complexity (relative since it is related to the initial set of alternatives), but which does not depend on the models of the projects (the only expert evaluation of the projects regarding sub-criteria is needed). .Subscales can then be defined in the same manner to focus on specific aspects of project complexity and highlight how a project is complex regarding interdependencies or context for instance. An even more precise level can be defined similarly (when descending to sub-criteria in the hierarchical structure) to underline how a project is complex regarding specifications interdependence for instance. Before obtaining a first validation on a case study, a last point should be stressed. As mentioned before, Saaty scales are built up to transform the users' evaluations into numerical data. An example of a basic Saaty scale is given hereunder for team cooperation and communication criterion in Figure 22. When team cooperation and communication is judged less achieved in project i than project j, then more project complexity is generated in project i than project j. The corresponding Saaty scale is built to express numerically this difference with odd values. The reader should note that margin is given since intermediary even values can be used to refine the judgments.

Team cooperation and communication criterion	Saaty scale
Team cooperation and communication is judged equal in projects i and j.	$A_{ij} = 1$
Team cooperation and communication is judged is moderately less achieved in project i than project j.	$A_{ij} = 3$
Team cooperation and communication is judged is strongly less achieved in project i than project j.	$A_{ij} = 5$
Team cooperation and communication is judged is very strongly less achieved in project i than project j.	$A_{ij} = 7$
Team cooperation and communication is judged is extremely less achieved in project i than project j.	$A_{ij} = 9$

Figure 22. Example of a basic Saaty scale (Team cooperation and communication criterion)

However, such judgments can be uncertain for such evaluation scales are directly influenced by the users' subjectivity. This work thus proposes that, whenever it is possible, Saaty scales should be refined by objective measures or evaluations. An example is to be given later in the case study as an illustration. No absolute Saaty scales which could be used for any project in any firm is defined in this work. This would seem to be irrelevant, since a given project may appear much more complex in a firm A than in a firm B, for instance because of differences in project management maturity within the two firms. This remark does not diminish the pertinence and usefulness of the complexity measure which is proposed. Indeed, what is interesting for final users is to know whether a given project is complex within a portfolio or regarding their usual industrial activity (for instance compared to their usual projects) and what sources of complexity appear in this specific project. The methodology and measure proposed here permits to answer this question, as illustrated by the case study in paragraph III.5.

But before going on, as underlined by some works (Isaacs, 1963), (Erkut and Tarimcilar, 1991), (Bayazit, 2005), (Cheng and al., 2007), sensitivity analysis in multi-criteria decision-making, and notably when using the AHP, should be performed in order to underline the robustness of a choice. Sensitivity analysis indeed permits to understand the consequences of a change in the weights of criteria and sub-criteria. For instance, decision makers are likely to change their opinion about (sub-)criteria over time because of an evolving context. Or in the case of multiple decision makers, disagreements when performing the AHP evaluations may involve future changes or some confidence intervals for the definition of the weights. In the end, whatever the reasons of the doubts and the 'what if" questions, sensitivity analysis improves the credibility and reliability of the AHP model and results. That is why the next paragraph analyses the sensitivity of the proposed project complexity evaluation model.

III.4. Sensitivity analysis

III.4.1. The AHP score reformulation

As a whole, in the AHP hierarchy proposed in the formulation of our problem, the decision-maker formulates several pair-wise comparison matrices:

- A matrix C comparing the four criteria to one another (size, variety, interdependency and context-dependence), the eigenvector of which permits to identify the relative weights of these categories W_1, W_2, W_3, W_4.
- For each j from 1 to 4, let K_j be the number of sub-criteria corresponding to criterion C_j. Four matrices SC_1, SC_2, SC_3 and SC_4 permit to compute T other weights $w_k^{(j)}$, where $T = \sum_{j=1}^{4} K_j$. K_j can easily be identified thanks to the reading of the refined framework. However, new sub-criteria might be included in the hierarchy or some existing sub-criteria might be deleted from the hierarchy in order to cling better to a specific industrial context. That is why we choose to keep this generic formulation here.
- Then, T comparison matrices are built up to compare the alternatives regarding each sub-criterion. This permits to define for each evaluated project P_i a set of T scores $b_{ki}^{(j)}$.

In the end, the overall score of project P_i (which permit to perform the ranking of the projects and identify the most complex ones in the end) can be formulated as

$$S(i) = \sum_{j=1}^{4} \sum_{k=1}^{K_j} W_j w_k^{(j)} b_{ki}^{(j)}$$

This formulation of the score of each project P_i is the one which is going to be used to perform the several steps of the sensitivity analysis that is proposed in this Ph.D. thesis.

III.4.2. Overall gradient analysis

A first overall sensitivity analysis is proposed. In order to do, S(i) is to be rewritten in the following manner

$$S(i) = \sum_{j=1}^{4} \sum_{k=1}^{K_j} W_j w_k^{(j)} b_{ki}^{(j)} = \sum_{k=1}^{T} w_k b_{ki} ,$$

Where

$$\begin{aligned}
&\forall k, 1 \le k \le K_1, w_k = W_1 w_k^{(1)} \ \& \ \forall i, b_{ki} = b_{ki}^{(1)} \\
&\forall k, (K_1 + 1) \le k \le K_2, w_k = W_2 w_{k-K_1}^{(2)} \ \& \ \forall i, b_{ki} = b_{(k-K_1)i}^{(2)} \\
&\forall k, (K_2 + 1) \le k \le K_3, w_k = W_3 w_{k-K_1-K_2}^{(3)} \ \& \ \forall i, b_{ki} = b_{(k-K_1-K_2)i}^{(3)} \\
&\forall k, (K_3 + 1) \le k \le K_4, w_k = W_4 w_{k-K_1-K_2-K_3}^{(4)} \ \& \ \forall i, b_{ki} = b_{(k-K_1-K_2-K_3)i}^{(4)}
\end{aligned}$$

Moreover, we know that the following condition is respected on the overall weights w_k

$$\sum_{k=1}^{T} w_k = 1$$

As suggested in (Erkut and Tarimcilar, 1991) with calculations on cases with T = 2 or T =3, we propose that S(i) can be considered as a linear function of a given weight under certain conditions. Let us suppose that a weight w_r can vary from 0 to 1 and that the ratios of the other weights are fixed (to keep the same proportion that is given after performing pair-wise comparisons). The gradient sensitivity can be studied in order to analyze in a first manner the sensitivity to the variation of w_r. In order to facilitate the notations, let us suppose that one wants to study the case of w_1. Let the ratios of other weights be

$$p_1 = \frac{w_2}{w_3}, p_2 = \frac{w_3}{w_4}, \ldots, p_k = \frac{w_{k+1}}{w_{k+2}}, \ldots, p_{T-2} = \frac{w_{T-1}}{w_T}$$

Then,

$$\begin{aligned}
&w_1 + p_1 w_3 + w_3 + \ldots + w_k + \ldots. + w_T = 1, \\
&w_1 + p_1 p_2 w_4 + p_2 w_4 + w_4 + \ldots + w_k + \ldots. + w_T = 1, \\
&\ldots, \\
&w_1 + (\prod_{l=1}^{T-2} p_l) w_T + (\prod_{l=2}^{T-2} p_l) w_T + \ldots. + (\prod_{l=k-1}^{T-2} p_l) w_T + \ldots. + w_T = 1
\end{aligned}$$

As a whole, we can write

$$w_T = \frac{(1-w_1)}{(1+\sum_{m=1}^{T-2}(\prod_{l=m}^{T-2} p_l))},$$

And

$$\forall k, 2 \le k \le (T-1), w_k = \frac{(\prod_{l=(k-1)}^{T-2} p_l)(1-w_1)}{(1+\sum_{m=1}^{T-2}(\prod_{l=m}^{T-2} p_l))}$$

As a whole, for any i, we can rewrite the score S(i) as

$$S(i) = \sum_{k=1}^{T} w_k b_{ki} = w_1 b_{1i} + \sum_{k=2}^{T-1}\left(\frac{(\prod_{l=(k-1)}^{T-2} p_l)(1-w_1)}{(1+\sum_{m=1}^{T-2}(\prod_{l=m}^{T-2} p_l))}\right) b_{ki} + \frac{(1-w_1) b_{Ti}}{(1+\sum_{m=1}^{T-2}(\prod_{l=m}^{T-2} p_l))},$$

Meaning that S(i) can be rewritten as an expression which is linear in w_1,

$$S(i) = w_1\left(b_{1i} - \sum_{k=2}^{T-1} \frac{(\prod_{l=(k-1)}^{T-2} p_l) b_{ki}}{(1+\sum_{m=1}^{T-2}(\prod_{l=m}^{T-2} p_l))} - \frac{b_{Ti}}{(1+\sum_{m=1}^{T-2}(\prod_{l=m}^{T-2} p_l))}\right) + \left(\sum_{k=2}^{T-1} \frac{(\prod_{l=(k-1)}^{T-2} p_l) b_{ki}}{(1+\sum_{m=1}^{T-2}(\prod_{l=m}^{T-2} p_l))} + \frac{b_{Ti}}{(1+\sum_{m=1}^{T-2}(\prod_{l=m}^{T-2} p_l))}\right)$$

This permits to identify the gradient sensitivity of each S(i) regarding the variation of w_1. If this gives first interesting information, we need to have a closer at the sensitivity analyses since the weights w_k do not correspond directly to the evaluations of the decision-makers. That is why the next section focuses more directly on the variations on criteria weights W_1 to W_4 and on sub-criteria weights $w_k^{(j)}$.

III.4.3. Deeper gradient sensitivity analysis

III.4.3.i. Sensitivity regarding criteria weights

We know that

$$\sum_{j=1}^{4} W_j = 1$$

By rewriting

$$S(i) = \sum_{j=1}^{4}\sum_{k=1}^{K_j} W_j w_k^{(j)} b_{ki}^{(j)} = \sum_{j=1}^{4} W_j (\sum_{k=1}^{K_j} w_k^{(j)} b_{ki}^{(j)})$$

For each j and i, let $F_j(i)$ be

$$F_j(i) = (\sum_{k=1}^{K_j} w_k^{(j)} b_{ki}^{(j)})$$

We can conduct an analogous approach (as in III.4.2.), meaning that if we want to study the variation on the evaluation of W_1 for instance, with the ratios of other weights fixed

$$p_1 = \frac{W_2}{W_3} \;\&\; p_2 = \frac{W_3}{W_4}$$

As a whole, we can rewrite

$$S(i) = W_1(F_1(i) - \frac{p_1 p_2 F_2(i) + p_2 F_3(i) + F_4(i)}{1 + p_2 + p_1 p_2}) + \frac{p_1 p_2 F_2(i) + p_2 F_3(i) + F_4(i)}{1 + p_2 + p_1 p_2},$$

Which means that S(i) can be considered as such expressions which is linear in W_j. In order to study visually this sensitivity of S(i) regarding the variation of the criteria weights W_j, we propose to draw different synthetic graphs. The first gathers the variations of a given score $S(i_0)$ regarding the variations of the criteria weights. Let $S(i_0)$ be the score of project i_0. As shown on Figure 23, a graph can be drawn to understand this linear sensitivity of $S(i_0)$ regarding the variation of W_1, W_2, W_3 or W_4.

This graph (as well as the analytical formulations) permits to compare the sensitivity to any criteria weight variation. This also permits to show the lower and upper bounds of the scores that can be reached for a given project if a criteria weight varies from 0 to 1, with the ratios of the initial evaluation kept identical. This is all the more interesting when two projects initially get two close scores: studying the possible variations of their scores S(i) permits to highlight the robustness of their ranking regarding project complexity evaluation.

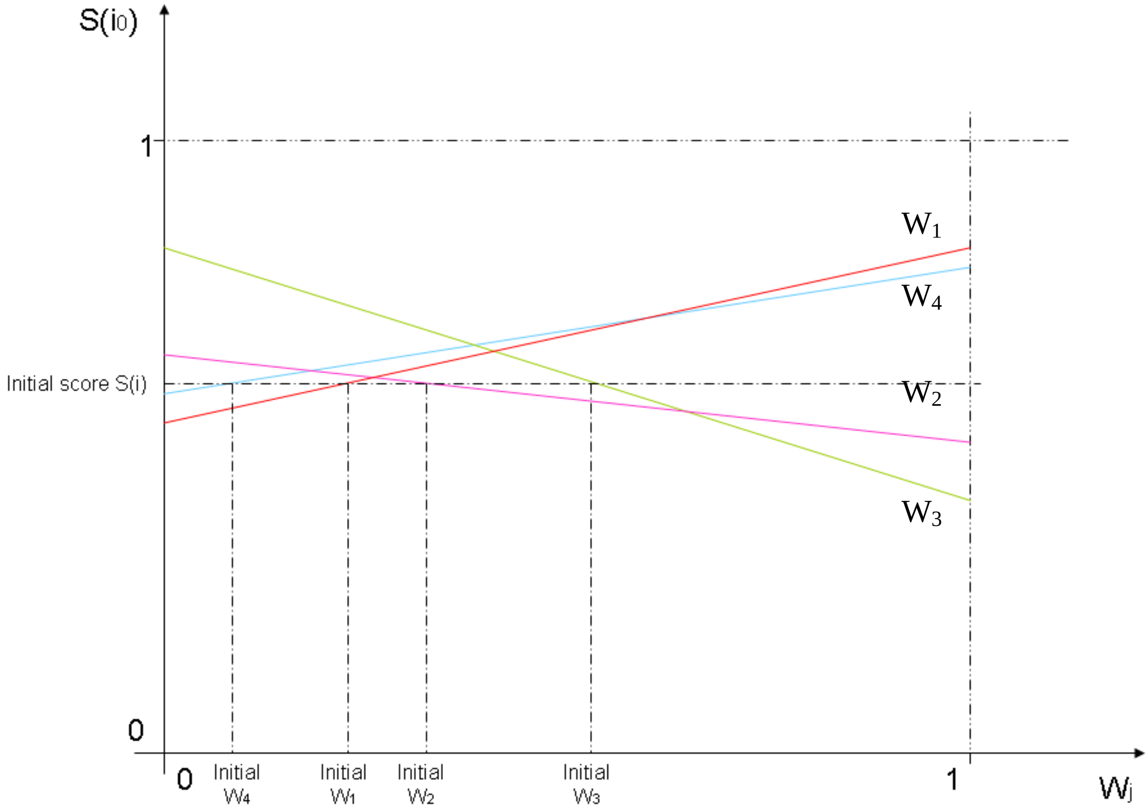

Figure 23. Sensitivity analysis of score $S(i_0)$ regarding the variations of any criteria weight W_j

Another interesting graph which can be built up can be seen on Figure 24.

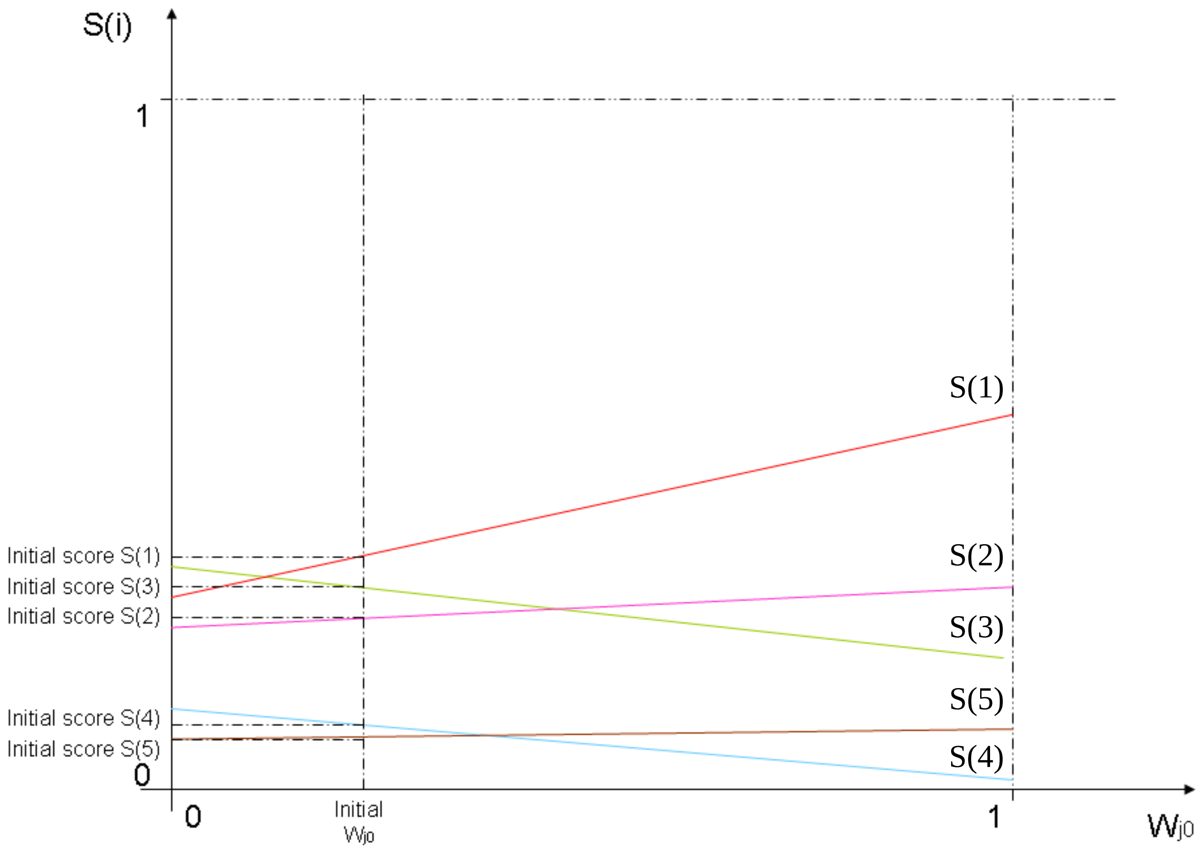

Figure 24. Sensitivity analysis of any score S(i) regarding the variations of criteria weight W_{j0}

This graph shows the possible variations of the scores of all evaluated projects S(i) regarding the variation of a criteria weight W_{j0}. This gives particular insights as the variations of the scores are compared. Interestingly, by studying first the close neighbourhood of the initial evaluation, one can analyse the robustness of the initial ranking. Moreover, one can underline when and how the initial ranking of the projects is going to change thanks to the crossings of the lines on the graph. This point is interesting since it permits to see the level of variation which is needed to have a change in the initially obtained ranking. In other terms, this permits to stress how robust the initial ranking is by defining the interval of possible variation of W_{j0}, where the ranking is kept the same.

III.4.3.ii. Sensitivity regarding sub-criteria weights

Here, we want to understand the sensitivity of the scores S(i) regarding the variations of sub-criteria weights. In order to so, we fix a certain sub-criterion weight $w_k^{(j)}$, for instance $w_1^{(2)}$. Then we suppose that the ratios of all other $w_k^{(2)}$ are fixed and we note that

$$\sum_{k=1}^{K_2} w_k^{(2)} = 1$$

Then, we can rewrite the scores S(i) in the following manner

$$S(i) = \sum_{j=1}^{4}\sum_{k=1}^{K_j} W_j w_k^{(j)} b_{ki}^{(j)} = \sum_{\substack{j=1 \\ j\neq 2}}^{4}\sum_{k=1}^{K_j} W_j w_k^{(j)} b_{ki}^{(j)} + W_2 (\sum_{k=1}^{K_2} w_k^{(2)} b_{ki}^{(2)})$$

By performing analogous calculations as in the former paragraphs, we can rewrite

$$S(i) = \sum_{\substack{j=1 \\ j\neq 2}}^{4}\sum_{k=1}^{K_j} W_j w_k^{(j)} b_{ki}^{(j)} + W_2 (w_1^{(2)} \theta(i) + \pi(i))$$

Where $\theta(i)$ and $\pi(i)$ can be calculated similarly as in III.4.2. by replacing T and K_2. As a whole, this permits to show that S(i) can be considered as this expression which is linear in $w_1^{(2)}$. That is why we suggest the drawing and analysis of similar graphs than those built up in III.4.3.i.

III.5. Case study

III.5.1. Introduction

The case study takes place within a start-up firm, the main activity of which is the production of stage musicals in France. Staging musicals or theatre plays are definitely projects, as underlined by Lehner (Lehner, 2009): it refers to all artisitical, technical and organizational processes which permit to stage a musical. Project start corresponds to the idea and choice of the show to stage. Project end is generally considered as the first performance or the first week of performances (the activities which follow are often considered as the core day-to-day running activities of a theatre production firm). In the case studied, the firm has a portfolio of 7 projects of musicals to be staged in 2010-2011. The managers of the firm, who are at the start of their activity (with both artistic and industrial backgrounds), are assisted by several possible investors and partners. They wonder which show(s) they should produce first.

As for them and as for us, project complexity appears here as one of the criteria which should be considered before making a decision on this issue. Other criteria may notably be linked with the overall project performance regarding the values creation processes of the project (notably in terms of profit, image, etc…). A global project selection process may then be defined after this study in order to include all these factors in a multi-criteria approach to select the best project. Here, we do focus on project complexity evaluation for the moment. Actually, in the context of this firm, the importance of project complexity as a factor for selection is all the more true than the lack of experience in star-up firms implies even greater difficulties to handle properly project complexity. As a consequence, a proper evaluation of relative project complexity appears to be really necessary. Some project complexity aspects are very present or specific to this sector, and as an introduction to this case study, we need to describe this specific context.

- Since they progress in the cultural sector, such projects are very likely to face scarcity and problems of matching incomes and expenses. The struggle for income also means that most long-term planning must be kept open for very swift changes as new orders and constraints are likely to appear. Incomes are also very difficult to foresee in France since French audiences are not used to musicals (for the staging of musicals has been rarer than in other countries for decades).
- Project management techniques are generally very new in this sector, and the majority of stakeholders may not be used to it. This lack of experience and maturity may imply some difficulties when dealing with project complex issues. Lack of experience is also present in this case since these projects occur within a start-up firm: people have very little experience working together for the majority of them.
- Logistic and technical constraints are much higher in the sector of musicals than in any other artistic domains. First, three artistic disciplines and thus three cultures (comedy, singing, dancing) have to coexist. Moreover, technological complexity is generally greater than in other artistic domains since musicals' sets and direction often imply more elaborated technological tools and mechanisms for staging.

In Figure 25, the reader can find a brief description of the 7 projects. Cast, creative team and project team size are notably given hereunder. Note that global budget is a first assessment of the overall budget of the project and that project duration is estimated work before staging. The achievement of the first performance is considered as part of the project. Project 1 is the production of a French adaptation of a Broadway musical, whereas projects 2 to 7 are original creations. Projects 1, 2, 6 and 7 include some special effects (notably pyrotechnical ones for some of them). Projects 1 to 6 require detailed work on costume and set design (notably with advanced mechanical structures and machinery for some of them).

	Global budget	Duration	Min. Staging Duration	Project team	Creative team	Cast
Project 1	3 000 000 €	18 months	1 year	10	10	40
Project 2	3 000 000 €	12 months	1 year	9	8	30
Project 3	1 500 000 €	12 months	1 year	8	8	30
Project 4	300 000 €	6 months	6 months	4	9	10
Project 5	500 000 €	9 months	1 year	5	8	14
Project 6	3 500 000 €	12 months	2 years	9	8	35
Project 7	150 000 €	6 months	6 months	4	8	4

Figure 25. Brief description of the seven projects

III.5.2. Results and discussion

We carried out our research thanks to interviews of some possible future project team members (5 participants) following the AHP evaluation process, given our hierarchical structure. These people were asked to perform an a priori ranking of the projects in terms of complexity. This a priori ranking was necessary to highlight the possible differences between their initial perception and the results obtained. Then, as mentioned before, specific advanced Saaty scales were elaborated with the interviewees in order to perform pair-wise comparisons with less subjectivity. For instance, if we note NS(i) the number of stakeholders for a given project i, the advance Saaty scale built in this case for the number of stakeholders criterion was the following (Figure 26). Building up such advanced scales permit greater consensus when performing the study in group and facilitates communication on the results of the study when performed by a single user.

Number of stakeholders criterion	Corresponding Saaty scale
If NS(i)-NS(j) = 0 then contribution to complexity is equal	$A_{ij} = 1$
If NS(i)-NS(j) ≤ 2 then contribution to complexity is moderately more important for project i	$A_{ij} = 3$
If NS(i)-NS(j) = 3 then contribution to complexity is moderately more important for project i	$A_{ij} = 5$
If NS(i)-NS(j) = 4 then contribution to complexity is moderately more important for project i	$A_{ij} = 7$
If NS(i)-NS(j) ≥ 5 then contribution to complexity is moderately more important for project i	$A_{ij} = 9$

Figure 26. Advanced Saaty scale in the case study (Number of stakeholders criterion)

The methodology and measure proposed in this research work proved to be helpful in this case study. First, as shown in Figure 27, a first table is to be built to analyse the situation of the firm regarding project complexity. The relative weight of each sub-criterion can be evaluated, which gives information on where projects are likely to be more complex within the firm. Project managers should indeed pay particular attention to the project complexity factors which get the best relative score (last column) in this evaluation. On the contrary, some aspects of project complexity (low scores) may potentially be more neglected at a first sight. This piece of information thus permits one to concentrate more efficiently on the principal factors of project complexity under a given firm and project environment.

Criteria (C)	C weights	Sub-criteria (SC)	SC weights	Total weights	Relative value
C1 - Project Size	**0,142**	SC1 - Number of stakeholders	1,000	**0,142**	**0,804**
C2 - Project variety	**0,151**	SC2 - Variety of informations systems to be combined	0,057	**0,009**	**0,049**
		SC3 - Geographic location of the stakeholders	0,295	**0,045**	**0,252**
		SC4 - Variety of the interests of the stakeholders	0,649	**0,098**	**0,555**
C3 - Project interdependencies	**0,556**	SC5 - Dependencies with the environment	0,092	**0,051**	**0,290**
		SC6 - Availability of people, material and… due to sharing	0,042	**0,024**	**0,133**
		SC7 - Interdependence between sites, departments and…	0,062	**0,034**	**0,194**
		SC8 - Interconnectivity/Feedback loops in the project networks	0,020	**0,011**	**0,062**
		SC9 - Team cooperation and communication	0,189	**0,105**	**0,596**
		SC10 - Dependencies between schedules	0,042	**0,024**	**0,133**
		SC11 - Interdependence of information systems	0,019	**0,011**	**0,060**
		SC12 - Interdependence of objectives	0,122	**0,068**	**0,383**
		SC13 - Level of interrelations between phases	0,094	**0,052**	**0,297**
		SC14 - Specification Interdependence	0,318	**0,177**	**1,000**
C4 - Project context-dependence	**0,151**	SC15 - Cultural configuration and variety	0,633	**0,096**	**0,542**
		SC16 - Environment organisational complexity	0,260	**0,039**	**0,223**
		SC17 - Environment technological complexity	0,106	**0,016**	**0,091**

Figure 27. Overall criteria and sub-criteria weights: project complexity factors comparison

As said before, we left the users the possibility to follow the entire AHP process, meaning that the relative weights of each criterion and sub-criteria obtained thanks to the Delphi study were not given to the users. It is undoubtedly interesting to see that the panel of interviewees in our case study obtained a ranking of the criteria and sub-criteria which were consistent with the one obtained with the Delphi study. For instance, as shown on Figure 28, project interdependencies notably appear as the greatest source of global project complexity, since they globally account for more than 55% of the final sum score of the project in our evaluation. The reader should note that in this case, project context appears to be a slightly more important driver of project complexity than in the Delphi study (accounting for around 15% of the final score, equal to the score of variety and slightly superior to the one of project size).

	Size	Variety	Interdependencies	Context	Total
Project 1	0,029	0,056	0,142	0,064	0,292
Project 2	0,031	0,019	0,096	0,017	0,162
Project 3	0,017	0,017	0,058	0,012	0,105
Project 4	0,004	0,007	0,024	0,006	0,040
Project 5	0,007	0,009	0,026	0,014	0,055
Project 6	0,051	0,038	0,185	0,033	0,308
Project 7	0,003	0,006	0,025	0,005	0,038
Total	0,142	0,151	0,556	0,151	1,000

Figure 28. Relative weights of the seven projects

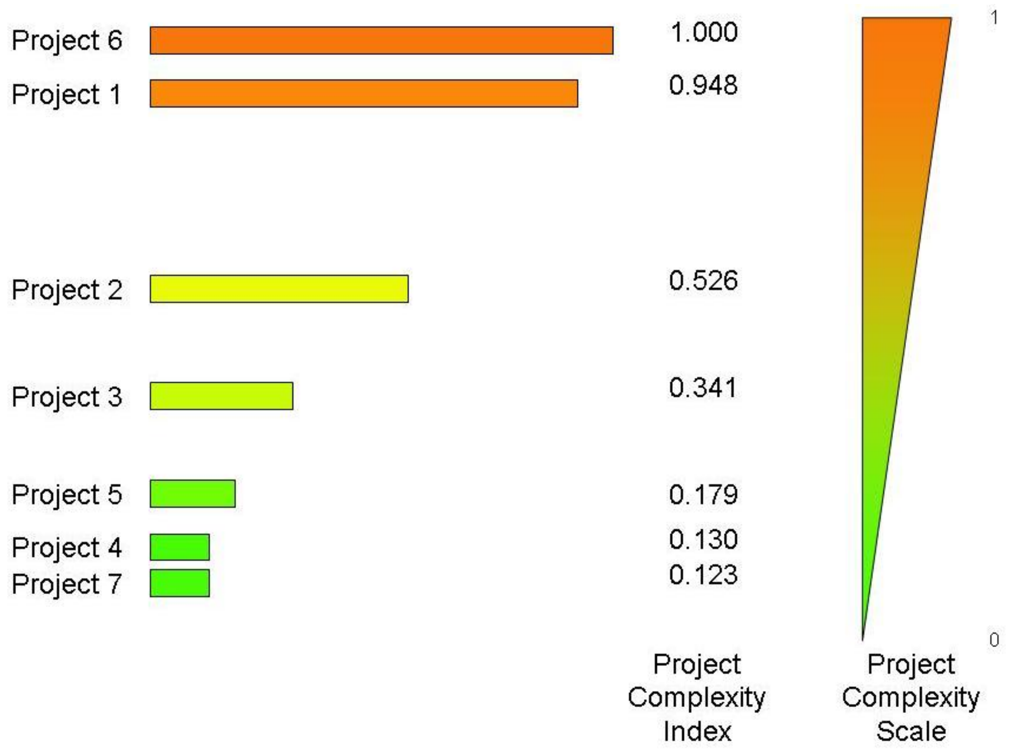

Figure 29. Relative project complexity index in the case study

In the end, final results are obtained and permit to realise a ranking of projects according to a complexity scale / index (from 0 to 1), as shown on Figure 29. It can be noted that two projects (P6 and P1) appear to be much more complex than the others, then Project 2 appears to be significantly more complex than the other ones.

First, the existence of a numerical relative evaluation of project complexity within a project portfolio appears to be promising since it permits to know which projects are to be the most complex ones, but also how complex projects are. Future research works are carried out to set out a methodology which could define a threshold value (in the context of the studied project portfolio) over which projects could be rejected (notably given the experience and project maturity of the firm). Moreover, this global ranking according to the relative project complexity index we propose is all the more interesting in this case study since the employees which were interviewed had made an a priori ranking which was different. In that a priori ranking, P3 was ranked second and P7 was ranked third, whereas P6 was only placed fourth. With this numerical assessment of complexity and this ranking given, discussions were held with the participants, and communication around the notion of complexity was facilitated.

They started to share their experience on complexity factors and realized that the difference with the a priori ranking they had done was mainly due to some communication and psychological barriers they had. For instance, P7 was a priori ranked by them third because the majority of them did not know where to find the skills and competence for the design of a specific special effect. Four of them had thus ranked this project as one of the most complex ones (two of them had even ranked it as the most complex). But when performing the pair-wise comparisons, the fifth employee, who had ranked a priori P7 as the less complex, said that he had already worked with such special effects and knew who could design them easily. The others changed their minds. Such example in our case study proves both the necessity to facilitate and promote communication in order to manage complex projects more efficiently and the benefits obtained with the project complexity refined framework and index we propose.

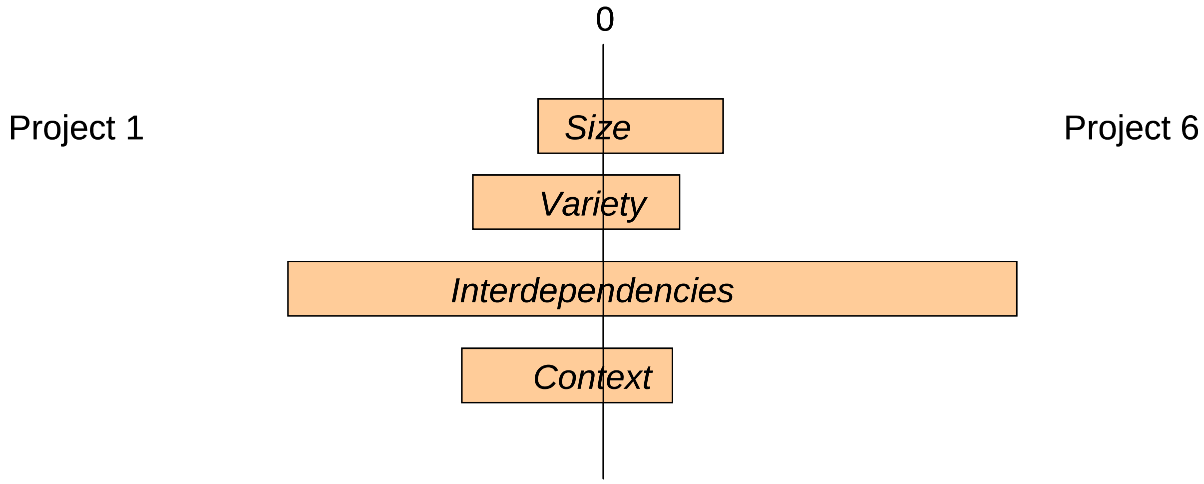

Figure 30. Specific graphical comparison of projects 1 and 6.

Finally, before performing a sensitivity analysis, as shown on Figure 30, we claim for the use of specific numerical and graphical comparisons of projects which obtain close scores. For instance, in this case, project 6 obtains a global score of 0.308 when project 1 obtains a score of 0.292, which makes in the end a small difference (around 5%). In order to assist the decision-makers with their decisions, a closer look is to be done over the two projects. When realizing that the score of interdependencies (the main factor) is 0.185 for project 6 and 0.142 for project 1 (difference of around 25%), the people which were interviewed in this case study definitely evaluated project 6 more complex that project 1. Indeed, when analysing closer why such a difference was obtained, the participants underlined notably a greater specifications interdependence and interdependence of information systems for project 6. These specific interdependencies seemed all the more difficult to handle for the participants, which led them to the conclusion to reject project 6 at the time of this study. More precise comparisons can even be performed when descending to the level of sub-criteria and comparing projects on 0 to 1 relative subscales, as shown on Figure 31 with specifications interdependence sub-criterion.

	Specifications interdepence index
Project 1	0,499
Project 2	0,554
Project 3	0,219
Project 4	0,096
Project 5	0,071
Project 6	1,000
Project 7	0,140

Figure 31. Building up comparison subscales on sub-criteria

Finally, sensitivity analyses are likely to be performed in order to study the variation and robustness of the results and ranking which is obtained, so that decision-makers are more confident with the decisions they make. For instance, we notably studied the possible variations of the seven project scores regarding any criteria weight variation.

We knew that, with the notations of III.4.3.i.,

$$S(i) = W_1(F_1(i) - \frac{p_1 p_2 F_2(i) + p_2 F_3(i) + F_4(i)}{1 + p_2 + p_1 p_2}) + \frac{p_1 p_2 F_2(i) + p_2 F_3(i) + F_4(i)}{1 + p_2 + p_1 p_2}$$

Whatever j and i, the scores $F_j(i)$ can be calculated with the results that were obtained before (they can be found hereunder in Figure 32).

	F1(i)	F2(i)	F3(i)	F4(i)
Project 1	0,204	0,371	0,255	0,424
Project 2	0,218	0,126	0,173	0,113
Project 3	0,120	0,113	0,104	0,079
Project 4	0,028	0,046	0,043	0,040
Project 5	0,049	0,060	0,047	0,093
Project 6	0,359	0,252	0,333	0,219
Project 7	0,021	0,040	0,045	0,033

Figure 32. Synthesis of the $F_j(i)$ scores

This permits to draw four graphs which synthesise the sensitivities of all scores S(i) regarding any criteria weight variation (W_1 related to size, W_2 related to variety, W_3 related to interdependency and W_4 related to context-dependence). The one related to W_3 can be found hereunder in Figure 33 and is built up thanks to following equations corresponding to the sensitivity to W_3 variation.

$$S(1) = 0{,}335 - 0{,}080 \times W_3$$
$$S(2) = 0{,}151 + 0{,}022 \times W_3$$
$$S(3) = 0{,}103 + 0{,}001 \times W_3$$
$$S(4) = 0{,}038 + 0{,}005 \times W_3$$
$$S(5) = 0{,}068 - 0{,}021 \times W_3$$
$$S(6) = 0{,}275 + 0{,}058 \times W_3$$
$$S(7) = 0{,}031 + 0{,}014 \times W_3$$

As a whole, we can see that the obtained results are not too sensitive since the rankings of the project do not vary so much. Project 2, Project 3 and Project 5 are to keep always the same ranking whatever the value of W_3 (with ratios of other weights kept constant): project 2 is third, project 3 is fourth, project five is fifth. Project 4 and Project 7 are always very close to one another and alternate the position of fifth and sixth project. The two first projects are the most sensitive ones to a variation in the value of W_3. When W_3 is inferior to 0.435, then project 1 is the most complex. Project 6 is the most complex in the other case, and thus notably when W_3 is 0.556 (corresponding to the initial evaluation of the members). The obtained ranking may in the end give quite good confidence in the analysis made for decision-making (regarding a change in W3) since no change in the ranking occurs if W_3 is kept between 0.435 and 0.778. In other terms, unless a variation of 21.7% downwards and 39.9% upwards.

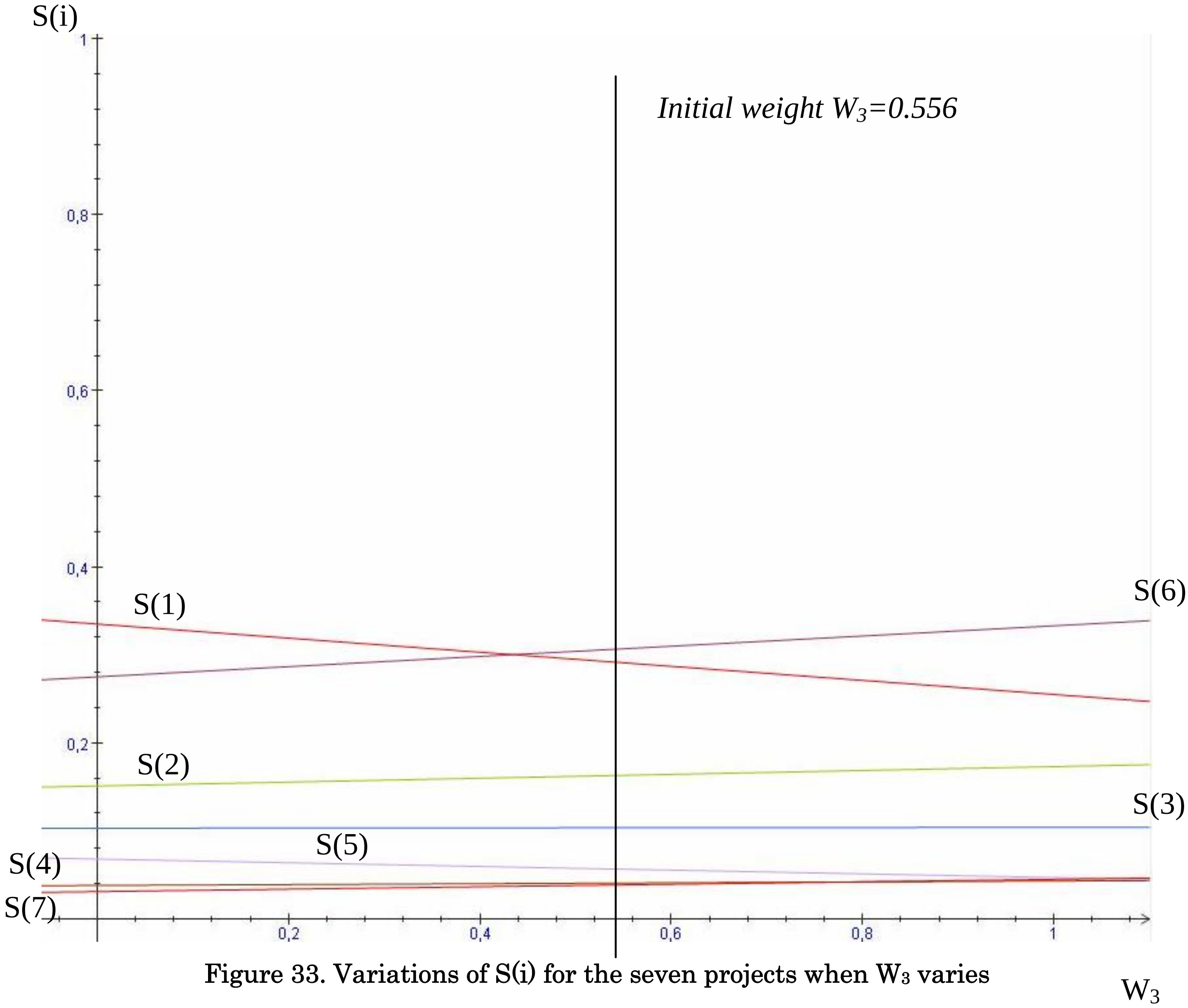

Figure 33. Variations of S(i) for the seven projects when W_3 varies

However, these sensitivity analyses are based on gradient calculations which assume that the ratios of other weights are kept constant. In order to be more precise, the weight spaces should be explored. As underlined by Erkut and Tarmicilar (Erkut and Tarmicilar, 1991), hypervolumes of convex subsets of the weight space (corresponding to the dominance of a project) should then be calculated, notably thanks to the works of Cohen and Hickey (Cohen and Hickey, 1979).

III.6. Conclusions and perspectives

As a whole, this chapter elaborates an AHP-based methodology and measure to evaluate relative project complexity. The works proposed here answer the problem which was set after the literature review on existing (project) complexity measures. Indeed, as shown theoretically and validated with a first case study, the project complexity index proposed here permits to overcome to a great extent the limits of existing ones as it is:

- **Reliable**, since the final users are confident wit the results, measures and scales which are proposed. First, during the case study, no numerical result was ever challenged by the participants of the case study. On the contrary, the results permitted to identify more precisely project complexity sources which were consciously or unconsciously felt without being clearly mentioned or stated. Furthermore, the reliability of the results was also underlined when comparing with the a priori ranking which was made. The obtained results permitted to underline what they had forgotten in their a priori ranking and all the users agreed in the end on the ranking obtained by the complexity index proposed in this work.

- **Intuitive** and **user-friendly**, since the users understand the construction of the measure and scales, and why they do measure project complexity or the level of complexity regarding a given criterion, sub-criteria, or set of (sub-)criteria. This results in the end in a facilitation of communication on project complexity and project complexity factors. Finally, the measures and scales were easily computed and permitted rapid calculations and quick changes, which was an important requirement for an industrial use.
- Globally **independent of the project models** which are used for project management. Indeed, no reference to project management tools or models (WBS, PERT networks, GANTT charts, risk lists, etc…). was ever made during the construction of the measure or during the case study. This means that none of these models is needed as a reference to assess project complexity through this method. However, a limitation exists on this point. The (refined) project complexity framework built in Chapter 2 is the basis of the measure proposed in this Chapter. But, one should not forget that this framework is in essence a specific model, not of a project, but of what project complexity stands for. As a consequence, the measure which is proposed refers theoretically to this project complexity model. However, the final user is free to add some aspects (project complexity factors) in the AHP hierarchical structure proposed in this study. The methodology which is proposed here is thus quite generic with the project complexity model used, as long as it can be modelled as a hierarchical structure of project complexity factors.
- Able to **highlight project complexity sources** when building up the global complexity scale and the subscales. As shown by the case study, these scales enable the user to address many issues regarding decision-making and project complexity:
    - Project prioritization within a portfolio in order to focus on the most complex projects (the ones where more complexity-related management methods and tools are needed).
    - Project areas (for instance thanks to a classical WBS decomposition, or according to geographical areas) prioritization in order to focus on the most complex areas of a given project (the ones where more complexity-related management methods and tools are needed).

- Comparison of present projects with past projects.
- Project scenario prioritization in the case of mono-project management.
- One-to-one detailed comparison of two projects which exist in the same portfolio in terms of project complexity.
- Global identification of the principal project complexity sources within a given project / a given portfolio / any set of projects.

- Finally, some sensitivity analyses can be conducted in order to analyse the robustness and stability of a given ranking which is obtained. Such analyses permit to elaborate linear equations which describe the possible variations when the weight scores may evaluate due to a change.

However, some limitations do appear in this work and offer perspectives for future research on project complexity evaluation.

- First, the Analytic Hierarchy Process has received some criticisms on the fact that rankings can vary when adding or subtracting an alternative to the set of alternatives on which the study is performed (Holder, 1990). We thus recommend the users to give specific attention to the step when the set of alternatives to be compared is selected. First, all alternatives in this set should strictly correspond to the final selection or comparison objective which is addressed. Second, projects on which the final users have few information or data may not be selected first as the quality of pair-wise comparisons may be considerably reduced. Finally, even with these recommendations, we need to underline that as for any decision-making process and tools, great caution and awareness should be taken when making the final decision (significant gaps should exist between scores and results may not be too sensitive).
- Second, despite the sensitivity analyses which are proposed here, uncertainty in the judgment of the users is not much taken into account with this methodology. To address this issue, we plan to introduce a fuzzy AHP-based method with triangular fuzzy numbers in future research works. Such applications of this method in project management can notably be found in (Mahmoodzadeh and al, 2007)
- Finally, future research is going to explore the possible to extend this model to a ANP (Analytic Network Process) model. Indeed, Taslicali and Ercan (Taslicali and Ercan, 2006) say that their results suggest that "the ANP model represents reality as well as reliability better than the AHP model" due to the better integration of the interactions which exist between criteria. However, "the managerial implications of the execution of ANP and AHP are factors that vary from organization to organization" and the AHP seems to be an easier methodology which may be accepted and understood better by managers. We think that in our case, exploring the possibility of using the AHP may be

interesting since in essence, the criteria and sub-criteria of our structure are not independent. Building up a ANP network structure for project complexity evaluation may then be interesting as it includes interdependence and feedback. However, the number of judgement elicitations needed are likely to increase and become tougher when dealing with the interrelation between criteria or sub-criteria.

Chapter IV.

Understanding the stakes of project complexity. Implications on project risk management.

Abstract

The overall ambition of this chapter is to describe the consequences of project complexity and to understand the stakes of project complexity management. In order to do so, an analysis of some academic works permits to identify four kinds of complexity-driven phenomena:

- Project ambiguity as a lack of awareness of the project system and a lack of a shared vision within the project team.
- Project uncertainty as the inability to pre-evaluate the impact of events, actions and decisions and thus foresee and control the project evolution.
- Project propagation phenomena due to the interdependence of project elements, including loops.
- Project chaos, mainly in terms of the sensitive dependence on initial conditions.

Practical implications on project risk management are then underlined. First, a state of the art on project risk management methodologies is proposed. Then, some lacks regarding the integration of complexity-driven effects lead in the end to the proposal of two research issues:

- A systemic approach to integrate complexity in the project risk management process through the concept of project vulnerability (Chapter 5).
- An analytic approach to integrate complexity in the project risk management process through the identification of risk interactions and the clustering of risks regarding these interactions (Chapter 6).

As a consequence, this chapter is a transition between the two main parts of this thesis. Indeed, after understanding and measuring project complexity to focus on the most complex projects or zones of a project (Chapters 2 and 3), we propose to understand the stakes of project complexity and show the lacks of existing methods (Chapter 4) in order to raise research issues for the end of this Ph.D. thesis (Chapters 5 and 6).

Chapter Keywords

Project, Complexity, Ambiguity, Uncertainty, Propagation, Risk.

IV.1. Introduction

Project must be managed to achieve their objectives (Turner and al, 1988) but project risks are likely to prevent them from doing so (Gautier and al., 1997). Even if the relation between risks and complexity is still to be clarified, project complexity is defined in this work as the property of a project which makes it difficult to understand, foresee and keep under control its overall behaviour, even when given reasonably complete information about the project system.

As mentioned in the project complexity framework that was built in Chapter 2, there is a great number and high diversity of objects to manage, with a high number and great diversity of parameters that characterize them. The amount and diversity of interactions and interdependencies between these objects are so huge that they rapidly become unmanageable thanks to the sole use of classical tools and methods of project management. Identifying specific zones of complexity within a project or particularly complex projects within a portfolio thanks to the results of Chapter 3 then permits to focus on smaller parts of a project (or a portfolio), which assists project (portfolio) management.

As seen in the former chapters, this work claims for the conjoint use of traditional methodologies and new complexity-integrating tools in order to establish more efficient and effective project management processes. Indeed, both the complexity of the evolving environment and the internal complexity of the project justify the need for this new approach that would assist the existing ones. But before doing so, one should understand what the complexity-driven phenomena within a project are and what the stakes of project complexity management and integration into project management processes are.

<u>PROBLEM SETTING OF THIS CHAPTER</u>

That is why this chapter focuses on the stakes and consequences of project complexity in order to rise some research questions. As shown after, project complexity consequences regarding project risk management are to be studied.

In order to do so, the following points must be addressed:

- Understanding the stakes and consequences of complexity by linking it with the concepts of ambiguity, uncertainty, propagation and chaos.
- Understanding as a whole the implications on project risks.
- Carrying out a state of the art on existing project risk management methodologies and tools.
- Identifying the lacks of the traditional project risk management and tools.
- Rising research issues regarding the integration of complexity into innovative project risk management methodologies and tools. (These questions are to be solved in Chapters 5 and 6 of this Ph.D. thesis).

IV.2. Understanding the stakes of project complexity

This section aims at describing some of the consequences of project complexity (thanks to an analysis of the literature review) in order to understand the stakes of project complexity management and to characterize how it can be helpful to assist project risk management. The links between project complexity, project risks, project uncertainty and project performance are still unclear in the academic world as well as in the industrial one. For instance, Parsons-Hann and Liu state that "it is clear that requirements complexity contributes to project failure in organisations, what is not apparent is to what degree this statement holds true" (Parsons-Hann and Liu, 2005).

IV.2.1 The consequences of project complexity

Uncertainty appears as one of the possible negative consequences of project complexity. This paragraph illustrates how project complexity can be a source of uncertainty, thus making a distinction between these concepts as some research works argued for it before (Pich and al., 2007), (Little, 2005). In order to follow this paragraph more easily, the reader should refer to the drawn synthesis on Figure 34.

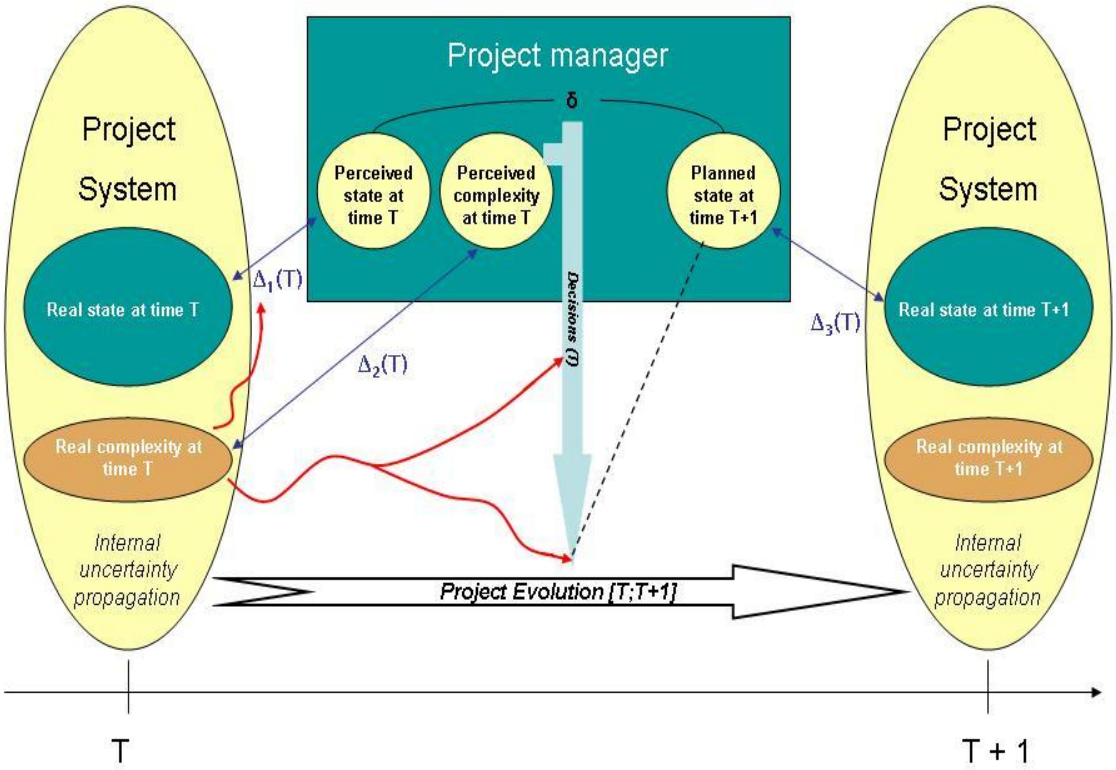

Figure 34. Project complexity-driven phenomena

Let a project manager analyse a project system at a given time T in order to plan his decisions and actions for the next period to reach a state at time T+1. The project system can be described by its real state at time T, a state the real complexity of which can also be considered at time T.

IV.2.1.i. Project ambiguity

When analysing and monitoring the project system at time T, the project manager first perceives the real state at time T, introducing a difference between the real project state at time T and the perceived project state at time T (Δ_1(T)).

This difference has two principal causes. On one hand, the project manager has its own culture and references, and thus, his perception of the project system alters reality. On the other hand, real project complexity implies that the project system cannot in essence be completely understood. Indeed, there is always an irreducible residual source of non-exactitude caused by complexity (mainly due to the high number and variety of elements and interactions that cannot be completely neither identified nor understood) when trying to identify the project system state. For the same reasons, there is a difference (and thus another source of non-exactitude Δ_2(T)) between perceived project complexity at time T and real project complexity at time T.

This question of perception is approached by Jaafari (Jaafari, 2003) and appears to be a crucial issue for project complexity. Jaafari insists on the fact that individuals, depending on their mental models and representations, perceive the outside reality in their own way. As a consequence, project complexity is dealt with through a filter, which is the individual perception of the project system and environment (based on one's representations). This is all the more true since the semantics used may be different from a project team member to another. In other terms, the difficulty is that the gaps Δ_1(T) and Δ_2(T) are different for any project team member as anyone has its own perception of reality.

These two phenomena can be grouped under the sole name of project ambiguity. Referring to some works (Pich and al., 2007), (Haas, 2008), a definition of project ambiguity is proposed hereunder

<u>Definition</u>

Project ambiguity can be divided into two main aspects:

- The lack of awareness of elements, events and their characteristics (due to the overall lack of understandability of the project system), particularly when evaluating them.
- The differences in the perception of the project system by team members, notably because of their different cultures.

Axiom: Project ambiguity is a consequence of project complexity.

The leadership and adaptability of the project manager is thus crucial in order to try to share a common reference and perception of reality within the project team, so that part of project ambiguity can be reduced.

IV.2.1.ii. Project uncertainty

Let us now have an overall look at the global process of project management. The project manager analyses the state of the project at a given time T and considers the difference δ between this state at time T and the state he planned for the next period at time T+1. The project manager then makes decisions under the constraints of project context and perceived complexity and does the corresponding actions to influence the project evolution in order to reach the planned state at time T+1. This process is also altered by complexity-driven phenomena in terms of uncertainties.

First, decisions can be directly altered by real project complexity. For instance, the transmission of the information on a decision can be altered because of cultural variety, staff diversity and staff interdependences: as a matter of fact, when turning this decision into an action (at the end of the information transmission process), the real action can be different from the action the project manager wanted. Moreover, real complexity has an influence on the impact of the decisions made and the subsequent actions done. The project manager deals with perceived (and not real) project complexity when making its decisions and moreover, real project complexity entails the project manager's inability to forecast efficiently both the impact of its decisions and the project evolution. Because of these those two reasons, real project complexity is one of the causes of the difference between the planned state at time T+1 and the real state at time T+1, introducing another difference $\Delta_3(T)$. This difference calls for project uncertainty.

<u>Definition</u>

Project uncertainty corresponds to the inability to pre-evaluate project objectives and characteristics of the project elements as well as the impact of actions and decisions.

Axiom: Project uncertainty is a consequence of project complexity.

IV.2.1.iii. Project propagation phenomena

Finally, project complexity is also a source of non-exactitude in terms of propagation. Indeed, let an uncertain parameter P be in the project system, meaning that the value of P is known under conditions of uncertainty $P \pm \delta_P$.(confidence interval). P can be for instance the duration of a task, the cost of a deliverable, or any dimension of any object of the project system. Since the project system is complex, it includes interdependencies and interconnectivities between its elements (tasks, resources,…). As a consequence, the corresponding uncertainty δ_P on a parameter P can spread through the entire system, as any element in relation with parameter P faces uncertainty and transmits to all its neighbours in the same manner.

<u>Definition</u>

It corresponds to the fact that any change in the parameters of the project system is to propagate through the entire project system due to its numerous and varied interdependencies.

Axiom: Project propagation phenomena are a consequence of project complexity.

As Heylighen and al. (Heylighen and al., 2006) underline it, "as technological and economic advances make production, transport and communication ever more efficient, we interact with ever more people, organizations, systems and objects." In the case of project management, one of the main consequences is that any change in any component in the project system may thus affect any other component of the project system in an unpredictable way because of change propagation.

Propagation phenomena are all the more complex to manage since a project, as any complex system, has a high number of various elements and interactions, meaning for example that uncertainty on the duration of a task T_i can be transmitted in terms of uncertainty on the duration of a task T_j, which can be transmitted in terms of uncertainty on the cost of a deliverable D, which can then be transmitted in terms of uncertainty on the quality of the global project outcome… In other terms, propagation in the project system is even more complex since the project manager has to manage the change of the nature of non-exactitude at each stage it is transmitted within the system. The reader should particularly note that ambiguities and uncertainties are to be analysed regarding propagation phenomena.

IV.2.1.iv. Project chaos

Chaos and turbulence phenomena may appear in a project due to complexity. Chaos refers to a situation, where the short-term developments cannot be accurtely predicted, notably because of the joint impact of interdependence and variability (Tavistock 1966), which were identified as complexity drivers. Chaotic phenomena are sometimes hard to separate from ambiguity, uncertainty and propagation phenomena. However, they particularly correspond to a sensitive dependence on initial conditions. This Ph.D. thesis work does not insist on the aspects of chaos and turbulence. However, the interested reader may find appropriate concepts and references in (Dörner, 1996), (Laufer, 1997), (Bertelse and Koskela, 2003) and (Pich and al., 2007).

IV.2.2 Project complexity and project risks

Complexity-driven phenomena are as a whole of four kinds: ambiguity, uncertainty, propagation and chaos. These phenomena are a major source of non-decidability and unpredictability for the project system (meaning that the inability to know what is to happen implies difficulties in decision-making processes). As a consequence, complexity-driven phenomena are a major source of risks for the project. These risks (whether coming from uncertainties, ambiguity, propagation or chaotic phenomena) are to increase project complexity (defined in this work as the property of a project which confers the inability to understand, foresee and keep under control the project's overall behaviour). This leads to the existence of a vicious circle as shown next page in Figure 35.

This circle between the project system universe and the project risk universe is to be attentively kept in mind (as already mentioned in Chapter 2).

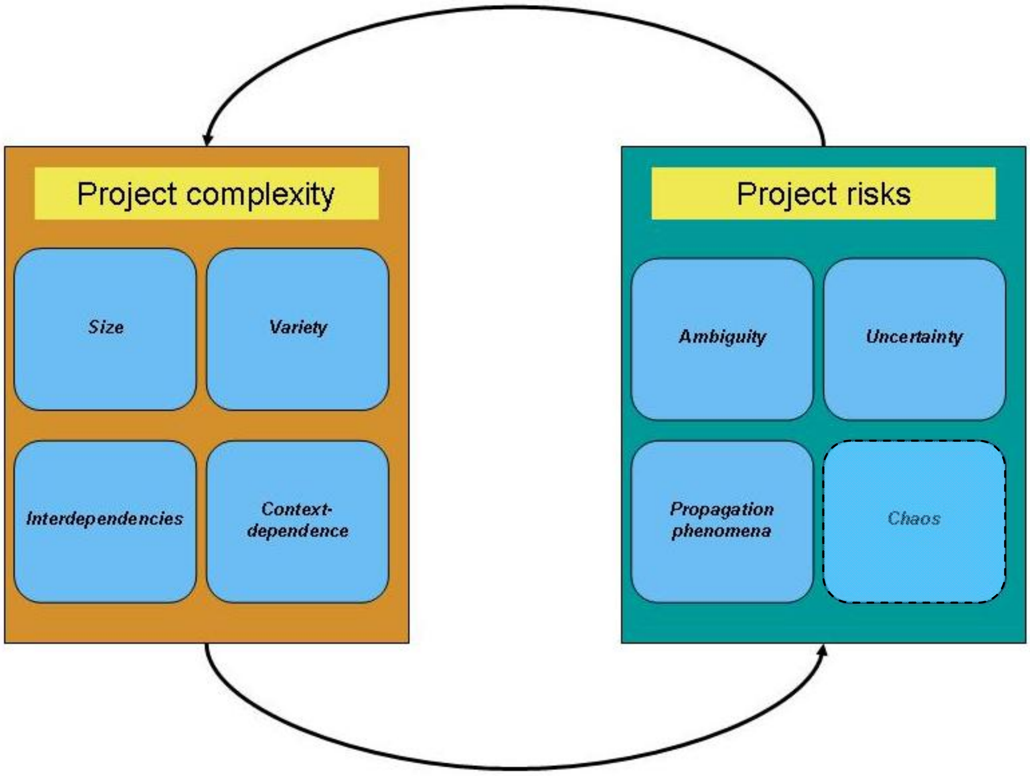

Figure 35. Project complexity and project risks

The point is that the project complexity framework is not sufficient to identify efficiently project risks and to quantify them under complex situations. Notably, there is a crucial need for efficient risk management processes and tools in order to identify and assess those risks. That is why, after defining the concept of project risk, the next section reviews the existing traditional project risk management methods and tools. It also aims at analysing these methodologies regarding complexity, addressing how such methods can or cannot take into account complexity-driven phenomena.

IV.3. Implications on project risk management

IV.3.1. Project risks

Many definitions of project risks can be found in the literature:

- A risk corresponds to the possibility that the objectives of a system regarding a certain goal are not achieved. (Haller, 1976)
- A risk measures the probability and the impact of possible damaging events. (Lowrance, 1976)
- A risk consists in the realisation of a feared event with negative consequences (Rowe, 1977).

- A project risk is the possibility that a project is not executed with conformity to the previsions of end date, budget and requirements, the gaps between previsions and reality being considered as not or moderately acceptable. (Giard, 1991)
- A project risk is the possibility that an event occurs, an event the occurrence of which would imply positive or negative consequences for the project execution (Gourc, 1999)

In this Ph.D. thesis, the definition of the PMBOK (PMI, 2004), which seems to encompass most of the aspects of most of risk definitions, is firstly used for project risk, stating that

Definition
A project risk is defined as an event that, if it occurs, causes either a positive or a negative impact on a project.

This definition underlines two aspects: risk probability and risk impact. In the rest of this Ph.D. thesis, a project positive risk is to be called an opportunity, and a project negative risk is to be called a risk as a simplification. One should keep in mind this semantic simplification. Another important mention is that ambiguity, uncertainty, propagation phenomena and chaos are aggravating conditions for the existence of project risks defined that way.
Finally, before going on, we remind the reader that, because of the property of emergence, complexity can be a source of risks as well as a source of opportunities. The aspect of opportunity seizing is not dealt within this Ph.D. thesis but the reader should undoubtedly keep in mind that complexity is not only a cause of problems. In other terms, no project manager should struggle for complexity reduction: the stake is to properly manage project complexity in order to avoid the negative aspects of it and seize at the same time the opportunities that it creates. For instance, when staffing a project, one should keep in mind some aspects of complexity such as staff quantity (avoiding oversize,…) or staff diversity. Millhiser and Solow indeed explain for example that, in theory, an optimal level of interaction can be reached in order to make the best compromise between opportunity and project risk emergence when facing complex situations (Millhiser and Solow, 2007).

IV.3.2. State of the art on project risk management methodologies

From the birth of project management, the notion of risk has grown within the field of project management, even if there are still lots of theoretical problems and implementation lacks (Gautier, 1991). For all practical purposes, the growing interest in risk management is often pushed by law & regulation evolutions. The society is namely more and more risk averse, and stakeholders are more and more asking for risk management, in order to cover themselves against financial or juridical consequences. People can be accountable during or after the project for safety, security, environmental, commercial or financial issues.

Everybody have to manage their own responsibility and own risks. That is why it has become more and more important to manage effectively and efficiently project risks (Ariyo and al., 2007), in order to give more success warranty and comfort to project stakeholders, or at least to warn them from possible problems or disasters (Cooper and Chapman, 1987).

According to Raz and Hillson, "the origins of operational risk management can be traced to the discipline of safety engineering". Modern risk management has evolved from this concern with physical harm that may occur as a result of improper equipment or operator performance (Raz and Hillson, 2005). Lots of risk management methodologies and associated tools have been developed, with qualitative and/or quantitative approaches, often based on the two concepts of probability and impact (or gravity) of the risky event. As for it, the PMI, in its worldwide standard PMBOK, describes project risk management purpose as "the increase of probability and impact of positive events, and the decrease of probability and impact of negative events" (PMI, 2004). Other processes aim at increasing the success probability.

As a consequence, various risk management methodologies have been developed (Gautier, 1995): some standards have indeed developed risk management methodologies, which are specific or non-specific to project context (IEC, 1995), (AFITEP, 1999), (APM, 2004), (PMI, 2004), (IMPA, 2006), (BSI, 2008). Note that, when non-specific, these methodologies may have been introduced in several fields, like project management, systems analysis, design, insurance, food industry, information systems, chemical systems, industrial safety. A benchmark was done over various risk management methodologies, notably thanks to the exhaustive works of Marle (Marle, 2009). Of course, the question of relevance to project context has been discussed, and the benchmark was only conducted on selected methods. Figure 36 displays the four steps that appear as globally present in most of iterative risk management processes (Marle, 2001), (Pingaud and Gourc, 2003), (PMBOK, 2004), (Ravalison, 2004).

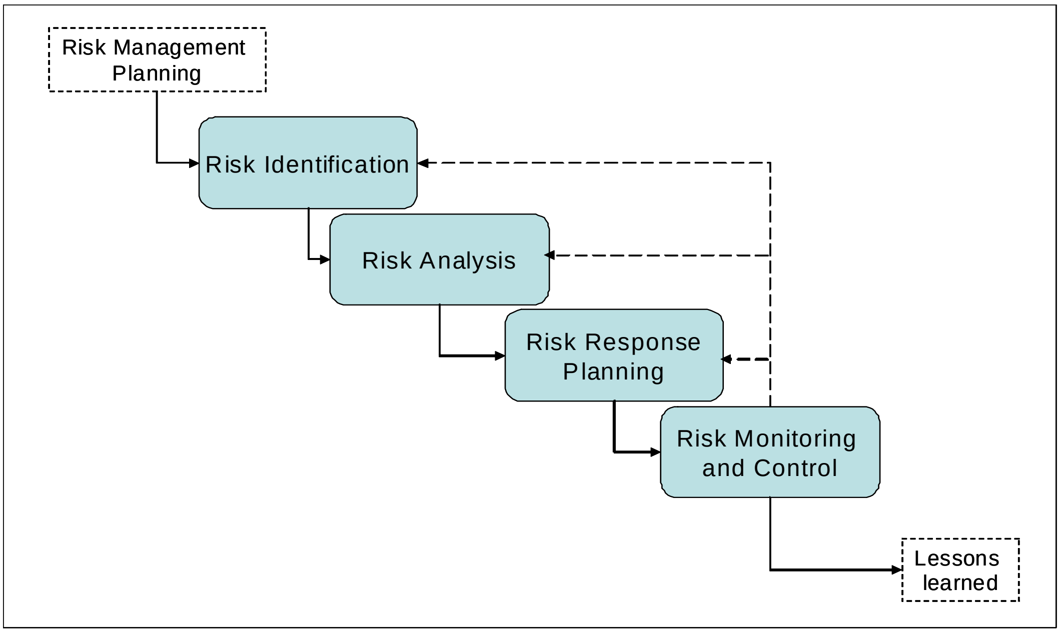

Figure 36. The steps of the project risk management process (adapted from (PMI, 2004))

It must be noted that the steps of risk management planning and lessons learned were not present in every methodology enlightened by the benchmark and were not selected as a consequence.

Moreover, the names of the four steps were not always the same in every methodology and it appeared that some of the steps were sometimes gathered, but the underlying principles and goals remained similar.

This paragraph is therefore organized according to these four general steps of the risk management process. The aim of this necessary preliminary state of the art is to identify the lacks and issues of current project risk management methodologies regarding complexity handling and to define potential research topics which may contribute to eliminate or reduce some of these lacks. The final goal is to bring value to users in projects, project managers, project risk managers, project members and project stakeholders.

IV.3.2.i Project risk identification

Risk identification is the process of determining events which could impact project objectives. Risk identification methods are classified according to two different families: direct and indirect identification of risks. The most classical tools and techniques for direct risk identification are diagnosis and creativity-based methods, meaning that direct identification is mainly performed thanks to expertise:

- The assessment of the present situation relies upon the analysis of its parameters in order to identify areas of risk. An example is systems thinking, which is used to describe exhaustively the studied area of the project, and then to identify potential problems.
- On the contrary, the assessment of the future situation can rely upon the ability that one has to imagine the risks that can affect a project. An example is brainstorming.

Another way to identify risks is to collect data about problems that occurred during previous projects (indirect risk identification, based on experience). Everyone should stay aware that issues of the past are risks of the future. Examples of such methods are the "5 why?" method, Ishikawa diagram, the Pareto diagramming technique or the use of check lists.

The reader should finally note that statistical studies can be conducted, as highlighted in (Gautier, 2004) and that several studies or surveys were carried out to summarize and categorize the most common problems in project management. One of them described the most relevant causes of failure in IT projects (The Standish Group, 2000). Those main causes have been categorized and sorted with a Pareto analysis. It appeared that less than 20% of the causes were responsible for more than 80% of failures. In the end, after risk identification, due to the high number of risks, they are grouped into smaller groups (or clusters) in order to permit practical management (notably for the identification of risk ownership, risk provision, etc…).

Such classification can notably be obtained thanks to the traditional risk breakdown structure, as shown on Figure 37.

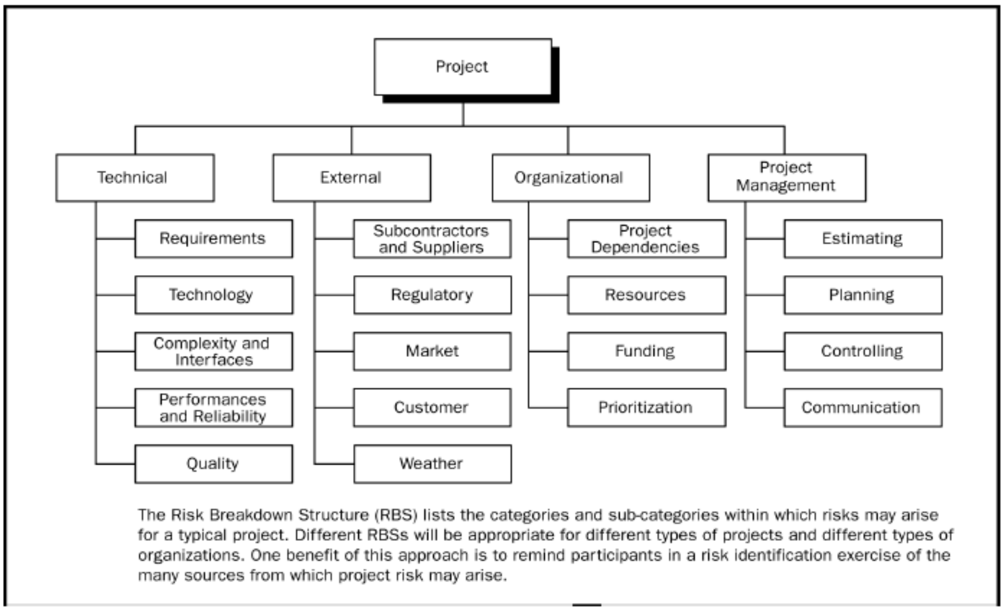

Figure 37. The Risk Breakdown Structure (PMI, 2004)

IV.3.2.ii Project risk analysis

Risk analysis is the process of prioritizing risks, essentially according to their probability and impact. There are two main types of risk analysis, which are discussed hereunder: quantitative and qualitative analysis.

Quantitative risk analysis is notably based on the proper estimation of probability through mathematical models, notably built on former experience. Qualitative risk analysis is the process of assessing by qualitative means the probability (P) and impact (I) of each risk. It assists risk comparison and prioritization. It is notably used when these parameters are difficult to calculate, using scales, like in Figure 38.

Impact (or gravity)			Probability (or likelihood)		
Class	*Name*	*Nature of consequences*	*Class*	*Name*	*Interval of occurrence*
I 1	Minor	No disturbation	P 1	Extremely unlikely	< 0,01 %
I 2	Significant	Project is disturbed / Not known by customer	P 2	Very unlikely	< 5%
I 3	Major	Project is disturbed / Customer upset	P 3	Unlikely	[5%, 25%]
I 4	Critical	Very difficult situation / Customer unsatisfied	P 4	Likely	[25%, 50%]
I 5	Disaster	Project in death hazard	P 5	Very likely	> 50%

Criticality		
Class	*Level of risk*	*Nature of decisions*
C 1	Acceptable	
C 2	Tolerable	Use of margins and reserves. Monitoring.
C 3	Unaffordable	Launch of urgent actions.

Figure 38. Scales to assess project risk probability, impact and criticality

The main risk analysis's output is the risk prioritization, function of their criticality. Criticality is often defined by the product of P and I, but other formulation should be proposed. Indeed, as underlined by Terry Williams (Williams, 1996) who carries out some calculations to prove his vision, "multiplying impact and [probability] to 'rank' risks is misleading, since the correct treatment of the risks requires both dimensions" and probably even some other.

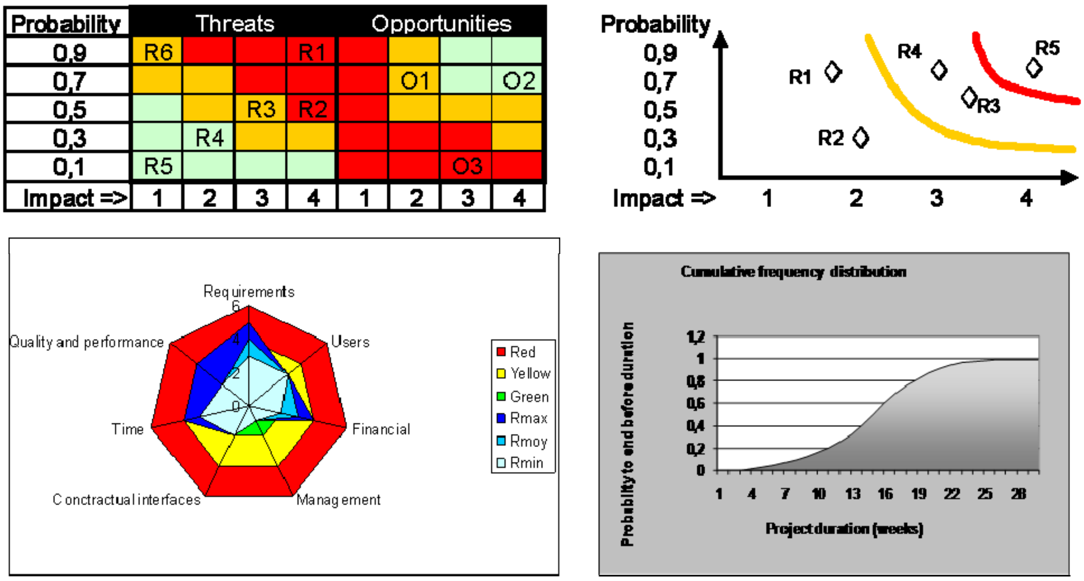

Figure 39. Representations during the risk analysis process (Marle, 2009)

However, the use of criticality permits to define a useful index for risk analysis. Indeed, criticality enables to classify risks into three categories: high risk (red or heavy grey), moderate risk (yellow or middle grey) and low risk (green or light grey). The result has often the shape of a P-I matrix or grid, which uses scales and points out each risk on this P-I graph. Note that other representations (Farmer diagrams, Kiviat graphs,…) may be drawn at this stage, as shown before in Figure 39.

IV.3.2.iii Project risk response planning

The process of risk response planning aims to choose actions in order to reduce global risk exposure at least cost. It addresses project risks by priority, defining actions and resources, associated with time and cost parameters. Almost every method mentions the same possible treatment strategies, including the following:

- Avoidance
- Probability or impact reduction (mitigation), including contingency planning
- Transfer, including subcontracting and insurance buying
- Acceptance

The aim is the same that in project planning: how to define actions that will reach the assigned targets under constraints? The only difference is that in risk management process, the targets are to reduce threats and to enhance opportunities. The final goal is the same as project management process: to reach project objectives with the maximum probability of success. So, estimation techniques, like analogous, parametric and bottom-up techniques may be used, and the important parameter is to measure action effectiveness, that is to say risk reduction induced by action success.

IV.3.2.iv Project risk monitoring and control

Risk monitoring and control is according to PMBOK the ongoing process of "identifying, analysing and planning for newly arising risks, keeping track of the identified risks and those on the watchlist, reanalyzing existing risks, monitoring trigger conditions for contingency plans, monitoring residual risks, and reviewing the execution of risks responses while evaluating their effectiveness" (PMI, 2004). It includes five classical tools:

- Risk reassessment: for new risks or for refinement of existing assessments,
- Risk audit: return on investment on the global risk management process,
- Variance and trend analysis : deviations from project plan may indicate potential threats for the project,
- Technical performance measurement: deviations from planned scope may indicate potential threats for future delivery and client acceptance,
- Reserve analysis: use of planned contingency reserves is tracked, in order to estimate the adequation between remaining reserves and remaining risks.

IV.3.3. Critical analysis of these methods and tools

IV.3.3.i Overall synthesis of the methods

When analysing the different methodologies and tools that presently exist within the context of project management, one can wonder how they permit to handle complexity-driven issues. Indeed, efficient project risk methodologies should permit the integration of complexity aspects (and it is all the more true for modern projects, the complexity of which is ever-growing).

IV.3.3.ii Issues regarding project risk identification

When performing risk identification, issues related to project ambiguity do appear as complexity-driven lack of awareness is to decrease the performance of risk identification.

First, exhaustiveness is definitely impossible to obtain. Ambiguity cannot permit exhaustiveness. Furthermore, the project context is likely to change, and new risks can occur although they were not identifiable when first identification took place. As a consequence, exhaustiveness is never warranted by any method, even though the identification can be facilitated by previous lessons learned.

Moreover, a first classification of risks is performed during the risk identification process. Classifying risks by nature, by causes, or by consequences, or by time location are valuable alternatives which are difficult to compare. The point is that project risks are in essence multi-criteria (Gourc, 2006) since they are related to several factors, project values, etc... But traditional methodologies fail in underlining these aspects and one tends to classify risks notably according to traditional classifications (the ones just expressed before). Choosing between these alternatives depends on the structure of the organization and of the project, on the risk management policy in the organization and on the ownership of risks. The choice of one of them is all the more difficult to do since ambiguity implies different visions within the project team.

But it is known that the classification method is likely to have an impact on the manner risks will be addressed among the other phases of the risk management process. The point is that, whatever the classification chosen, the traditional ways of grouping risks (even by criticality values) does not permit to handle properly project complexity as shown by Figure 40 next page. Risks are indeed mainly considered and identified as independent. But, for projects are complex, the project risks set is also complex since projects risks are interrelated too. Chain reactions and the butterfly effect are notably possible effects of complexity on project risks, due to propagation phenomena. To the best of our knowledge, no traditional methodology has been widely implemented and used to identify these phenomena.

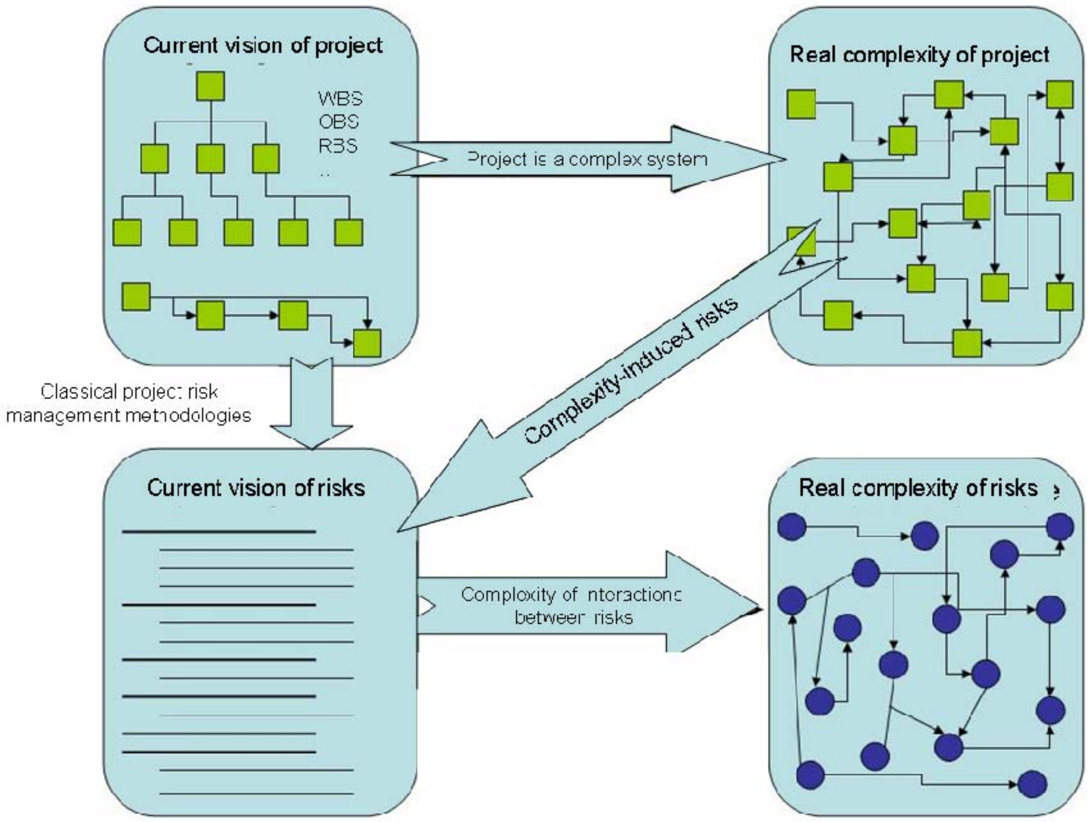

Figure 40. Current visions versus reality regarding project complexity and risks

IV.3.3.iii Issues regarding project risk analysis

This is also the point when trying to analyse risks and propagation phenomena. As far as we know, no traditional method can permit a global analysis of the risk propagation phenomena. And this, even though these phenomena may dramatically alter the rankings obtained since traditional analysis processes "ignore potentially relevant information about the spread of possible impacts" for instance (Ward, 1999). For all practical purposes, in the end, some risks that are traditionally neglected by current methodologies (because for instance, they have a very low impact) should not be neglected since they may be the root origin of more critical risks.

Some existing methods such as Bayesian networks (Ben-Gal, 2007) permit to underline to some extent propagation phenomena when performing a risk analysis. However, they do not permit to take into account feedback loops as one of the strong hypotheses of Bayesian networks is to work on directed acyclic graphs. Other methodologies such as Markov chains can permit to handle part of propagation phenomena. But such methods may appear as non-intuitive and non-user-friendly for industrial practitioners. Moreover, they do not permit a practical implementation of management modes which would handle risks in terms of their interactions. Finally, such methods are to be taken with caution, due to difficulty to manipulate the theoretical concept of probability when dealing with project risks, since references to the past are harder to do (Gourc, 2006) and conceptual limitations do exist, as underlined in (Pender, 2001).

Furthermore, ambiguity is also present in this step since the classical evaluation based on gravity or probability can generally be discussed regarding ambiguity. Indeed, gravity and probability appear to be subjective concepts, as the one of project risk: cultural phenomena, number of former experiences, the individual or group realisation of the analysis for instance influence the results of the risk analysis process (Gourc, 2006). To the best of our knowledge, apart the fact of dealing with confidence intervals or fuzzy numbers, no traditional risk analysis tool includes this ambiguity aspect.

IV.3.3.iv Issues regarding project risk response planning, monitoring and control

The two last steps of the risk management process also have lacks in terms of complexity integration. Indeed, uncertainty is not always considered in risk response planning methodologies. Uncertainty implies difficulty in the preparation of the preventive and curative plans. Uncertainty implies actions, which are themselves uncertain, and as a whole, "uncertainty will not necessarily diminish over time" (Jaafari, 2001). Moreover, some actions may affect several risks, and some risks may require several actions, which makes it even more difficult to estimate the relative contribution of each action for each risk.

Furthermore, chaos is to have influence on the efficiency of the response plan. Indeed, for instance, if some errors are made in the analysis and planning processes, it may have dramatic consequences during the decision process. The sensitive dependence on initial conditions implies that the even little differences in the decisions made during the risk response planning step may imply important difficulties.

Moreover, ambiguity implies difficulty when carrying out the project risk monitoring and control step (for the same reasons as in the risk identification step), making the process also subjective. In the end, project systems try to reduce subjectivity by expressing, monitoring and controlling the impact of risks on few limited scales (and especially the financial one), which does not permit to encompass the multicriteria nature of project risks (Gourc, 2006).

Finally, even though people and organizations tend to be more and more risk averse, risk management methodologies are still not so efficiently and effectively implemented, notably because of ambiguity and the lack of implication of management teams. Risk management is still too often considered as a waste of time and money, since working on potential events dose not permit to see directly the practical effects of such a work. And as a whole, even though "the need for project risk management has been widely recognized" (Williams, 1995), there is still some difficulty when trying to implement it properly in fieldwork.

IV.4. Conclusion : proposing research issues to integrate complexity aspects into project risk management processes

As a whole, project risk management methodologies have shown some limits and can not completely face the actual stakes any more, including the increase of project complexity:

- More and more parameters are to be taken into account, including safety, environment, health, ethics, ...
- More and more stakeholders are involved, which increases project complexity.

Even though traditional methods and tools are undoubtedly useful, there is therefore a need to find something else than rigid "plan and control" principles, in order to integrate the non-predictability of future and the non-rationality inherent to every human activity, especially decision-making and teamwork.

It is therefore needed to give a complementary point of view to the belief that managers face an objective reality that they can control by being rational technicians, dealing with issues that are resolvable through the application of planning and control techniques. This positivist statement of what project management is does not tell much about day-to-day reality, which is often messy, ambiguous, fragmented and political (Alvesson and Deetz, 2000).

Risk management methodologies have indeed been built on this overall principle of "plan and control" applied to risks. But it involves that new complementary approaches (notably based on systems thinking principles) should be considered as some theoretical problems are not yet solved, notably due to difficulties in the identification and analysis processes, as shown in IV.3.3. We thus propose research issues regarding two lacks of risk management identification and analysis processes due to complexity-driven phenomena.

IV.4.1 Project ambiguity : increasing one's awareness

One of the main limitations which is highlighted is that traditional project risk management methodologies do not permit to handle complexity-driven ambiguity. However, as shown by IV.4.3., this is all the more important since ambiguity has consequences in every step of the risk management process. Basically, complexity-driven ambiguity generates a lack of awareness and a lack of common and shared vision of what the project system and the project risks are.

In order to reduce this ambiguity, Chapter V proposes a systemic approach to integrate complexity aspects into the project risk management process. Based on the principle of systems thinking and the existence of values creations processes within a project, this chapter introduces the concept of project vulnerability.

This concept and the associated model first permits to consider the multiple impacts of events, thanks to the correct consideration of project values. Moreover, it permits to focus on the project system constituting elements instead of focusing on risks, which are sometimes difficult to communicate on. As a whole, we hope that it permits to draw the analysis by the final objectives (values creation), making vulnerability identification and analysis a more tangible process for project team members, instead of working on potential events. We claim that this systemic approach permits to reduce ambiguity by increasing both the awareness of the project system components and risks (including the multiple impacts of them), and the sharing of a common vision of these aspects.

IV.4.2 Project propagation phenomena: understanding them better

As noticed before, very few project risk management day-to-day methodologies permit to take into account propagation phenomena. Particularly, no traditional classification methodology permits to integrate this risk interaction aspect. As a consequence, when project risks are gathered in groups (in terms of nature or criticality value for instance), no focus on possible risk interactions and thus interactions between groups is proposed. In other terms, once an exhaustive project risk list is made, there would still be some work to be done to identify and assess the risk of a propagation of one of this identified risk within the project system (as well as the underlying risk of positive feedback and amplification through the system).

Even though not performed traditionally, this would be all the more relevant since the initial classification influences decisions (such as risk ownership) and implies how risks may be analysed, cured and controlled. Without including this interaction aspect, two connected risks may belong to different groups (for instance a technical risk which implies a financial one, or a low-criticality risk which generates a high-criticality one). Neglecting these interactions may have dramatic consequences in terms of project risk management and coordination.

Chapter 6 is then to propose an innovative analytic approach to integrate complexity aspects into the project risk management process. The first objective of this chapter will be to identify properly project risk interactions and possible propagation phenomena within the project risk network. The second objective of this chapter will be to cluster project risks into groups which have a maximum amount of possible risk interactions inside of them in order to facilitate project coordination in the end.

Chapter V.

A systems thinking-based approach – From project risk management to project vulnerability management

Abstract

The overall ambition of this chapter is to try to reduce ambiguity by proposing a paradigm shift from project risk management to project vulnerability management. By focusing on project vulnerabilities, i.e. weaknesses, this research work proposes to follow a systems thinking approach in order to describe the possible damage creation processes.

After reviewing the existing literature on the concept of vulnerability, this chapter aims at proposing a definition for project vulnerability. It claims for the use of a systems thinking approach to identify and understand project vulnerabilities, since it stresses that vulnerabilities are to be linked with project values. Indeed, values which can be at stake are necessary for vulnerabilities to exist.

This chapter then proposes a description of the project vulnerability management process and compares it with the traditional project risk management process in order to highlight the potential benefits of such a new approach. It also proposes a model/methodology to analyse project vulnerabilities by decomposing project vulnerabilities into three levels: values, processes and project elements. A stressor/receptor analogy-based model is then the basis to identify and evaluate project vulnerabilities. A simple cruciality index then aggregates the concepts of resistance, resilience and contribution to values creation in order to rank project vulnerabilities to assist decision-making.Finally, an industrial application is proposed by addressing the case of a software development project in the context of the pharmaceutical industry.

Chapter Keywords

Project, Risk, System, Values, Damage, Event, Vulnerability.

V.1. Introduction – Using a systemic approach to assist project risk management

Following a systemic approach when coping with project risk management in order to address the question of potential damages during a project permits to reduce ambiguity by increasing the awareness of the project system. By increasing awareness, we aim at:

- Concentrating on a systems-thinking based view in order to highlight the damageable values of the project and identify the potentially endangered processes and elements of the project system.
- Focusing therefore on the systems elements in order facilitate the identification and analysis of potential negative events and damages on the system.

As recent works or communications state it (Zhang, 2007), (EPM, 2007) the concept of vulnerability therefore appears to be an innovative and promising concept for efficient risk management, notably within the context of project management. Indeed, it enables to have a more systems-oriented vision than the traditional cindynics approach which focuses on the evaluation of risks (notably their probability), instead of focusing on the tangible weaknesses of a system. However, little work has been done on this concept, particularly in the contexts of industrial engineering and project management, even though exploring vulnerabilities may permit to underline and heal the existing weaknesses of a given project.

PROBLEM SETTING OF THIS CHAPTER

That is why this chapter aims at addressing the concept of project vulnerability by

- Carrying out a broad state of the art, in many scientific domains, to understand what the concept of vulnerability is in order to implement it in the context of project management.
- Defining project vulnerability and its characteristics in order to understand better the potential process of damage creation during a project.
- Permitting the identification of project vulnerabilities thanks to a systems thinking approach focusing on the potential degradation of the project values creation processes.
- Describing the steps of a project vulnerability management process in order to permit the industrial application of the concept of vulnerability in projects.
- Testing the whole approach on a case study.

V.2. The concept of project vulnerability

V.2.1. State of the art on the concept of vulnerability

Etymologically, the word *vulnerable* comes from the Late Latin *vulnerare*, which means "to wound". As for the Collins English Dictionary and Thesaurus, being vulnerable means either being "capable of being physically or emotionally injured, wounded or hurt", either being "open to temptation, persuasion, censure, etc.", or being "liable or exposed to disease, disaster, etc.". A reference to the military vocabulary is also made as being vulnerable is also defined in this context as being "liable or exposed to attack". Synonyms of *vulnerable* are for instance accessible, assailable, defenceless, exposed, open to attack, sensitive, susceptible, tender, thin-skinned, unprotected, weak, wide open, etc… Even though the words *vulnerable* or *invulnerable* are thus commonly used in everyday life, little insight has been given to the concept of vulnerability within the field of industrial engineering, project (risk) management, and management science. This paragraph aims at drawing a state of the art on the concept of vulnerability before extending it to project management.

Topic	Total	Global matter of interest	Number of articles
Health	269	*Psychology and psychiatry (and behaviour factors)*	91
		Disease factors	85
		Genetics	27
		Response to treatment	21
		Disease transmission	14
		Diagnosis fiability	12
		Global organs fragility	10
		Healthcare management	9
		Morbidity factors and evaluation	4
Climatology and sustainable development	193	*Reaction of biological entities to environmental stresses and biodiversity*	38
		Ethics and social development	36
		Groundwaters , soils and source waters pollution	35
		Environmental management	26
		Warming and climate change	25
		Earthquakes and landslides	15
		Floods and tsunamis	11
		Storms, cyclones and rainfalls	5
		Volcano eruptions and fires	2
		Wind	1
Information technology	24	*Communication and information networks security*	11
		Software failure	7
		Information systems management	6
Military strategy and defence	13	*Response to attacks (terrorism,…)*	8
		Geopolotics and geostrategy	3
		Military strategy	2
Industrial engineering	11	*Industrial systems security*	4
		Knowledge management	3
		Production management	2
		Innovation management	1
		Logistics	1
		Project management	0
Construction and urbanism	11	*Urban networks security*	7
		Structure resistance	4
Economics	4	*Macroeconomics*	3
		Microeconomics	1
Physics	4	*Nuclear science*	1
		Chaos	1
		Electromagnetism	1
		Materials resistance	1
Applied mathematics	4	*Networks and graphs*	2
		Insurance modelling	2
Chemistry	1	*Chemical reaction*	1
Total	534		

Figure 41. Occurrences of the word *vulnerability* in the Web of Science publications in 2007

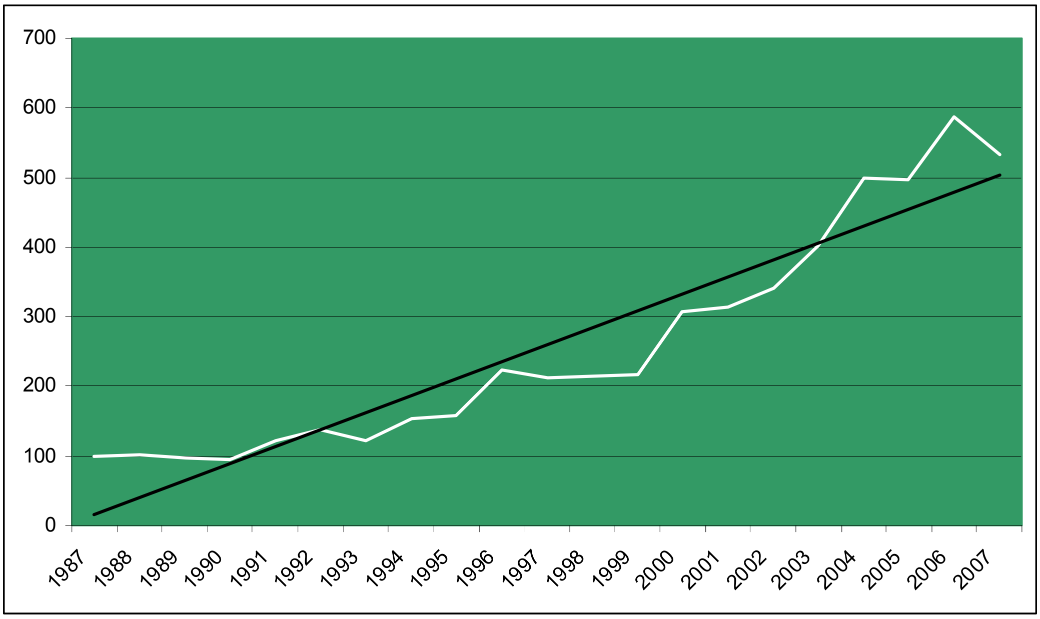

Figure 42. Web of Science publications the title of which contains the word *vulnerability* (1987-2007)

As an illustration of the interest of the present research community for the notion of vulnerability in different scientific fields, we carried out a review and classification of the 2007 Web of Science publications which mentioned the world *vulnerability* in their title (see Figure 41). 534 such publications were identified, which underlines the global interest of the scientific community for this concept. It must be noted that vulnerability seems to meet a growing interest in the scientific community as shown on Figure 42.

Some conclusions appear to be interesting, even at a first reading of this short survey of the Web of Science. First, two scientific topics (health, climatology and sustainable development) tend to appear as major contributors to research works using or developing the concept of vulnerability, since a Pareto law can approximately be observed (those two fields represent 20% of the identified fields and correspond to 86% of the identified publications). Figure 43 shows the ten most important matters of interest and research in terms of contribution to the vulnerability concept: they do all belong to the hereinbefore cited topics.

Moreover, this survey also enlightens the lack of use and study of the concept of vulnerability in the field of industrial engineering (only 11 publications out of 534; i.e. 2%), and particularly regarding project management (0 identified publications in the Web of Science), which motivates even more to work on this concept in accordance with project management principles.

The state of the art which was carried out on the concept vulnerability is obviously not using the Web of Science publications solely. But following the general trends of this short survey, the following state of the art is firstly carried out separately on the two most contributing topics: health, climatology and sustainable development. Finally, it focuses on some works about vulnerability in the fields of industrial engineering and project management.

Psychology and psychiatry (and behaviour factors)	91
Disease factors	85
Reaction of biological entities to environmental stresses and biodiversity	38
Ethics and social development	36
Groundwaters , soils and source waters pollution	35
Genetics	27
Environmental management	26
Warming and climate change	25
Response to treatment	21
Earthquakes and landslides	15

Health
Climatology and sustainable development

Figure 43. The 10 most important matters of interest for research around the concept of vulnerability in 2007 Web of Science publications.

V.2.1.i Health

As underlined by the short survey previously presented, research works within the field of health are major contributors to works and breakthroughs around the notion of vulnerability. “From a health perspective, vulnerability refers to the likelihood of experiencing poor health and is determined by a convergence of predisposing, enabling, and need characteristics at both individual and ecological levels” (Shi, 2001). Its study can be assisted by the determination for vulnerable groups or populations. The specific field of psychiatry is notably dealing with this notion, notably when considering post-traumatic effects. Considering psychiatry, the particular example of schizophrenia has been widely studied, notably by Strauss (Strauss, 1997), who followed a phenomenological approach to study it by proposing an analysis of one’s daily life to highlight the complex relations between the various factors and interactions which exist between the patient and its disorder. These works permit to underline the context-dependence of the concept of vulnerability, underlining notably that it evolves over time and that vulnerability perception differs from one to another.

On her side, Ezard (Ezard, 2001) calls for vulnerability reduction instead of risk reduction in the case of drug use and addiction vulnerability of individuals and groups. She explores vulnerability as a characteristic which “”incorporates the complex of underlying factors that promotes harmful outcomes as a result of drug use, and limits attempts to modify drug use to make harmful outcomes less likely”. She stresses that “vulnerability factors arise out of and are reinforced by past and present social **context** and experience”, insisting also on the influence of context and historicity. She explains (thanks to an analogy, which is that vulnerability is to risk what acceleration is to velocity) that “changes in vulnerability will determine changes in risk” as vulnerability determines risk. Her claim for a shift of management towards vulnerability reduction is explained thanks to a better depiction of the complex phenomena that cause vulnerability, and risk in the end. Complexity notably appears when considering exposure and responses as different stressors can interact and influence the global exposure of an individual or a group (Burkart and al., 1998). Some works focus on vulnerability in terms of patients’ responses in terms of **resistance** and **resilience**, that is to say how individuals or groups can resist to vulnerability (instantly or when recovering), notably thanks to healthcare. For instance, more illness resistance and faster recovering can be observed if the healthcare system resources are properly managed in terms of availability at any time (Perry and al., 2006).

V.2.1.ii Climatology and sustainable development

A close look at some research works around the notion of vulnerability within the field of climatology and sustainable development is now given. It must be noted that one of the most widely used definitions of vulnerability we found during our broad state of the art comes from a this field. This one is the definition proposed in the early 1980s by Chambers (Chambers, 1983): vulnerability is "the exposure to contingencies and stress, and difficulty coping with them. Vulnerability has thus two sides: an external side of risk, shocks and stress to which an individual or household is subject; and an internal side which is defencelessness, meaning a lack of means to cope without damaging loss".

Many definitions, such as the one in (Luers and al., 2003), only consider the aspect of incapacity to cope with the shocks and stresses: in this work, vulnerability is for instance defined as "the degree to which human and environmental systems are likely to experience harm due to a perturbation or stress". In their works, Waits and Bohle (Waits and al. 1993) add another side to vulnerability as they consider three aspects of this notion: exposure to crisis situations, incapacity to cope with these situations (and the reach objectives of life standards for instance) because of a lack of resources, potentiality of serious consequences to occur as a result of the crises (which can notably be characterized in terms of slow recovery).

Blaikie and al. (Blaikie and al., 1994) also define vulnerability, in respect of natural hazards, as "a measure of a person or group's exposure to the effects of a natural hazard, including the degree to which they can recover from the impact of that event". But as noticed in (Dibben and Chester, 1999), "there is a problem in defining vulnerability in terms of recovery per se. This is because it can be argued that a group who are poor before [a natural hazard], and whose recovery is likely to be back to the same level of poverty, are not vulnerable and a wealthy individual, who will lose much, but will still be better off than his or her neighbours, is vulnerable". The vulnerability of an element should then include more the core characteristics that can describe it.

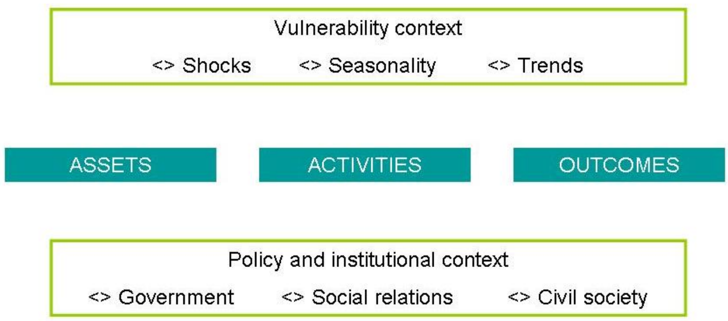

Figure 44. Vulnerability based on assets, activities and outcomes given a specific context (Ellis, 2003)

Another characterisation, based on the works of Scoones (Scoones, 1998) and Ellis (Ellis, 2000) is proposed in (Ellis, 2003), regarding the issue of human vulnerability and food insecurity in southern Africa. This one is exposed before in Figure 44. The assets, activities and outcomes that are associated when constructing robust, viable and sustainable livelihoods are to be studied in accordance with both the vulnerability and the institutional context. All those notions appear to be interrelated and, similarly, the vulnerability context should be considered regarding the assets, activities and outcomes that do exist in a specific policy and institutional context. This gives another grid to have a look at the concept of vulnerability and is to be kept in mind as the description in terms of assets, activities and outcomes may have similarities with the description of a project through **systems thinking**.

For his part, Maskrey (Maskrey, 1989) notices that "natural disasters are generally considered a coincidence between natural hazards (such as floods, cyclones, earthquakes and drought) and conditions of vulnerability. There is a high risk of disaster when one or more natural hazards occur in a vulnerable situation". This expresses that damages (turned out consequences of risks) can be understood as the coincidence between a dangerous event and a vulnerable ground. This vulnerable ground is in essence context-dependent, as stressed in many research works in this field: the balance of political power, the specific culture/context of societies and ethnic groups, economic constraints, spatial or political constraints, etc. are notably context factors that do have a clear influence on vulnerability regarding climate and sustainable development issues.

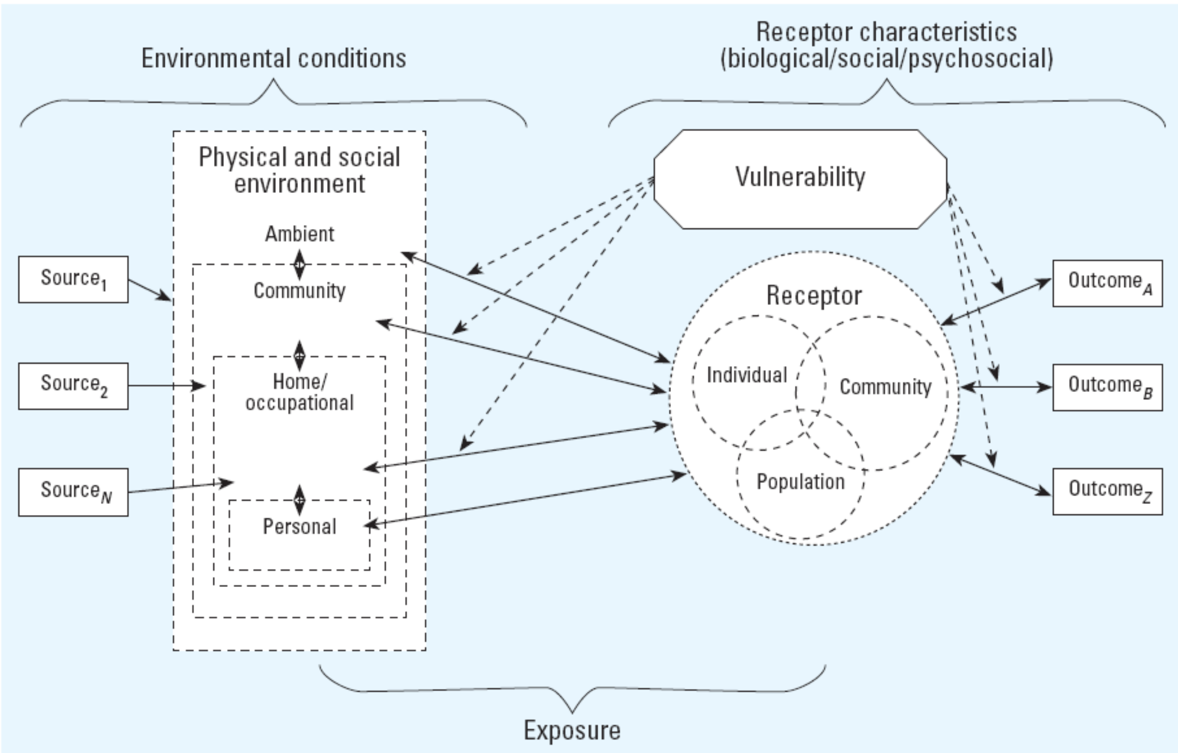

Figure 45. Vulnerability study thanks to a stressor/receptor model (de Fur and al., 2007)

Vulnerability is then highlighted thanks to the possible interaction between these stressors and these receptors (which corresponds to some extent to exposure), but also thanks to the possible reaction and adaptation of the receptors regarding the outcomes (basic needs, etc.) the population aims at achieving. However, Luers ans al. (Luers and al., 2003) explain tat "developing measures of vulnerability is complicated by the lack of consensus on the exact meaning of the term, the complexity of the systems analyzed, and the fact that vulnerability is not a directly observable phenomenon". For instance, approaches to the assessment of vulnerability to climate variability and change are studied by Kelly and Adger (Kelly and Adger, 2005). The approaches are compared according to their own definition of vulnerability which is "the capacity of individuals and social groups to respond to, that is, to cope with, recover from or adapt to any external stress placed on their livelihoods and well-beings". Assessing vulnerability is thus assessing a capacity to respond to occurring stresses which are likely to degrade some objective functions, which are in this case livelihoods and well-beings. Following the process of assessment, intervention should be done by encouraging a process of adaptation mixing both the characteristics of the vulnerable ground and the objective functions, notably by reinforcing, modifying or offsetting "trends in the factors that limit or enhance vulnerability as they emerge" and assessing them particularly in terms of resources availability. Vulnerability permits to identify tangible weaknesses of a population, a geographical zone, a natural system, etc… but is perhaps more difficult than risk to assess as it implies the consideration of numerous interrelated factors.

V.2.1.iii Industrial engineering and project management

Even though few works around the concept of vulnerability seem to be in the field of industrial engineering, some of them can highlight us for our works to develop the concept of project vulnerability. Charles Perrow (Perrow, 1984) states that the concept of zero risk in industrial systems is a chimera. Indeed, as he notices, since complex systems are in essence unpredictable and are operating thanks to a large number of interrelated objects, accidents appear to be inevitable structural elements of them. This issue is also stressed by Theys (Theys, 1987) since "the conjunction of uncertainty and vulnerability (and their destabilizing consequences) puts one in front of unacceptable dilemmas". As a consequence, the notion of risks and vulnerability should be unavoidable points to focus on when managing projects. Yet, Theys (Theys 1987) underlines that "there are still too few languages and tools for analysing vulnerability", which motivates to develop such languages and tools.

Some attempts were already done in the past. For instance, David and Marija Bogataj (Bogataj and Bogataj, 2007) try to measure the supply chain risk and vulnerability. They consider the risk in a supply chain as "the potential variation of outcomes that influence the decrease of value added at any activity cell in a chain, where the outcome is described by the volume and quality of goods in any location and time in a supply chain flow", explaining that "due to their complexity, the total added value of all activities is […] the result of exposure to different kinds of risk". As a consequence, they do place the notion of vulnerability at the centre of value creation, since value can be degraded because of exposure to risks and incapacity to cope with them. They then explore the notion of supply chain vulnerability by defining a typology of risks that a supply chain can encounter. This typology is then the basis for a vulnerability and risk model which can assist supply chain management.

As for him, Tomas Hellström (Hellström, 2007) considers the issue of critical infrastructure and systemic vulnerability. The article explores an analytical planning framework for identifying, formulating and mitigating vulnerability in critical infrastructures. As he notices, "because vulnerability has often been regarded as a property, and not as an outcome of social relations and technological systems, the concept is easier to deal with than that of risk, as it does not exclusively emphasize a future, or counterfactual state of affairs, but also, and perhaps most obviously, certain qualities of a system in the here and now". Dealing with vulnerability means thus dealing with a system in its systemic whole, that is to say with its complexity. Hellström then proposes a model adapted form the PAR (pressure-and-release) model of Blaikie and al. (Blaikie and al., 2001), which tries to express the complex dynamics of a system's vulnerability.

Within the same matter of reliability engineering and system safety, Aven (Aven, 2007) tries to elaborate a framework for risk and vulnerability analysis which could cover both security and safety. Some management pieces of advice are then given, knowing that risk should be viewed as the combination of sources of uncertainties and vulnerability (and its possible consequences related to the sources of uncertainties).

Moreover, the works of Durand (Durand, 2007) around the notions of organisational risks and vulnerabilities appear to be interesting. Through a systems approach based of the well-known works of Michael Porter, he defines vulnerability as the "extent to which an organisation is able or not to cope with the dangers it is exposed to", explaining that the notion of vulnerability permits to focus on an organisation's ability to resist to hazards and on the mechanisms that can weaken its overall functioning, behaviour and evolution. A model is then developed to assist vulnerabilities identification and is notably based on three dimensions of systems thinking: functional pole, ontological pole and genetic pole, which enables him to elaborate a typology of organisational and managerial vulnerabilities. The whole approach stresses how things should be drawn by the **values creation** processes of the project, which is in accordance with (Simon, 1981) or (Schneider, 2008), which underline the fact that possibly damaging events should be handled in accordance with their possible impact on the core values of a project (or a system).

V.2.2. Synthesis of the characteristics of vulnerability

As a synthesis of the former paragraph, before going on, we propose to list down the principal characteristics of vulnerability which can be synthesised after our state of the art.

- Vulnerability is in essence relative to a system which has weaknesses (regarding its objective values) which can alter its trajectory to reach its objectives.

- Vulnerability corresponds to **coexistence** of a level of exposure (or a susceptibility to be exposed) to stressors and a non-capacity level to cope with these stressors.
- Two aspects of the system's non-capacity are to be underlined
  - Static vision: **Resistance** of the system regarding the apparition of the stressor.
  - Dynamic vision: **Resilience** of the stressor corresponding to the recovering of the system.
- A system's vulnerability is in essence context-dependent and evolves over time, notably because of the changes over time in the systems' characteristics due to the natural evolution of the project system, notably in terms of its **objective values**.

Each of this aspect is therefore to be present in the definition of project vulnerability or/and its associated models and tools.

V.2.3. Defining the concept of project vulnerability

Before, defining properly the concept of project vulnerability, other concepts are to be properly defined (even though they might have been used before for practical purposes throughout this Ph.D. thesis).

First, let us define the concept of event regarding a project system. As an illustration to explain this concept, we might consider the daily life of anyone. A rainy weather is an event for any worker who goes back to home after work: it can appear to be a danger a the worker who goes to home by foot as he may get wet, but it can appear to be an opportunity for another one who plans to go fishing after work and who knows that fish catches tend to be better when it is rainy. This means that events can be considered as negative (dangers, threats, attacks, etc.) or positive (opportunities,…), depending on the points of view of what this event influences. As a consequence, that is why in this thesis, we generally speak of events, without expressing any opinion on their positive or negative influence, unless it is clearly mentioned.

Definition : An **event** regarding a project system is something occurring in a project or in its environment and that is likely to have an influence on them.

Events regarding a project system can be classified thanks to another typology due to the following property. As a whole, we can deal with:

- Negative events: Events which are likely to degrade at least one of the project system's created values.
- Positive events: Events which are likely to upgrade at least one of the project system's created values.

It must be noted that an event can be both positive and negative, as it can degrade some value creation of the project, but upgrade some other. This notion can now be linked with the concept of project risk. Indeed, given a risk, the triggering event corresponding to it finds (within the project system) a ground that is susceptible to let the influence of the event express itself. In other terms, a risk is the coexistence possibility of a triggering event and a susceptible ground which is sensitive to it (see Figure 46). This coexistence has notably been enlightened by the works of Durand (Durand, 2007), as mentioned before. Coexistence implies in essence an aspect of temporality. If an event occurs when the project is not sensitive to it, then it will not turn into a risk (positive or negative). Risk needs vulnerability to exist for all practical purposes.

Property : A project risk is the expression of an **impact** regarding the project system due to the **coexistence possibility** of a triggering event regarding the project system and a state of the project system that is sensitive to this event (susceptible to let it express).

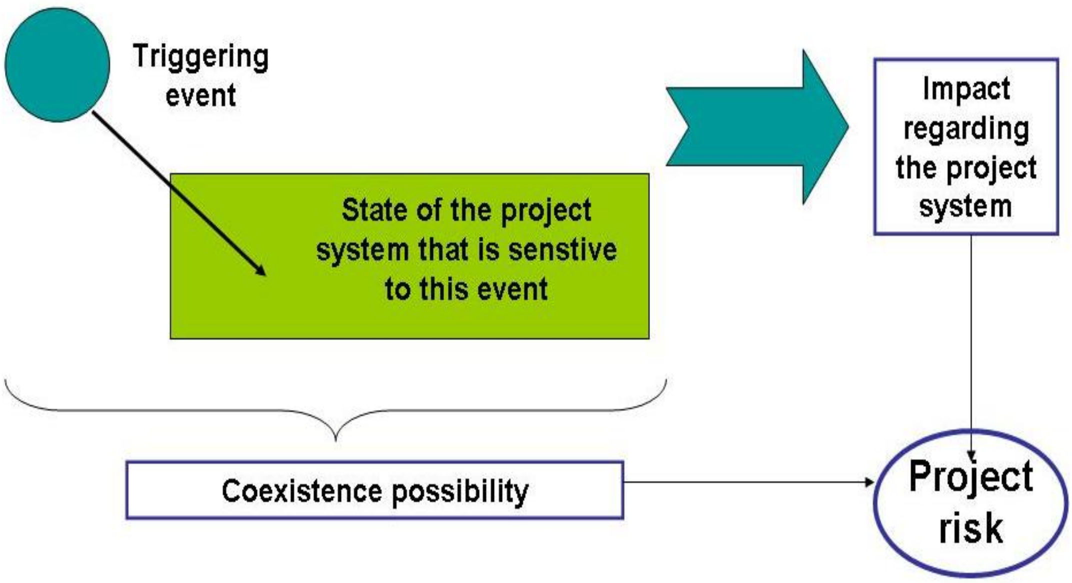

Figure 46. Project risk as an impact due to coexistence

These concepts being explained, we can wonder why a state of the project is likely to be sensitive to an event. From now on, we will focus in this thesis on negative events. That is where we introduce the notion of project vulnerability. It should be stressed that similar studies are likely to be done on positive events, exploring thus the issue of opportunity seizing in projects.

We now propose a definition of the concept of project vulnerability and discuss it, notably thanks to the state of the art we presented above. Our state of the art presented notably two important aspects we rely on to elaborate our definition and build our frameworks and tools: exposure and incapacity.

Definition : **Project vulnerability** is the characteristic of a project which makes it susceptible to be subject to negative events and, if occurring, which makes it non capable to cope with them, which may in the end allow them to degrade the project performances.

This definition includes three important aspects:

- Project susceptibility to be subject to negative events
- Project non capability to cope with negative events when occurring, which includes *non-resistance* (instantaneous damages) and *resilience* (recovery over time)
- Relationships with project values creation degradation.

This definition is instantly followed by a property which is to be noticed.

Property : Project vulnerability exists **if and only if** project susceptibility to be subject to negative events and project non capability to cope with them if occurring coexist, i.e. if and only if they simultaneously exist at a given time.

To illustrate this property, we can consider an analogy with health. Let us consider a patient which has no more or a very weak immune system (non capability of coping with viruses, bacteria, etc. if he is in contact with them): he cannot be considered as vulnerable if the medical team decides to confine him in a sterile room (as he is no more subject to, i.e. in contact with, viruses, bacteria, etc.). Let us now consider a human being whose immune system is strong and who received protection against influenza thanks to vaccination: as this human being has an even more strengthened immune system which is very resistant to the influenza virus (very good capability to cope with it), this person will not be vulnerable even if it is directly exposed to the virus (subject to it). These very simple examples explain how the coexistence of two parameters is necessary to consider the existence of vulnerability.

As a whole, project performance degradation is the consequence of two coexistences. The first one conditions the apparition of vulnerability: coexistence of susceptibility to be subject to negative events and incapacity to cope with them if occurring. The second one is the temporal coincidence of a triggering event and a vulnerable ground for a risk to occur and to degrade the processes of values creation during the project.

Now that the necessity of these coexistences is cleared, the aim of this work is to propose a systems thinking-based model of vulnerability to assist complex project risk management. The aspect of susceptibility is neglected in the following section since susceptibility is closely linked to probabilistic aspects of possible negative triggering events, which we do not aim at addressing here.

The aim of the next section is to focus on the project system weaknesses and thus on the identification, evaluation and management of non-capabilities in terms of resistance and resilience. As a whole, this section thus proposes a paradigm shift since it focuses on the project system existing elements instead of focusing on possible events.

V.3. Proposal of a project vulnerability management process

V.3.1. Challenging the definition of a project risk

Before questioning how one can manage project vulnerability, this paragraph aims at linking it clearly the concepts of project risk and project vulnerability. As mentioned in Chapter IV, a project risk is defined as an event that, if it occurs, causes either a positive or a negative impact on a project. This definition underlines two aspects: the existence of a probabilistic triggering event, and its impact on the project. But as noticed in V.2., when focusing on negative events, this triggering event is to have an impact if and only if occurs on a vulnerable state of the system. As a whole, we propose here to focus not only on the probabilistic event and the possible damages, but also on project vulnerability when performing a project risk analysis. When not doing so, a crucial aspect of the possible damage creation processes is to be neglected. We thus propose to refine the definition of a project negative risk, stating that

Definition : A **project negative risk** is an event that, if it occurs, causes a negative impact on a project (as a whole or some of its aspects) due to existence of project vulnerable states. A project risk can thus be expressed as a conjunction of a probabilistic aspect depending on the triggering event and its impact depending on the project vulnerability. In other terms,

$$P.Risk = PROBABILITY(TRIGGERING.EVENT) \otimes IMPACT(PROJECT.VULNERABILITY)$$

In this formulation, impact is to be decomposed into three aspects:

- Intensity of the triggering event
- Resistance and resilience of the vulnerable elements of the project
- Final impact on the project values creation processes.

The concept of vulnerability implicitly implies the existence of stakes and values in the project system which can be damaged and/or altered. Indeed, without such stakes, no one would care about potential damages. What makes damages important is that damages can affect the values creation processes of the project, thus putting in danger the objectives and raison d’être of the project. Vulnerability is to be understood as the function which permits a transmission from negative events to damages in the project values creation processes. As a consequence, project vulnerability makes sense if and only if it is related to the values the project. That is why it is necessary to come back to the notion of project created values.

V.3.2. A methodology to model and manage project vulnerability

In order to do so and to properly identify the complex project values creation processes, we claim for the use of systems thinking, which permits to have an overall vision of these aspects. Our methodology to model project vulnerability is therefore the following:

- Identifying the objectives of the project in terms of values creation thanks to the study of the teleological pole of the project system in all of its phases, particularly its execution phase. These values appear to be the vulnerable stakes of the project.
- Identifying elementary vulnerable process and elements of the project systems (vulnerable tasks, actors, resources, etc…) thanks to the proper identification of the functional and ontological poles of the project system. These two first steps permit to perform project vulnerability identification.
- Then, by assigning a contribution rate of any of these elements to each value creation process, one is to perform the first step project vulnerability analysis.
- The second step of project vulnerability analysis is to concentrate on a particular value and vulnerable element in the system regarding this given value creation process. By identifying possible triggering events which can damage this project vulnerable element and analysing its resistance and resilience through a stressor/receptor model, one is to perform the second step of project vulnerability analysis.
- Then, after performing project vulnerability identification and analysis, a project vulnerability response plan can be built up to cure the weaknesses of the project system and prevent it from possible damages.
- Finally, a project vulnerability monitoring and control activity is to be performed during the whole project in order to watch over the project evolution.

As a whole, four steps (which are similar to the ones of the project risk management process) can be built for the project vulnerable management process. They are synthesised in Figure 47. Each of them is developed in the following paragraphs in order to introduce the reader with the whole process of project vulnerability management.

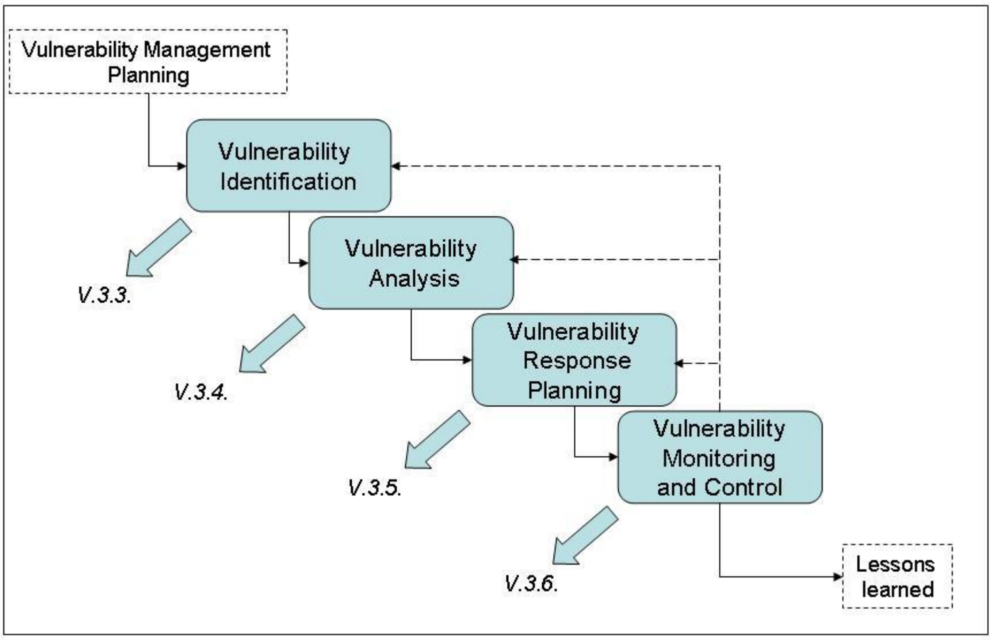

Figure 47. The project vulnerability management process

V.3.3. The project vulnerability identification step

As mentioned in V.3.2., in order to identify properly project vulnerabilities, the use of systems thinking is proposed. It must be underlined that vulnerability permits to focus on the project system (its processes, elements, structure,…) which make project vulnerability a more tangible concept than project risk. For all practical purposes, identifying project vulnerabilities means identifying the weaknesses of a project system which make its values creation vulnerable.

In order to do so, a four step processes bases on the system thinking approach is proposed. The use of this methodology permits to identify vulnerabilities systemically through the logical linkages which exist in the processes of values creation. Vulnerability is therefore identified at three levels:

- The teleological pole of the project system, which permits to identify the vulnerable stakes of the project (negative impact on its objective performances, i.e. degradation of its objective targeted created values) thanks to the prerequisite which is the proper identification of the project stakeholders.
- The functional pole of the project system, which permits to identify the vulnerable processes / tasks of the project system.
- The ontological pole of the project system, which permits to identify the vulnerable elements (actors, resources, inputs of processes, …) of the project system.

The reflexion on a stressor / receptor model to identify project process vulnerabilities is thus to be based on triplets (project value, project process, event), which implies that project elementary vulnerabilities are to be defined as triplets (project value, project element, event).

Since project vulnerability identification is closely linked to systems thinking, the genetic aspect (evolution of the project system) is also to be considered. Indeed, whenever the project phase changes, or whenever considerable changes in the project system (notably its context through the necessary identification of project stakeholders) occur during a project phase, the vulnerability identification process is to be performed again, or at least refined / updated.

Furthermore, contrary to identification step in the project risk management process, project vulnerability identification (as we propose it) is to be based solely on the (expert) analysis of the project system for the first three steps. Finally, a natural classification of project vulnerabilities is to appear thanks to the identification of project values. This classification helps to reduce ambiguity and doubts on usefulness since everything is drawn by the final objectives of the project, that is to say values creation.

V.3.3.i. Identification of vulnerable values, processes and elements

As a whole, thanks to systems thinking (as exposed in Chapter 1), a list of project values can be identified thanks to the proper identification of the project stakeholders.

A project is vulnerable if and only if one of its objective values may not reach its target. That is why we argue that project vulnerability should be addressed regarding each value of a given project, in order to underline the different possible kinds of damages within the project.

In the end, this research work proposes that the first deliverable of the project vulnerability identification step is a three-level hierarchical structure composed of (see Figure 48):

- The project values which are likely to be damaged and make thus the project vulnerable regarding them.
- For each value V_i, the project processes/tasks which contribute to V_i creation. These processes are likely to be altered (and thus to be vulnerable) by negative events, which makes as a consequence the project vulnerable regarding V_i.
- For each process P_{ij}, the project elements which permit to perform P_{ij} (actors, resources, other inputs). These elements are likely to be altered (and thus to be vulnerable) by negative events, which alters P_{ij}, which makes as a consequence the project vulnerable regarding V_i.

An arborescence is thus to be built in order to classify project vulnerable values, processes and elements as shown hereunder on Figure 48. The reader should note that this decomposition is analogous to the one mentioned in V.2.1.II. and proposed in (Ellis, 2003) in terms of outcomes (values), activities (processes) and assets (project elements).

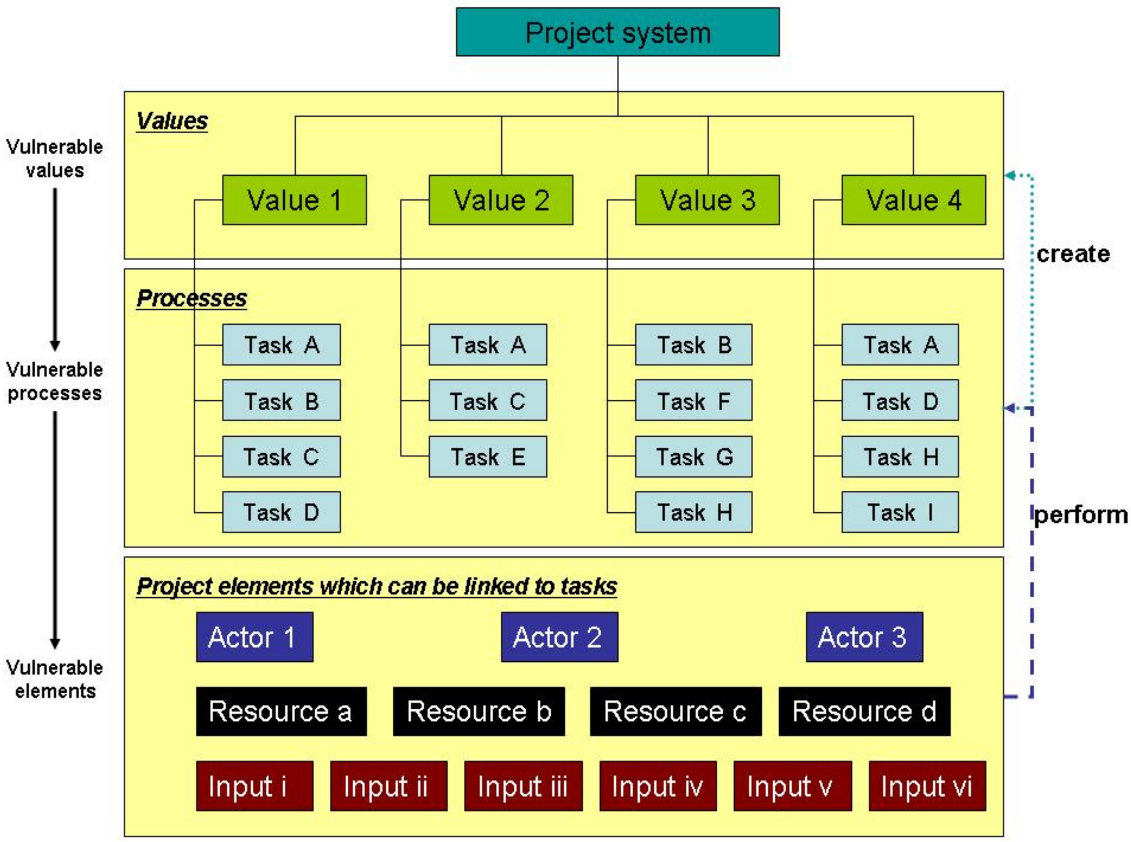

Figure 48. Levels in the project vulnerability identification step

V.3.3.ii. Identification of process and elementary vulnerabilities

Let (V_1, V_2, …, V_n) be the set of values created by the project. For each V_i, we have identified the corresponding vulnerable project processes and elements. Each value V_i can be weighted by a coefficient α_i which permits to set priorities in the values creation processes (the sum of all these coefficients is equal to 1). If $\alpha_i > \alpha_j$, then project vulnerability regarding value V_i is all the more important to control than project vulnerability regarding value V_j since the creation of V_i is preferred to the one of V_j. Such weights are notably to be set by project stakeholders, by the project management office or by the firm, notably thanks to the consideration of strategic or tactical aspects.

Given a value V_i, as mentioned before, there are several project processes/tasks (P_{i1}, P_{i2}, …, P_{ip}) which contribute to V_i creation. In the same manner, the project manager, the project team or external experts can permit to determine weights β_{ij} which permit to determine the importance of each task regarding V_i creation (for each i, the sum of all β_{ij} is equal to 1). At this stage, one should particularly notice that tasks can contribute to several values creation processes.

The same work can be done on every category of project elements. In the end, determining all the weights in the hierarchical structure (by expertise or experience) permits to determine the maximum possible degradation linked to a project element/process if it is altered. This first analysis thus permits to identify aspects which can be neglected due to their low implications in possible damages regarding values creation, which permits to diminish the number of vulnerable processes or elements to deal with. This is all the more important to perform since the combinatorial aspects of project vulnerability identification are likely to be very important.

Once refined, as underlined by the literature, we claim for the use of a stressor / receptor model to identify key project vulnerabilities, that is to say key project process vulnerabilities which are triplets (value, process, event) and key project elementary vulnerabilities which are triplets (value, element, event). The first steps of the identification process permitted to identify project values, processes and elements and to refine their lists thanks to issues about contribution rates to values creation. This work now proposes that, given a process or element the vulnerability of which is to be studied, one focuses on this process / element as a receptor and tries to list down as exhaustively as possible the possible negative events it may be exposed to (that is to say its potential stressors). This aspect is to be performed thanks to the conjoint use of expertise and experience. We may recommend here the use of some creativity methods such as brainstorming, dissociation or inversion.

As a whole, an initial list of project process and elementary vulnerabilities is done. Identifying project vulnerabilities is in itself a first result. However, one should be able to evaluate/analyse them in order to manage them better.

V.3.4. The project vulnerability analysis step

One should note that the tools which are proposed here are first analysis tools and that, as in project risk analysis, many other qualitative/quantitative tools are likely to be developed to perform further project vulnerability analysis. Once the set of project process or elementary vulnerabilities is identified, theses ones are to be analysed regarding the two principal aspects of vulnerability in terms of non-capability, that is to say non-resistance and resilience (as stated p.106). As mentioned before, we focus on these two aspects and neglect the one of susceptibility (which is closely related to the events apparition) to focus directly on the weaknesses of a project system. In order to do so, objective scales which permit to assess the non-resistance and resilience of project elements/processes regarding possible negative events should be built up.

One is then to evaluate the corresponding resistance and resilience of a given project process or elementary vulnerability. In order to do so, a first tool is proposed: objective 1 to 10 evaluation scales should be built by experts, like in the risk analysis process when performing the evaluation of probability and impact. Such examples of scales can be found hereunder in Figure 49. This choice of expert evaluation corresponds to a first approach in order to build up the whole process of project vulnerability management: some more precise analysis methodologies are likely to be elaborated in the future.

Figure 49 also shows how synthetic diagrams (non-resistance and resilience on axes, contribution rate to the project value V as the diameter of the circle) can be built to highlight principal project vulnerabilities. We recommend that in a diagram, there should be only the project vulnerabilities which correspond to a same value possible degradation, so that the analysis of this diagram is of interest for management use.

Project vulnerability scales examples

Values	1	3	5	7	9
Non-resistance	Alters less than 20% of the value creation process (VCP)	Alters between 20% and 40% of the VCP	Alters between 40% and 60% of the VCP	Alters between 60% and 80% of the VCP	Alters more than 80% of the VCP
Resilience	Recovers before time T_1.	Recovers between time T_1 and T_2.	Recovers between time T_2 and T_3.	Recovers partially after time T_3	Never recovers, even partially

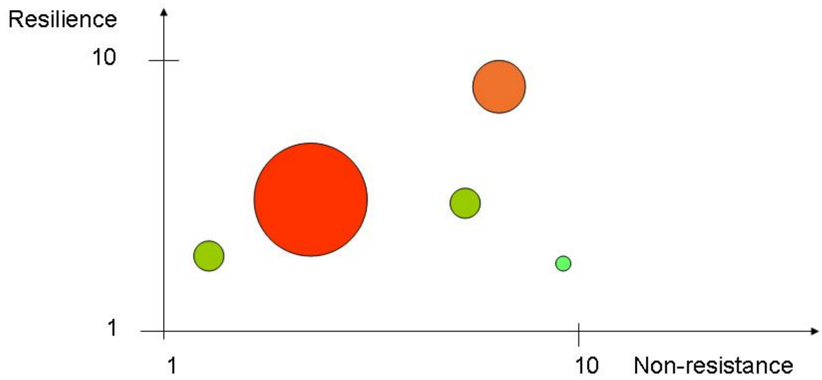

Figure 49. Project vulnerability analysis

In the end, a global cruciality index can be calculated in order to give a simple indicator to rank project vulnerabilities regarding a project value V.

Let CR(V) be the contribution rate (to the project value) of the vulnerable element/process which is addressed (CR(V) is a percentage). Let NR be the evaluation of its non resistance. Let R be the evaluation of its resilience. Then, a synthetic aggregated measure (which can help to underline higher priority vulnerabilities), which we name the Crucial Index Γ(V) is to be given by the following equation (the reader should note that Γ(V) is an index varying between 0 and 100).

$$\Gamma(V) = NR \times R \times CR(V)$$

As during any aggregation operation, part of information is lost. Indeed, several different triplets can have the same value when multiplying the values of its elements. As a consequence, when ranking according to the Γ(V) index, one may rank at the same level several triplets which could not be handled the same way (for example high non-resistance and low resilience versus low resilience and high non-resistance with the same value of Γ(V)). In the end, this classification according to Γ(V) should always be considered with the initial evaluation of NR, R and CR(V) in order to make more relevant decisions during the project vulnerability response plan step.

V.3.5. The project vulnerability response plan step

The project vulnerability response plan step permits to decide on the actions which are needed to reduce the threat of the existence of project process or elementary vulnerabilities. This step is to be performed after vulnerability identification and analysis, which permits to focus on high priority vulnerabilities within the project system. The project vulnerability response is to determine the overall strategy for strengthening a project. In the end, possible project contractual agreements can thus be written in order to take into account project vulnerabilities. These agreements depend on the strategies which are chosen to cope with the project vulnerabilities. As in the risk management process (PMI,2004), even though slightly different, there are five basic strategies to cope with project vulnerabilities.

- <u>Mitigation</u>

  Mitigation is the strategy which consists in making decisions in order to improve the resistance of the project processes / elements and / or to lessen their resilience regarding negative triggering events. Another strategy would be to diminish the contribution rate of the process / element to the value creation but this strategy is not always possible, and whenever possible, it is to be classified under the name of transfer since contributions are transferred to other entities.
- <u>Avoidance</u>

  Avoidance is the strategy which consists in making decisions in order to eliminate project vulnerabilities by improving to 100% the resistance of the project processes/elements. The reader should note that for project risk management, there are two ways to avoid risks (reducing to 0 probability or impact). But there is only one way to avoid vulnerability (reducing to 0 non-resistance). Indeed, resilience has no direct impact on avoidance since resilience underlines a dynamical aspect of vulnerability (evolution over time). Avoiding a project vulnerability means that it never exists, which means that resistance must be total. The reader should also note that another possible avoidance strategy is to reduce to 0 the contribution rate of the project process / element to the corresponding value creation but first, it isn't always possible, and second, once again, these strategies are to be classified under the name of transfer since contributions are transferred to other project entities.

- <u>Transfer</u>

  Transfer is a strategy which consists in making decisions in order to transfer project vulnerabilities to other project processes/elements which have less influence in the values creation processes. This strategy is really different than the transfer strategy in the project risk management process which consists in the transfer of the risk responsibility to a third party.

  Here, vulnerabilities exist within the project system and there is no reason to transfer them to third parties which would be external to the system (however, one should note that decisions can still be made to transfer the final risk responsibility to any of the project stakeholders). However, transfer strategies can be defined in the following manner. For instance, if an actor appears to be vulnerable and thus to be the source of a project process degradation, then one can choose, whenever possible, to transfer this actor to other processes which have less impact on the creation of project values.

  The transfer strategy is thus the strategy which proposes to handle contribution rates (to the corresponding value creation) as potential levers for vulnerability reduction.

- <u>Acceptance</u>

  Acceptance is a strategy which is notably designated for low resilience and high resistance project vulnerabilities. It consists in saying that little or nothing can be done expect letting things run their course, knowing that these low Crucial Index vulnerabilities however exist.

- <u>Contingence</u>

  Contingence response is an intermediary manner to cope with vulnerabilities. It is associated with the one of the other strategies (especially mitigation) and determines the actions which should be done if the chosen vulnerability response should fail.

Any of these possible solutions should be explored when trying to cope with a project vulnerability. The choice of the suitable strategy is to be performed notably thanks to the project manager / team experience.

V.3.6. The project vulnerability monitoring and control step

In essence, a project system is evolving, which means that project vulnerabilities do not remain static. New vulnerabilities may pop up, the characteristics of project vulnerabilities may change or vulnerability responses may not have the effects which were planned.

Watching for such changes in the project system is therefore necessary to manage project vulnerability in the end. Particularly, vulnerabilities are to be re-identified and re-assessed during the project, since they refer to a project system which is in essence in constant evolution. This step is very similar to the project risk monitoring and control step in the risk management process (PMI, 2004).

V.3.7. Synthesis : comparison with the project risk management process

Figure 50 proposes a critical comparison of the project risk management process and the project vulnerability management process. One should notice in the end that project vulnerability management as proposed in this thesis is a systems thinking oriented approach, which implies a better integration of project complexity thanks to a systemic vision of the weaknesses of the project system. Moreover, the fact that one is to focus on the elements and processes of the project system permits to reduce ambiguity as a more formalized and precise description of the possible damage creation process is enhanced by this approach.

	Project risk management process	Project vulnerability management process
Identification step	**One step process** as it Identifies **possible** triggering events, and often their effects and their causes. Notice these events can be either positive or negative. Performed through expertise / experience / creativity.	**Two main step process** as it first identifies **existing tangible** aspects of the project system which appear to be vulnerable regarding the project values creation processes. Then it identifies project process or elementary vulnerabilities. First step performed through expertise, seconde one through expertise / experience / creativity.
Analysis step	Evaluates risk **probability and impact**. Numerous methods to perform such **quantitative or qualitative** analysis. Classification is proposed to focus on high priority risks, notably thanks to the definition of a **criticality index**. One of the main difficulties is to assess possible events.	Evaluates the **resistance and resilience** of project vulnerabilities. First proposal is a **qualitative analysis**. Classification is proposed to focus on high priority vulnerabilities thanks to the definition of a 0 to 100 **cruciality index**. One of the main difficulties is to assess resistance and resilience regarding possible events.
Response plan step	Proposes strategies for risk responses. Leaves possibilities for risk mitigation, **avoidance on two factors** (probability/impact), acceptance, contingence or **transfer to a third party**.	Proposes strategies for vulnerability responses. Leaves possibilities for vulnerability mitigation, **avoidance on a single factor (resistance)**, acceptance, contingence and **transfer within the project system**.
Monitoring and control step	Very similar to one another	Very similar to one another

Figure 50. Comparison between project risk and vulnerability management processes

As a whole, this approach may diminish the observed (in fieldwork) reluctance to risk management processes as vulnerability management processes focus on existing tangible aspects of the project. It permits to cope with the existing weaknesses of a project system which need to be strengthened. When possible risks were underlined before, existing weaknesses of the project are stressed thanks to this approach. In the end, the vulnerability response plan may thus appear more relevant as the responses directly focus on the project system instead of dealing with probabilistic events: the required efforts (notably in terms of time and money) for these responses may thus appear more necessary as real project weaknesses are underlined.

V.4. Case study: the FabACT project

V.4.1. Introduction

A case study is performed during the FabACT project (Vidal and al., 2009a), a software development project within the context of the pharmaceutical industry. This project was executed in collaboration with the UPIO (Unité Pharmaceutique en Isotechnie et Oncologie – Chemotherapy Compounding Unit) at the Georges Pompidou European Hospital. This paragraph is an introduction to describe the FabACT project and its context. The French health system faces ever growing demands under very pressuring conditions as it is much constrained in a complex environment. The most recent statistics published by the French government indicate that in 2005, the number of new cancer cases has increased by 89% since 1980, reaching the number of 320 000 new cases for the first time (Jemaa and al., 2005). As a consequence, oncology-related services (such a radiology, surgery and chemotherapy) have to face an ever-growing level of activity. In order to contain cost, most of French hospitals are gradually centralizing the compounding of sterile products such as anti cancer drugs. At the Georges Pompidou European Hospital (HEGP, AP-HP, Paris), these drugs are produced within the chemotherapy compounding unit called UPIO which performs about 20 000 preparations per year (Bonan and al., 2009). The production of anticancer drugs must satisfy subsequent production volumes, while guaranteeing a high quality product preparation level in the name of good practice guidelines (Maestroni and al., 2007). Furthermore, with the new work regulations adopted in France (notably the 35-hours working week) and without the possibility to expand the pharmaceutical staff, the pharmacists of this hospital are facing new challenges. Discussions we had with the pharmacists of the UPIO led to the idea that the anticipation of anti-cancer drug preparations could be a potential solution to support this increased workload. Hence, by anticipating the production, one part of the preparations can be done on a MTS (Make to Stock) basis, which may improve significantly several aspects: first, the service provided to patients can be improved since waiting times are reduced; secondly, this may contribute to the reduction of errors that pharmacy technicians may do while preparing drugs in short time schedules; thirdly, this constitutes a framework for optimising the production planning process.

There are 2 categories of drugs that are prepared at UPIO, depending on information available:

- Some of preparations are prepared on a MTO (Make–to–Order) basis: in this case, pharmacists do not have any visibility on the amount of preparations needed for each patient. The time that elapses between the prescription of the medicine and its production is no longer than 1.5 hours. Such urgent production may stem from a patient that needs a non planned urgent administration in a very short time frame or from organisational failures such as prescription keypunching errors, production orders that are forgotten to be integrated to the daily production, etc.

- The other part of preparations is produced on a MTS (Make-to-stock) basis. In this case, pharmacists have a greater visibility on demand. In fact, the prescription for drug already exists on the computerized physician order entry software used at UPIO (Chimio®) and the production starts when this prescription is confirmed by the doctor. This validation of the prescription confirms that the patient, waiting for the administration of the drug, can receive the chemotherapy in the hospital. Such drugs can be produced by anticipation due to the information available on the Chimio® software. The proportion of such products was very small at UPIO at the beginning of the study. In fact, the production of only two molecules was anticipated based on a subjective and empiric approach due to the lack of a pertinent decision support tool.

The chemotherapy compounding process can be separated into several steps. According to the compounding sheet, the technician prepares all the material needed including gowns, syringe, needle, drug vial, infusion bag, gloves, etc… These are manipulated within a sterile workstation (isolator or laminar hood). A 1ml sample is withdrawn from the infusion bag in order to be controlled before dispensing the preparation into the medical unit where the patient is treated. One complex aspect of this process is that the preparations differ in terms of dose, final volume, stability, cost and lifetime (as they are in essence perishable products). In addition, these drugs are sterile and each drug belongs to a single patient. The dose prepared and then administered to the patient is determined solely according to the patient's weight, size and background (generally obtained from a blood check-up including creatinine blood level). Those parameters are moreover updated very regularly. According to the evolution of the patient's status, a significant change in any of them can make the drug useless and the preparation should be re-performed according the new dose calculated (Hassan et al., 2004). Concerning production volumes, in 2005, 17 690 preparations were made up, while in 2007, the number of preparations reached 18 492 preparations, which is an increase of 802 preparations (4.5 %) in a two years time. To support this increasing workload, pharmacists wanted to evaluate how anticipating the production of certain drugs may help them in improving the organisation of the production process.

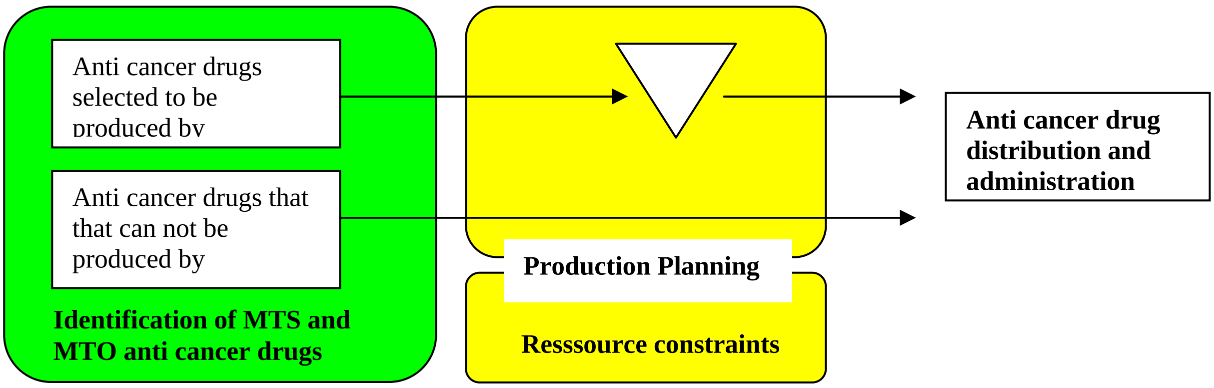

Figure 51. Anti-cancer drugs production and distribution process

Within this context, the FabACT project has been launched at HEGP Pharmacy department in 2006. The aim was to achieve a better balance between the workload and the ability to hold the admixture compounding burden while respecting constraints such as drug stability and quality of service. As shown on Figure 52, the first step of this project was the identification of drugs that can be prepared on a MTS basis.

Once these drugs are determined, the second step would be to organise the production planning process by smoothing the quantities to be produced over a time horizon, by mixing MTO and MTS type preparations. This second step aims at smoothing the workload over time thereby reducing the stress of the pharmacy technicians and increasing preparation quality. Finally, mixing MTO and MTS type preparations is also expected to allow urgent demands to be handled more easily due to the fact that MTS type preparations can be temporally postponed.

The aim of the FabACT project was therefore to develop a decision support tool in order to assist pharmacists while choosing the anti-cancer drugs that can be produced in advance. Anticipated manufacturing generates a risk in terms of cost and preparation time. Indeed, products can sometimes be produced and finally not used because of many reasons, generally related to the patient clinical status. Drugs are then recoverable if and only if the treatment can be delayed within the drug lifetime.

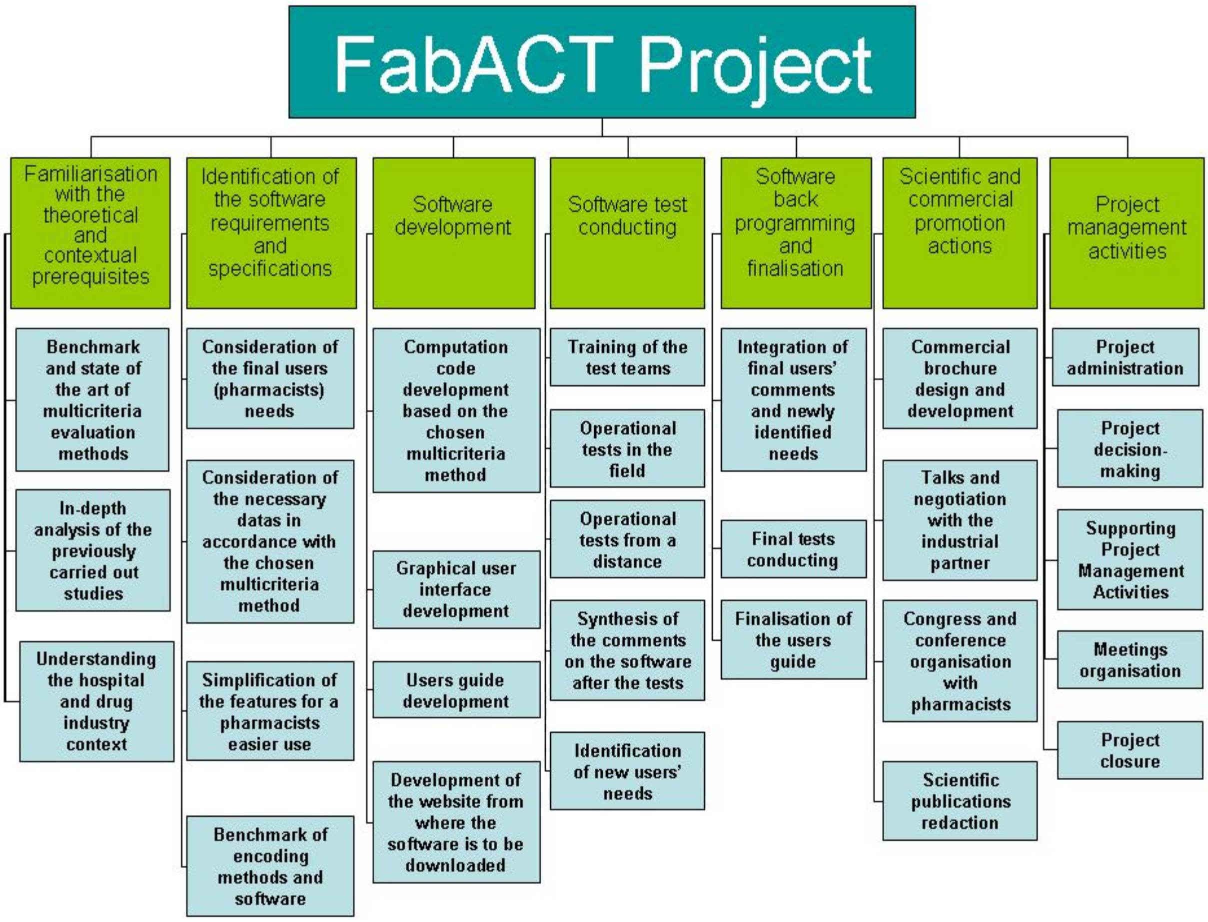

Figure 52. Work Breakdown Structure of the FabACT project

However, anticipated drug production tends to become a crucial need for anti-cancer production units since demand is ever growing without extra staff being hired. The decision support tool which was developed was to be multi-criteria and implemented as a software which could be used in any hospital pharmacy in France. Initially, the Work Breakdown Structure of the FabACT project was defined as the following one (Figure 53). Four researchers from an academic institution (Ecole Centrale Paris), three researchers/pharmacists from the UPIO, 2 consultants specialized in the communication within medical and healthcare contexts constituted the core team of the project. Graphical design of the software is subcontracted to a person working in a specialized firm. The whole project was to last around a year. Budget is not mentioned here. A pharmaceutical industrial group (drug combination producer) finances the major part of the project as its client. Final software products are going to be distributed by this industrial group to hospital pharmacies with the logos of some stakeholders (UPIO / ECP / Industrial Partner) but not commercialised.

Due to the importance of this project, a study was to be launched in order to identify the possible cases of failure for the project. This project therefore constituted the fieldwork to test the project vulnerability approach we propose in order to identify its weaknesses. Simultaneously, a traditional project risk identification and analysis process was performed to compare the two approaches.

V.4.2. Results and discussion

V.4.2.i Identification of project vulnerabilities

In order to perform the step of project vulnerability identification, as proposed in this Ph.D. work, one should use a systems thinking approach, which starts with the identification of project stakeholders Considering the execution phase of the project, the teleological pole of the project system (entities of this pole, the requirements they have, the constraints they exert) can be identified as the following one.

- **UPIO team of the Georges Pompidou Hospital (APHP)**

  WANTS TO

  Create scientific, industrial and societal values.

  Promote its image thanks to the success of one of its member's initiative.

  Have priority access to the beta versions of the software to test it in their unit..

  Improve its relationships with the industrial partner

  Earn some money

  EXERTS CONSTRAINTS SINCE IT

  Delivers some inputs for the software and website development (pharmacists' needs, drug selection criteria, test data, visual specifications,…).

- **Ecole Centrale Paris (ECP) – Industrial Engineering Department**

  WANTS TO

Create scientific, industrial and societal values.

Improve its corporate image and valuate its research teams and students

Manage the project properly to improve its image.

Earn some money

EXERTS CONSTRAINTS SINCE IT

Delivers some inputs for the software and website development (problem modelling, first versions of the software,…)

- **Healthcare consulting group**

WANTS TO

Improve its corporate image and/or create relationships with healthcare industries

Earn some money

EXERTS CONSTRAINTS SINCE IT

Delivers some inputs for the software and website development (first versions of the website and user guide,…)

- **Industrial partner (drug combination producer)**

WANTS TO

Improve relationships with hospital drug production units.

Improve its corporate image.

EXERTS CONSTRAINTS SINCE IT

Wants a certain number of software products at a given time T.

Wants a reliable decision support tool to satisfy the final users.

- **Indeed, the final users (anti-cancer drug production units in french hospitals)**

WANT TO

Find an assistance to decision-making to anticipate anti-cancer drug production

Have a user-friendly interface, that is to say a quick and easy to handle software

Have a software which is compatible with the existing computer equipment

As a whole, the project created values must meet all the requirements and respect all the constraints cited before. These values must be found through the elaboration of the project final deliverables (decision-making software, associated products (website, users guide, commercial brochure,…), scientific publications, participation to industrial congresses). The project values were thus listed as the following ones (since they were the most meaningful ones after the identification of project stakeholders):

- **Completion of the project on time**
- **Profit due to the project**
- **Quality of project processes**
- **Industrial, scientific and societal quality of project deliverables, which are mainly influenced by**
  - ❖ Rigor of the scientific approach. (Sc)
  - ❖ Reliability of the result. (In) (Sc) (So)

	Completion on-time	Profit for stakeholders	Quality of project processes	In. quality of deliverables	Sc. quality of deliverables	So. quality of deliverables
Familiarisation with the theoretical and contextual prerequisites	5%	10%	20%	5%	40%	25%
Benchmark and state of the art of multicriteria evaluation methods	2%	3%	5%	0%	15%	0%
In-depth analysis of the previously carried out studies	2%	4%	5%	2%	15%	5%
Understanding the hospital and drug industry context	1%	3%	10%	3%	10%	20%
Identification of the software requirements and specifications	5%	8%	5%	15%	10%	15%
Consideration of the final users (pharmacists needs)	2%	4%	0%	5%	2%	10%
Consideration of the necessary datas	2%	1%	0%	4%	3%	4%
Simplification of the features for a pharmacists easier use	0%	1%	0%	4%	0%	1%
Benchmark of encoding methods and softwares	1%	2%	5%	2%	5%	0%
Informatics development	15%	6%	0%	35%	10%	10%
Software computation code development	7%	3%	0%	15%	10%	5%
Graphical user interface development	7%	1%	0%	10%	0%	3%
Users guide development	0%	1%	0%	2%	0%	1%
Development of the download website	1%	1%	0%	8%	0%	1%
Software test conducting	15%	7%	0%	20%	15%	10%
Training of the test teams	2%	1%	0%	2%	1%	1%
Operational tests in the field	5%	2%	0%	8%	6%	3%
Operational tests from a distance	5%	2%	0%	6%	6%	3%
Synthesis of the comments on the software after the tests	2%	1%	0%	2%	1%	2%
Identification of new users'needs	1%	1%	0%	2%	1%	1%
Software back programming and finalisation	10%	4%	0%	10%	5%	5%
Integration of final users'comments and newly identified needs	8%	2%	0%	7%	3%	3%
Final tests conducting	2%	1%	0%	2%	2%	1%
Finalisation of the users guide	0%	1%	0%	1%	0%	1%
Scientific and commercial promotion actions	0%	55%	0%	10%	20%	30%
Commercial brochure design and development	0%	22%	0%	4%	0%	5%
Talks and negociation with the industrial partner	0%	22%	0%	2%	1%	5%
Congress and conference organisation with pharmacists	0%	9%	0%	3%	1%	10%
Scientific publications redaction	0%	2%	0%	1%	18%	10%
Project management activities	50%	10%	75%	5%	5%	5%
Project administration	5%	2%	10%	1%	1%	1%
Project decision-making	10%	2%	15%	1%	1%	1%
Supporting project management activities	20%	3%	30%	2%	2%	1%
Meetings organisation	10%	2%	15%	1%	1%	1%
Project closure	5%	1%	5%	0%	0%	1%

Figure 53. Identifying project tasks contribution to project values creation

- ❖ Adjustement of the software to the hospital and drug production context. (In) (So)
- ❖ Friendliness and easiness of understanding and use of the software. (In)
- ❖ Compatibility with existing computer equipments in hospital pharmacies. (In)
- ❖ Number and quality of scientific publications, congresses and conferences. (Sc) (So)
- ❖ Number of conference and congresses organised for industrials. (In) (So)

By going back to processes and tasks, (some of them were slightly redefined), it is possible to build up a table which synthesises the contribution of any task to any of theses values creation. This table can be seen before on Figure 54. This table permits, as suggested, to refine the analysis of fewer tasks / processes and project elements (corresponding to theses tasks and processes) when performing the project vulnerability analysis thanks to expert judgement (once again, future work is to be done in order to develop finer and deeper methodologies to perform these evaluations).

Indeed, for instance, when studying the vulnerability of the FabACT project regarding the creation of deliverables of high scientific quality, one is to have a closer look at this table, identify the tasks which have significant contribution rates regarding the creation of this value (over 10% in orange, over 5% in yellow). Only the vulnerability of these tasks is then to be analysed further as a first result since if other tasks are altered because of their vulnerability, they can in the worst case alter less than 5% of the scientific quality of the project deliverables. This step is absolutely necessary in order to lessen the combinatorial aspects of a project vulnerability study.

All the results of this study regarding the FabACT project cannot be presented here directly. The following parts of this paragraph focus on the project vulnerability regarding the creation of high scientific quality deliverables.

	Actor 1	Actor 2	Actor 3	Actor 4	Actor 5	Actor 6	Actor 7	Actor 8	Actor 9	Actor 10
Familiarisation with the theoretical and contextual prerequisites										
Benchmark and state of the art of multicriteria evaluation methods	70%	20%	10%	0%	0%	0%	0%	0%	0%	0%
In-depth analysis of the previously carried out studies	50%	10%	10%	5%	5%	10%	10%	0%	0%	0%
Understanding the hospital and drug industry context	40%	20%	20%	10%	0%	0%	0%	5%	5%	5%
Identification of the software requirements and specifications										
Benchmark of encoding methods and softwares	90%	5%	5%	0%	0%	0%	0%	0%	0%	0%
Informatics developement										
Software computation code development	75%	5%	5%	0%	0%	0%	0%	0%	0%	15%
Software test conducting										
Operational tests in the field	60%	0%	0%	0%	10%	15%	15%	0%	0%	0%
Operational tests from a distance	60%	5%	5%	0%	10%	10%	10%	0%	0%	0%
Scientific and commercial promotion actions										
Scientific publications redaction	0%	25%	25%	5%	10%	15%	20%	0%	0%	0%
Total contribution to the value "Sc. Quality of Project Deliverables"	41%	12%	11%	3%	4%	6%	7%	1%	1%	2%

Figure 54. Identifying the actors which contribute more to the tasks which make the project vulnerable regarding scientific quality creation

In order to close the vulnerability identification steps, one is to identify the projects elements which contribute to the tasks which were identified before. In the same manner, contribution rates tables can be built. The reader will find an example of such a table in Figure 55. (corresponding tasks and project actors). Refining can also be performed. In the end, a list of vulnerable tasks and associated project elements is built.

As a whole these first identification steps are the basis to identify project processes or elementary vulnerabilities. By focusing on process or elements as potential vulnerable receptors of events, one is able to set the list of project process and elementary vulnerabilities.

Figure 55 proposes here the corresponding list of project elementary vulnerabilities in terms of project actors. This list is to be analysed in the following step as an illustration on how to perform project vulnerability analysis.

V.4.2.ii Analysis of project vulnerabilities

After refining the vulnerability (regarding a project value creation process) studies to a precise set of project tasks and elements (the ones which can be the source of potential damages which are over a certain threshold), one is to study their resilience and resistance in order to quantify their weakness regarding possible negative events. For instance, one can perform it here on the identified project actors which make the project potentially vulnerable regarding the creation of high scientific quality deliverables (due to their contribution to the tasks which make the project vulnerable regarding this same value creation process). We obtained a list of five actors which contribute to this value creation: ACTOR 1, ACTOR 2, ACTOR 3, ACTOR 6, ACTOR 7. These actors are the ones to be watched over because of their potential impact on the targeted value creation if their usual behaviour during the project is altered. One is to find hereunder an excerpt of the FabACT project actor vulnerability analysis. The project actor vulnerabilities are ranked according to their Crucial Index Γ(V).

Value	Element	CR(V)	Event	NR	R	Γ(V)
Scientific Quality	Actor 1	0,41	Unclear software requirements and specifications	8	8	26,24
Scientific Quality	Actor 1	0,41	Error when encoding the software	6	8	19,68
Scientific Quality	Actor 1	0,41	New requirements appearing	8	6	19,68
Scientific Quality	Actor 1	0,41	Bad communication within the project team	6	6	14,76
Scientific Quality	Actor 1	0,41	Misunderstanding of previously carried out studies	6	6	14,76
Scientific Quality	Actor 1	0,41	Lack of information	8	4	13,12
Scientific Quality	Actor 1	0,41	Uncorrect information	7	4	11,48
Scientific Quality	Actor 2	0,12	Unclear software requirements and specifications	8	8	7,68
Scientific Quality	Actor 3	0,11	Unclear software requirements and specifications	7	8	6,16
Scientific Quality	Actor 2	0,12	Illness	7	7	5,88
Scientific Quality	Actor 2	0,12	New requirements appearing	8	6	5,76
Scientific Quality	Actor 7	0,07	Misunderstanding of the publication target requirements	9	9	5,67
Scientific Quality	Actor 7	0,07	Unclear software requirements and specifications	9	8	5,04
Scientific Quality	Actor 1	0,41	Too short test phase	6	2	4,92
Scientific Quality	Actor 6	0,06	Misunderstanding of the publication target requirements	9	9	4,86
Scientific Quality	Actor 3	0,11	New requirements appearing	7	6	4,62
Scientific Quality	Actor 7	0,07	Misunderstanding of previously carried out studies	9	7	4,41
Scientific Quality	Actor 2	0,12	Misunderstanding of the publication target requirements	4	9	4,32
Scientific Quality	Actor 6	0,06	Unclear software requirements and specifications	9	8	4,32

Figure 55. Excerpt of the FabACT project actor vulnerability analysis

V.4.2.iii Vulnerability response plan

This analysis underlines here that ACTOR 1 is the most vulnerable one regarding scientific quality creation during the project. The vulnerability response plan should therefore focus on the accompaniment of this actor in order to guarantee its performance regarding value creation or it should propose transfer strategies which transfer some tasks to less vulnerable actors.

This analysis particularly permits to underline that ACTOR 1 is particularly vulnerable to problems regarding the requirements of the software (whether they are unclear, changing or potentially misunderstood). As a consequence, this underlines that specific attention should be given to the definition of requirements and specifications as they are likely to condition. This is all the more true than the event "unclear software requirements and specifications" appears to participate to 5 of these 19 most important project actor vulnerabilities, causing the potential vulnerability of any actor within the project.

Other specific attention should be paid to the event "misunderstanding of the publication target requirements" since it directly impacts several actors in the FabACT project regarding scientific quality creation. This can be understood since the FabACT project is at the meeting point of industrial engineering and pharmacy and that publication targets requirements may not always be clear in the possible integration of articles dealing about this issue in the corresponding journal or revue.

V.4.2.iv Comparison with a traditional risk management process

Once can find hereunder an excerpt of a traditional risk management process performed for the FabACT project to be a point of comparison in order to underline the potential benefits of a project vulnerability analysis.

No.	Potential failure mode	Potential cause	Potential effect	Gravity	Occurrence	Criticality
1	Unsatisfying software development	Error when encoding the software	Unreliable results	9	6	54
2	Unsatisfying software development	Too short test phase	Too few comments	8	6	48
3	Unsatisfying software development	Misunderstanding of software specifications	Errors in the software, no consistence with specifications	9	5	45
4	Unsatisfying software development	Misunderstanding of the previously carried out studies	Misunderstanding of software specifications	9	5	45
5	Unsatisfying software development	Bad communication with test teams	Misunderstanding of specifications	6	7	42
6	Unsatisfying software development	Conflicting comments given by the test teams	Bad integrating of the test phase comments	7	6	42
7	Unsatisfying software development	Bad integrating of the test phase comments	Errors in the software, no consistence with specifications	8	5	40
8	Project delay	Conflicting comments given by the test teams	Bad coordination	6	6	36
9	Project delay	Error when encoding the software	Extra work	6	6	36
10	Unsatisfying software development	Unclear software requirements and specifications	Errors in the software, no consistence with specifications	9	4	36
11	Project delay	Bad communication with test teams	Misunderstanding of specifications, extra work	5	7	35
12	Unsatisfying software development	Difficulty to understand the hospital context	Misunderstanding of specifications	7	5	35
13	Unsatisfying software development	Low standard graphical user interface	Non user friendliness of the software	5	7	35
14	Unsatisfying software development	New requirements appearing	Errors in the software, no consistence with specifications	7	5	35
15	Low profit	Unforeseen issues	Overcost	7	5	35
16	Unsatisfying software development	Errors in the previously carried out studies	Errors in the software	8	4	32
17	Unsatisfying users guide development	Misunderstanding of the previously carried out studies	Errors in users guide	8	4	32
18	Unsatisfying software development	Too little information given by the test teams	Unefficiency of the test phase	8	4	32

Figure 56. Excerpt of the FMECA of the FabACT project

First, one should notice that the lack of integration of project values does not permit to understand properly the consequences of the potential failure modes, even though there effects are likely to be mentioned. Vulnerability analysis permits to understand better the possible damage chains which exist within a project. It must be notices that for instance, no aspect about publication target requirements had been mentioned in the FMECA although it appeared to be a high potential source of vulnerability regarding scientific quality creation during the project.

Second, by analysing the project system's weaknesses, one is to make better and more specific decisions when establishing a response plan. Indeed, the FMECA mentions "unclear software requirements and specifications" or "misunderstanding of software specifications" as potential causes of important failure modes. This is consistent with the project vulnerability analysis which was performed. However, the project vulnerability analysis permits to focus on the project elements or processes which are impacted the most by this potential cause / stressor event. For instance, actors did not appear equally vulnerable to these events and the fact that project vulnerability analysis underlines the vulnerability of ACTOR 1 regarding these events permits to concentrate on weakest, and thus most dangerous regarding value creation, parts of a project.

V.5. Conclusions and perspectives

As a whole, this chapter presents an innovative way to assist project risk management through the integration of the concept of project vulnerability. This concept permits to analyse a project system and focus on its existing weaknesses thanks to a systems thinking-based approach. After proposing a definition and a description of project vulnerability, a proposition to describe the project vulnerability management process into four successive steps is done. The reader should remind them as a first proposal to perform project vulnerability analysis:

- Project vulnerability identification consists in identifying project process or elementary vulnerabilities thanks to a systems thinking-based approach which permits to focus on the existing weaknesses of a project system.
- Project vulnerability analysis permits to rank project vulnerabilities according to a Crucial Index Γ(V) based on the evaluation of non-resistance and resilience, allied to the initial evaluation of contribution rates of processes and elements to value creation.
- Project vulnerability response plan permits to address the issue of vulnerability management thanks to the use of different possible strategies: mitigation, avoidance, transfer, acceptance and contingence.
- Finally, the project monitoring and control process suggests that the former processes were to be performed several times during the project in order to keep an up-to-date version as vulnerability management directly focuses on the project system, which evolves over time (genetic aspect of the system).

This project vulnerability management process permits to concentrate directly on the existing weaknesses of a project system which may create potential damages regarding the project values creation. By focusing on this system, response plans may be more adapted to the existing lacks of the project, as shown by the case study with the FabACT project. Such focus on the system is to be of great interest for project managers and project teams. When before there was ambiguity or lack of confidence in dealing with potential events and potential impacts, vulnerability management permits to point out the weak aspects of a project. Attention should however be paid on vulnerability communication so that it is not seen as a way to underline low performance elements or actors in a project. Vulnerability management must therefore be highlighted as a promising tool for complex project performance management as it permits a more effective and efficient accompaniment of project teams thanks to a better understanding of possible damage creation within complex project systems.

Some aspects of this work may however be discussed. We thus identify several research perspectives to consolidate the proposals of this chapter.

- First, as already noted, new evaluation methods should be elaborated to assess more efficiently non-resistance and resilience during the project vulnerability analysis step. Moreover, the susceptibility aspect of vulnerability is neglected in this first approach of project vulnerability management. Future research work may explore the following issues. What are the relationships between a project process or elementary vulnerability susceptibility and the related event apparition probability? In particular, is it only related to the event, meaning that ($value_1$, $actor_1$, $event_1$) and ($value_2$, $actor_2$, $event_1$) have the same probability or does it depend on other factors? Whatever the answer, further work is also to address the issue of the integration of the susceptibility aspect into the vulnerability analysis step, maybe in order to study project vulnerabilities regarding their pair (Susceptibility, $\Gamma(V)$).
- Moreover, the calculation of the Crucial Index $\Gamma(V)$ is to be improved thanks to the integration of the connectivity of the vulnerable processes and elements with the other processes and elements of the project system. Indeed, as highlighted in works such as the ones of Latora and Marchiori (Latora and Marchiori, 2005), some indexes can be used to underline how the dysfunction of a given system element can damage the whole execution of the system. Such approaches are notably to use graph theory and may be developed in future research work (they will be all the more developed than the results of Chapter 6 are based on graph theory, which could make a link between the systems oriented vision of this chapter and the more analytical one of Chapter 6).
- Another interesting work on several project case studies may be to build up in the end a typology of mostly encountered project vulnerabilities. Such a typology could be a basis for vulnerability identification (even though this step remains very specific to the project system) for two reasons. First, it could permit to propose a standard classification of project vulnerabilities when identified and not analysed. Second, it could be helpful when performing the identification step as it may offer a framework for a check-list when identifying project vulnerabilities.

- Other promising works may focus on the evaluation of the non-resistance and resilience of project vulnerabilities. Indeed, this work proposes a first qualitative evaluation of these characteristics which is notably based on an analogy with existing qualitative evaluation of project risks. Some methodologies may be developed to propose quantitative evaluation of these aspects or to refine the qualitative evaluation which is proposed in this work.
- Finally, new case studies are to be performed in order to validate even more this approach and study both the practical applications (and improvements) of these results and their future implications on project management processes and organisation.

Chapter VI.

An analytical approach – Interactions-based clustering and other tools to assist complex project risk management

Abstract

The overall ambition of this chapter is to propose an innovative way to cluster risks in order to facilitate coordination in the process of complex project risk management. As shown in Chapter 4, traditional project risk management methodologies do not permit to catch project risk interactions when clustering them into manageable and analysable entities. Moreover, propagation phenomena within the project risk network are often neglected and there is crucial need for the use of some tools to understand them better.

We first identify the requirements of the tools which should be proposed to improve these current lacks in project risk management. Two issues are to be addressed: risk propagation and interactions-based risk clustering. In order to address them, a brief state of the art on graph theory and the Design Structure Matrix (DSM) approach is carried out.

Two risk matrices are built up to model the complex project risk network. A binary matrix, the Risk Structure Matrix (RSM) corresponds to the adjacency of the project risk finite directed weighted graph. A numerical version of this matrix, the Risk Numerical Matrix (RNM) is then proposed thanks to an assessment of risk interactions through the achievement of pairwise comparisons. These matrix representations are then used directly to propose some tools to analyse better propagation phenomena within the project risk network.

Then, a state of the art on graph clustering and partitioning issues permits to formulate our goal thanks to the values of the RNM. The objective is to cluster risks according to the strength of their interactions (thanks to the minimisation of the cutsize in the problem of graph K-partitioning), in order to reduce interfaces for all practical purposes. A linear programming formulation of the problem is proposed and some conditions of invariance of the results are

studied. Since this problem is NP-hard, two elementary approximate iterative algorithms are proposed. Performance measures are then identified to compare possible clustering solutions.

The whole is tested on two case studies. The first one takes place in a firm within the stage musicals production industry. The second one studies the case of the Jerasulem tramway construction and future exploitation project. After concluding on the validity and practical interests of this approach thanks to this case study, some conclusions are drawn on its implications on project risk management. Final conclusions and research perspectives are then given.

Chapter Keywords

Project, Risk, Interactions, Graph theory, Design Structure Matrix (DSM), Clustering, Partitioning, Linear Programming.

VI.1. Introduction

As an introduction to this chapter, a study was carried out to identify which conventional project risk methodologies were able to address the issue of risk propagation and risk possible interactions due to the complexity of project systems.

This study proved us that vey few methods permitted to manipulate this concept, and well-established ones do not permit to handle possible risk interactions at all. And even when doing so or part of so, existing methodologies have their limits. As highlighted in Chapter 4, the direct use of the concept of probability has also some limitations, which calls for the evaluation of the strength of possible precedence relationships in order to understand better possible propagation phenomena.

As a consequence, new methodologies and tools, even easy or intuitive, must be designed to facilitate the integration of complexity-related propagation effects into project risk management activities. And, as underlined in Chapter 4, project risks are more and more numerous and critical due to ever growing project complexity.

<u>PROBLEM SETTING OF THIS CHAPTER</u>

As a whole, risks are managed thanks to the elaboration of smaller clusters. As a consequence, a **classification issue** arises. Since decisions may be blocked, slowed down or ineffective if interactions are poorly taken into account, our research problematic in this chapter is thus to propose **a new additional clustering methodology**, which could take into account **interactions between risks (possible propagation)**, in terms of existence and strength.

In order to do so, the following points must be addressed:

- Proposing a **definition** of project risk interactions.
- Developing a methodology (and its associated tools) to **identify and assess** project risk interactions.
- Proposing intermediary **elementary tools** (which are directly based on the former point) to assist complex project risk management.
- Developing a methodology (and its associated tools) to **cluster risks** according to their interactions.
- Proposing possible **refinements** of obtained clustering solutions.
- Define **performance measures** to compare different clustering possibilities of a set or project risks.
- Express the **practical implications** and use of these methodologies and tools on complex project risk management.

As a whole, this chapter proposes to follow a several step approach which can be found hereinafter in Figure 58.

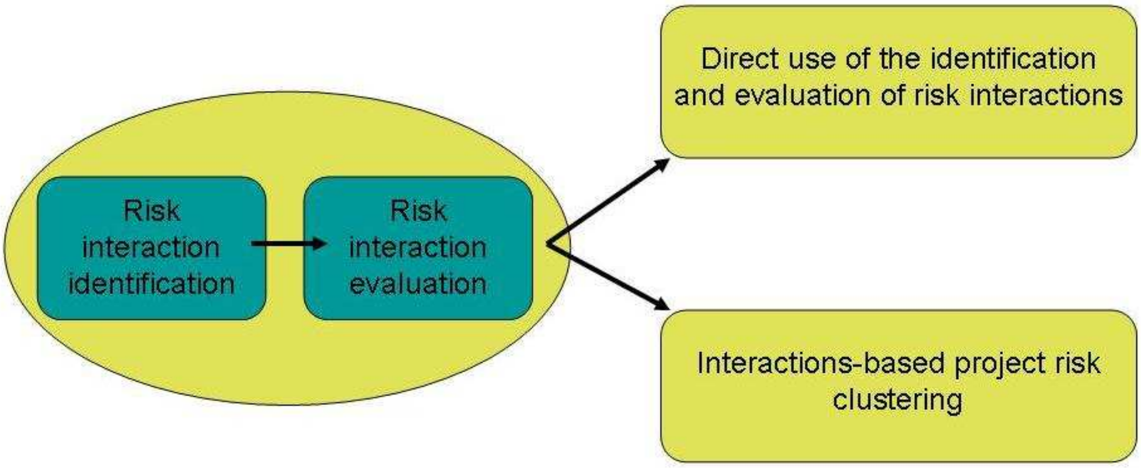

Figure 57. Content of chapter 6

The next section focuses specifically on the identification and possible evaluations of risk interactions and it also addresses how they can directly be used to assist complex project risk management by identifying possible intricate situations within project risk networks. Then section VI.3. addresses the issue of interactions-based clustering in order to facilitate the coordination and management of project risks. Case studies are finally carried out in VI.4.

VI.2. Identifying and measuring project risk interactions

VI.2.1. Defining project risk interactions

Before carrying out this study, the concept of project risk interaction is to be defined. In this work, the following definition is to be used.

Definition

A project risk interaction exists between two project risks R_i and R_j if a possible precedence relationship can be identified from R_i to R_j, i.e. if the occurrence of R_i might trigger the occurrence of R_j.

This means that:

- A project risk interaction is oriented from one risk to another.
- Project risk interactions can be assessed numerically thanks to the assessment of precedence possibilities.
- Mutually interdependent risks in terms of possible precedence generate two differentiated project risk interactions (from R_i to R_j and from R_j to R_i).

The reader should note that no relation between risks in terms of impact is considered in this work. The introduction of impact in the concept of risk interactions makes the point of future research works.

VI.2.2. Claiming for the conjoint use of graph theory and the Design Structure Matrix (DSM) approach

VI.2.2.i. Graph theory elementary tools and definitions

Graph theory (Bondy and Murty, 1976), (Biggs and al. 1986), (Diestel, 2005), (Bang-Jensen and Gutin, 2007), (Schaeffer, 2007) is based on the following concepts and semantics, which are to be used in the following paragraphs.

- A graph is a structure formed by a set of vertices V (also called nodes) and a set of edges E, each edge being a connection between a pair of vertices (they are called the endpoints of the edge). A graph is mathematically this pair of sets (V,E).
- The edge count accounts for the size *S* of the graph. The number of vertices n is called the order of the graph. A graph is finite if its size and order are finite. The neighbourhood Γ(V) of a vertex V is the set of vertices which are connected to V.
- A path from V_1 to V_2 is a sequence of edges starting from V_1 and ending at V_2. The length of the path corresponds to the number of edges in the corresponding sequence.
- In an undirected graph, each pair of connected vertices (V_1,V_2) is unordered. In a directed graph, each pair of connected vertices is ordered.
- A graph is weighted if a weight function assigns a weight on each edge.

According to the definition of risk interaction which is used in this work, project risk networks can be considered (see Figure 59) as finite directed weighted graphs (also called weighted digraphs). As a consequence, a brief state of the art on graph theory must be performed, be it only to note down elementary concepts and identify elementary tools.

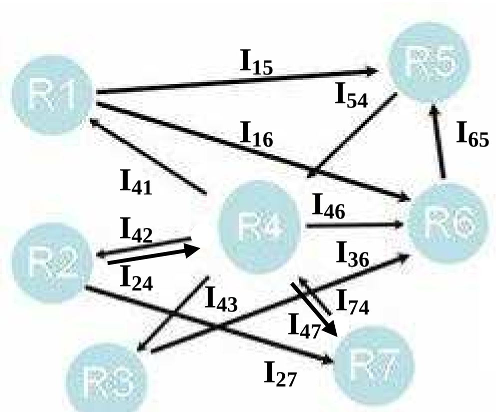

Figure 58. Project risk networks as finite directed weighted graphs

Some elementary tools and indicators can indeed be defined to analyse graphs:

- The density δ of a graph is the ratio of the number of edges over the maximum possible number of edges knowing the number of existing vertices n, which means that $\delta = \frac{S}{\binom{n}{2}}$

  When δ = 1, a graph is said complete.

- The adjacency matrix ADJ_G of a given graph G = (V,E) of order n is given by

  $ADJ_G(v_1, v_2) = 1$ if $(v_1, v_2) \in E$

  $ADJ_G(v_1, v_2) = 0$ otherwise

  These values can be replaced by weights in the case of weighted graphs. Note that the adjacency matrix is symmetric in the case of undirected graphs.
- A cut of a graph is a partition of the set of vertices into two non-empty sets C and V\C. The cut size corresponds to the number of edges which connect vertices in C to vertices in V\C. In the presence of weighted graphs (and thus weighted edges), the cut size is mainly defined as the sum of the weights of the edges which cross the cut (instead of the number of such edges).
- An induced sub-graph is the graph corresponding to the vertex subset W (included in V) and the corresponding edge set E(W) which exactly corresponds to all the edges of E that connect a pair of vertices V_1 and V_2 which belong to W. A complete induced subgraph is called a clique. The density of an induced sub-graph is given by $\delta_W = \frac{|E(W)|}{\binom{|W|}{2}}$.

VI.2.2.ii. The DSM approach

The Design Structure Matrix (DSM), which also referred to Dependency Structure Matrix or Design Precedence Matrix is a compact matrix representation of a design system or a design engineering project. This approach is widely used to model complex systems in systems engineering or systems analysis (Steward, 1981), (Eppinger, 1991), (Eppinger, 1997), (Browning, 2001), (Eppinger and Salminen, 2001), (Sosa and al., 2005), particularly in the contexts of project planning and project management (Eppinger and al., 1992), (Carrascosa and al., 1998), (Eckert and al., 2004), (Sosa and al., 2004).

This tool is undoubtedly one of the most established one for interactions management in the academic fields of industrial engineering, design engineering and project management. In its initial form, a DSM lists all constituent subsystems or activities, as well as the corresponding dependency patterns and information exchange.

A DSM consists is a square matrix. The cells along the diagonal represent the system elements. The off-diagonal cells are used to mention the presence of relationships between the elements. Reading across a row reveals what other elements the element in that row receives inputs from, and scanning a column reveals what other elements the element in that column provides outputs to. Alternatively, a transposed version of the DSM is sometimes used.

One should note that this matrix is very similar to the adjacency matrix in graph theory, assuming that a directed graph can be drawn to model the corresponding system, with edges representing information flows. The difference between these matrices lies in the diagonal elements which are null in the adjacency matrix.

The DSM aims at describing in detail what pieces of information are needed to start a particular activity and where the pieces of information which are generated by that particular activity lead. In this way, one can quickly recognise which other activities rely on a given activity's information outputs. The main advantage of the DSM is that it can represent a large number of elements and their relationships in a very compact way, compared to traditional representations such as PERT graphs or SADT documents, as argued in (Eppinger and Gebala, 1991).

Moreover, a DSM, whether it is binary or numerical (as for weighted or unweighted graph adjacency matrix) can easily highlight the presence of interfaces-related issues (for instance, the existence of feedback loops).

Finally, the matrix format of this tool induces matrix-based analysis techniques and matrix-based fast calculations which can be used to analyse the structure of the studied system and assist its management in the end (Eppinger and al., 1994). The use of DSMs in both research and industrial practice increased greatly in the 1990s. DSMs have as a whole been applied for various issues (change management, project planning, project success estimation, etc…) in various fields (building construction, chemical, automotive, aerospace, telecommunication industries to name a few), which make it a very generic and established tool.

In order to propose our analytical approach of complexity integration in project risk management, we claim for the use of such a matrix representation to model complex project risk networks. This makes the point of the following paragraphs.

VI.2.3. Building up the Risk Structure Matrix (RSM)

The construction of the Risk Structure Matrix (RSM) which is proposed is very similar to the one of the DSM. Indeed, the theoretical concepts of the DSM are used, but for other objects than components or tasks. These objects are project risks and the aim is to build the adjacency matrix of the project risk directed weighted graph, the vertices of which are project risks, and the edges of which are project risk interactions (as defined in this work). The reader should note that project risks are (or can at least be supposed as):

- in a finite number (since a project is in essence temporary, with finite resources, objectives, means, etc., i.e. a finite number of elements),
- managed during the project management process,
- interrelated, (notably because of project complexity factors (Vidal and Marle, 2007)) which justifies the use of a methodology for complex interactions management.

Given an existing project risk network, it can be expressed in the form of a binary matrix, where $R_{ij} = 1$ if a risk interaction exists from R_j to R_i. This binary matrix permits to express in a synthetic manner the interactions which exist between risks.

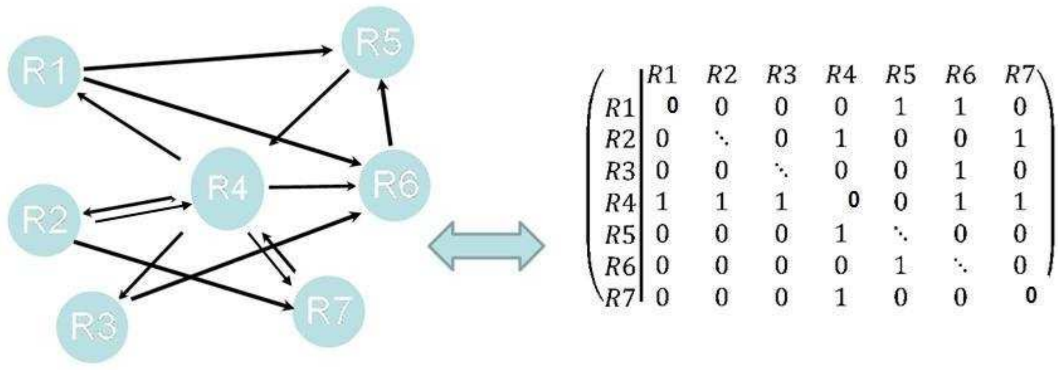

Figure 59. Transforming a project risk network into a RSM

In order to build up the RSM, risk interactions must be properly identified. This identification process is performed thanks to an iterative procedure. Classical risk identification enables to get a risk list, called L_0. L_0 has a dimension of N_0, which means that N_0 risks were identified. The aim of our procedure is to get a stable list of risks, which means that interactions between risks are inside this list. The aim is to obtain a closed system. The procedure for construction of the RSM matrix is the following one:

For each R_i in L_0, $i \in \{1..N_0\}$, we identify direct potential causes and consequences $\{DPC_k(i)\}$.

- Then, for each k, if $DPC_k(i) \in L_0$, then $\exists$ j $\in \{1..N_0\}$ so that $DPC_k(i) = R_j$

And we have else $RSM_{i,j}$=1 (if R_i is a potential consequence of R_j), else $RSM_{j,i}$=1 (if R_j is a potential cause of R_i), else the two of them.

- If $DPC_k(i) \notin L_0$, then we define $DPC_k(i) = R_{N0+1}$

$L_1 = \{L_0 + \{ R_{N0+1}\}\}$, L_1 is a N_0+1 long list.

$RSM_{i,N0+1}$=1 or/and $RSM_{N0+1,i}$=1 (depending whether R_{N0+1} is a cause or a consequence for R_i).

This operation is repeated until $L_{k+1} = L_k$, which means that no new risk is identified thanks to interaction with an existing risk of L_k. At the end, we obtain a matrix RSM which is NxN, by initiating a N_0xN_0 matrix and enriching it with new identified interactions ($N=N_0+k$). The process is a binary identification of interactions between risks.

This process enables to address partially a classical issue in risk identification which is exhaustiveness. Namely, projects may often stop to identification of L0, and then miss a potentially important number of other risks. Finally and more important in this case, this process enables to get exhaustive and consistent information about interactions between risks, as a sanity check is put between Ri and Rj. If Ri declared Rj as a cause, but Rj did not declare Ri as a consequence, then there is a mismatch. Each mismatch is studied and solved, like analogous works by Sosa about interactions between actors (Sosa and al., 2004).

Classically, the DSM is re-ordered in a way which permits to show first-level blocks, thanks to the well-established partitioning process (Gebala and Eppinger, 1991). This one applied to the RSM gives three types of information:

- the dependent risks: they are engaged in a potential precedence relationship,
- the interdependent risks: they are engaged in mutually dependent relation, directly or with a bigger loop,
- the independent risks: the risks are basically non-related.

The aim of this process is basically to obtain a matrix which is block-lower triangular matrix. Partitioning enables to isolate interdependent risks, but the final purpose of this work is different, since it aims at grouping risks in clusters with maximal internal interactions and minimal inter-clusters interactions. To do so, the RSM needs to be transformed into a numerical matrix which can to some extent catch the strength of local interactions (Marle and Vidal, 2008).

VI.2.4. Building up the Risk Numerical Matrix (RNM)

For this particular issue of transforming the RSM into the RNM, direct expert evaluation can be performed by judging on a several level (for instance 10) Likert-scale the strength of interactions. But, for all practical purposes, direct evaluation is sometimes difficult. We thus propose an assessment which is based on the AHP pair-wise comparisons as in (Chen and Lin, 2003). steps are necessary to carry out this work (see Figure 61):

- Step 1: For each R_i, isolating (from the RSM) the risks which are related with R_i in column (possible effects of R_i) and in row (possible causes of R_i). They are called the Binary Cause or Effect Vectors and are relative to one risk R_i ($BCV|R_i$ and $BEV|R_i$). An example is given for risk R_4.

- Step 2: Buiding up pairwise comparison matrices regarding the risk R_i based on the two previously isolated sets of risks (in rows and in columns), which are to be the set of alternatives on which the calculations are done. They are called Cause or Effect Comparison Matrices and are also relative to one risk R_i ($CCM|R_i$ and $ECM|R_i$).

- Step 3: Consolidating the results thanks to a proper consistency index and finding the eigenvectors of the previously built pairwise comparison matrices: the Numerical Cause or Effect Vectors and are relative to one risk R_i.(NCV_i and NEV_i).

- Step 4: Aggregating the results obtained for each risk R_i into global Numerical Cause or Effect Matrices (NCM and NEM).

- Step 5: Compiling the Numerical Matrices into a Risk Numerical Matrix (RNM).

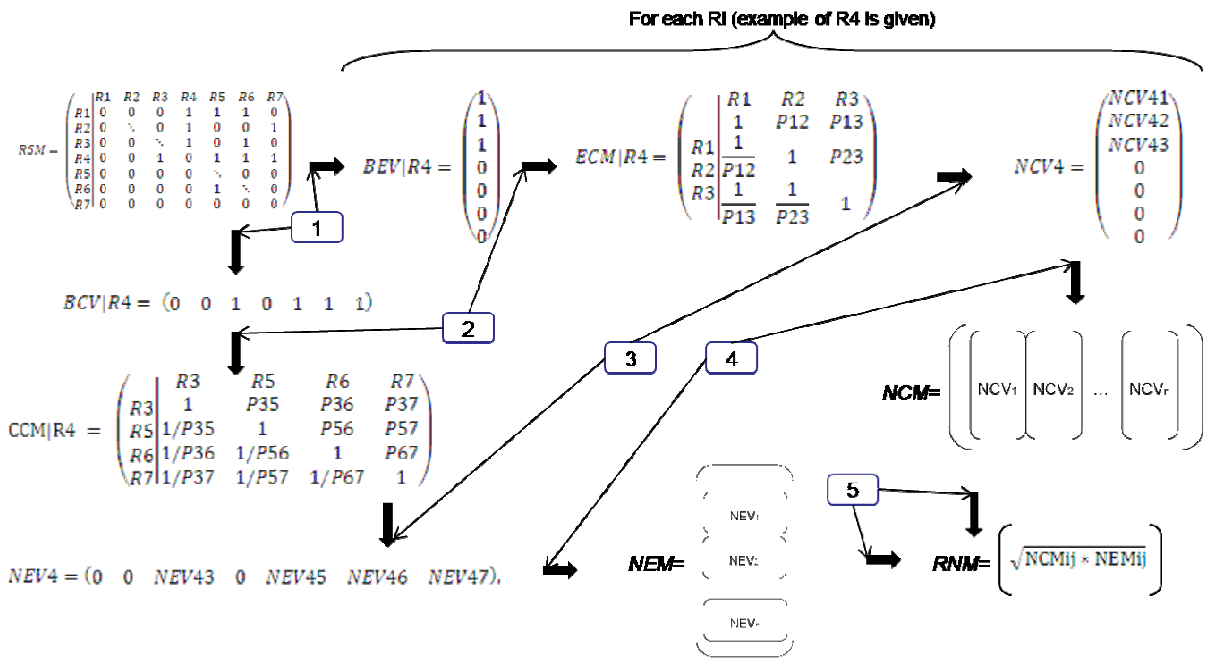

Figure 60. Transforming the RSM into the RNM

The presence of a 1 in the binary RSM expresses the existence of a possible precedence relationship between risks R_i and R_j. $RSM_{ij}=1$ implies two different possible ways to address the situation: this can be seen either as a possible risk input of R_i coming from R_j, either as a possible risk output from R_j reaching R_i. Similarly as in (Chen and Lin, 2003) for design tasks, these two visions are combined in this work. That is why a two-way comparison methodology is needed to achieve the project risks pairwise comparisons.

Two stages must indeed be performed successively. The first one consists in the ranking in rows for each project risk. Given the risk R_k, the set of alternatives are all the non-zero elements of risks other than the diagonal element in row k. The criterion on which the alternatives are evaluated is the contribution to R_k in terms of risk input: in other terms, for every pair of risks which are compared, R_i and R_j (thus following $RSM_{ki}=RSM_{kj}=1$), the user should assess which one is more important to risk R_k in terms of probability to be a risk input (i.e., a cause) for risk R_k. Numerical values can express these assessments thanks to the use of the traditional elementary Saaty scales. Eigenvectors of each matrix $ECM|R_k$ and $CCM|R_k$ should then be calculated. By combining the n eigenvectors NEV_k and NCV_k, we obtain two square matrices called NEM and NCM.

The i^{th} row of NEM corresponds to the eigenvector of $CCM|R_i$, which is associated to its maximum eigenvalue. The j^{th} column of NCM corresponds to the eigenvector of $ECM|R_j$, which is associated to its maximum eigenvalue. The traditional consistency index of the AHP is calculated to ensure the overall coherence of the judgments.

A geometrical weighting operation permits in the end to calculate the elements of the RNM (this permits a consideration of both evaluations at a same level).

$$RNM(i,j) = \sqrt{NCM(i,j) \times NEM(i,j)}$$

$$\forall (i,j), 0 \leq RNM(i,j) \leq 1$$

This calculation permits an overall estimation of the i-jth term since it permits to aggregate (at the same level of influence) the two approaches which were discussed before.

VI.2.5. *Direct uses of these matrices as an assistance to project risk management*

Before carrying out the works on an innovative interactions-based risk clustering methodology which is pursued here, some direct elementary applications of the RSM and RNM are mentioned in this paragraph. It aims at describing how the corresponding tools can directly assist complex project risk management.

VI.2.5.i. Identifying potential risk loops

Potential risk loops within the complex project risk network can be identified thanks to a method which uses the powers of the RSM (adjacency binary matrix) in order to identify successively higher order loops (Ledet and Himmelblau, 1970). Raising this matrix to the nth power permits to obtain two results:

- When calculating the nth power of the RSM thanks to Boolean arithmetic, the result is a higher-order binary matrix, where a non-null element a_{ij} corresponds to the fact that Risk i can be reached from Risk j in n steps.
- When calculating the nth power of the RSM thanks to traditional arithmetic, the result is a numerical matrix (integer values), where a non-null element a_{ij} corresponds to the number of possible paths from R_j to R_i, the length of which is exactly n.

Potential risk loops can then be identified thanks to the diagonal elements of these matrices. Risks which are potentially involved in loops should be highlighted in a risk analysis process, so that greater attention is paid to them if occurring during the execution of the project.

VI.2.5.ii. Studying the possible propagation of a given project risk

In order to study the propagation of a specific risk within the project risk network, may it occur, powers of the RSM can be calculated as before. Reading the jth columns of the nth power of the RSM permits to identify all the risks which can be reached from R_j thanks to a path of length n. Let N be the order of the corresponding project risk graph (i.e. the number of identified project risks). If two risks are connected along a path, then the maximum value of the shortest path which connects them is in essence (N-1). In other words, there is no use performing more than the (N-1)th first powers of the RSM to identify all the risks which can be reached along a path from an initial risk R_j. Distribution-like curves can then be built thanks to these matrices in order to study more precisely the possible propagation of a given project risk. An example of such curves can be found hereunder in Figure 62.

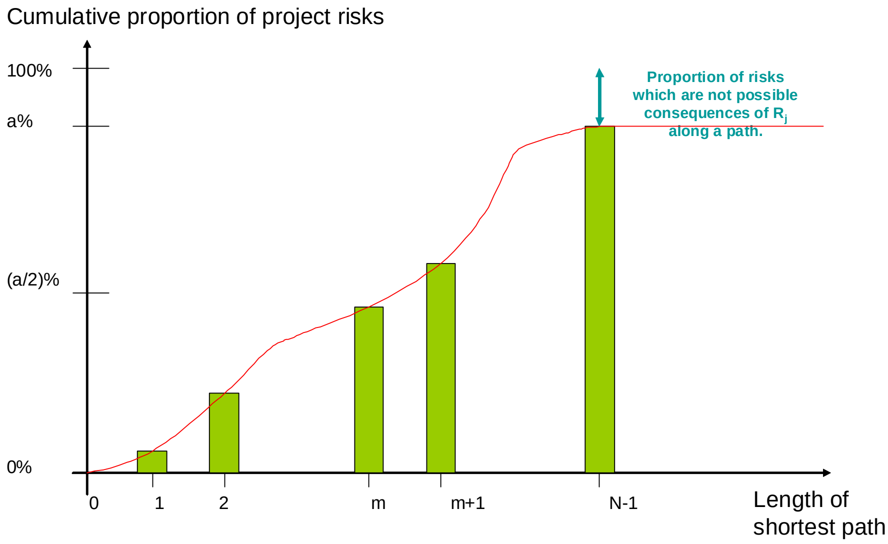

Figure 61. Analysing the possible propagation of a risk within the project risk network

As shown on this Figure, some indicators can be calculated in the end to analyse and compare risks in terms of their possible propagation within the project risk network in columns (ORCo – Other risks as consequences):

- α, which is the proportion of risks which are possible consequence of R_j along a path. This proportion thus gives the proportion of risks which can be reached according to propagation phenomena starting from R_j.
- Mean shortest path value (MSP_j) can be evaluated. This value is when the cumulative proportion of reached project risks curve crosses the (α/2) value (between m and m+1 in Figure XXXX). Average shortest path value (ASP_j) can be calculated too.
- Finally, the ratio FLR of first level risks (one edge) and the ratio SLR of second level risks (two edges) can be evaluated to highlight short path consequences.

Similarly, when analysing the powers of the RSM in rows (ORCa – Other risks as causes), one can calculate β, which is the proportion of risks which are non possible causes for a given risk R_i along a path (whatever its length). This proportion thus gives the proportion of risks which can reach R_i according to propagation phenomena within the project risk network. Similarly MSP^i and ASP^i can be evaluated to estimate the corresponding mean and average shortest paths.

For all practical purposes, all these indicators are likely to permit a finer process of risk analysis thanks to a better integration of propagation phenomena within the project risk network. For instance, risk managers can identify risks which are likely to have many children in the risk network and may decide to pay greater attention to them in the risk mitigation plan or in the risk monitoring and controlling processes.

VI.3. Interactions-based clustering of project risks

VI.3.1 Problem definition

As mentioned before, risks become higher in number, criticality and interdependence within projects, notably due to their increasing complexity. Clustering risks into relevant clusters for an assistance to project risk management is thus all the more important. The point is that traditional clusters (according to criticality, risk nature, etc…) do not take into account risk interactions. In the end, interactions between the obtained clusters do appear, and the corresponding interfaces are likely to be sources of difficulties for project risk management. Efficient risk clustering which can take risk interactions into account is thus needed for modern and complex project risk management.

This section thus addresses the following sub-questions:

- What clustering criterion should be used? Which clustering methodologies do exist? Since project risks form a graph as mentioned in VI.2.1, in order to answer these questions, a state of the art on the graph partitioning and clustering problems is performed in *VI.3.2*.
- How can the chosen clustering operation can be formulated mathematically? Knowing that the clustering operation is to be performed thanks to the data of the RNM (which are in essence approximation of real transition probabilities), the robustness and invariance of the clustering solution is also to be addressed. These points are addressed in *VI.3.3* and *VI.3.4.*
- Since the clustering operation is to be complex in terms of algorithm performance, can some approximate algorithms / heuristics be defined in order to approach the solution? Can the solution be refined thanks to other conditions for the clustering solution to be an efficient tool as an assistance to complex project risk management? These points are addressed from *VI.3.5* to *VI.3.7.*
- Finally performance indicators are proposed in *VI.3.8* to evaluate and compare possible clustering solutions.

VI.3.2 State of the art on graph partitioning and clustering

A state of the art on graph clustering and graph partitioning problems was carried out in order to define our problem more precisely, to identify possible clustering criteria and methodologies, and to formulate the problem mathematically in the end.

Two families of criteria (and the corresponding methodologies) do exist when dealing with the issues of project clustering and partitioning. The first one corresponds to criteria and methodologies which are based on the concept of vertex similarity and the second one corresponds to criteria and methodologies which are based on some cluster fitness measures, as underlined in (Schaeffer, 2007).

VI.3.2.i. Vertex similarity-based criteria and methodologies

There are several clustering algorithms which are based on similarities between the vertices. These methods are based on the assumption that the higher the vertex similarity, the stronger the need to cluster the vertices together. These measures are mainly based on additional properties of vertices which permit to compute a similarity matrix (see *VI.3.6* for more detail). Rather than defining similarity measures, dissimilarity measures such distance measures are usually defined, for instance the traditional Euclidean and Manhattan distances (Hennig and Hausdorf, 2006). More advanced distance such as Jaccard distance (Dong and al., 2006) or the Levenshtein distance (Gusfield, 1997) can be used to answer this issue. Rather than distances, some other coefficients can be calculated to evaluated vertex similarity and perform the corresponding clustering process: for instance there exists angle measures such as the cosine similarity (Lakroum and al., 2005) or numerical measures such as the Tanimoto coefficient (Tanimoto, 1957).

As noticed by (Schaeffer, 2007), “in some applications, the vertices lack additional properties and there is nothing in the vertices themselves that would allow the computation of a similarity matrix”. In this case, vertex similarity measures are often defined thanks to the structural characteristics of the graph. Some measures based on the correlation of the adjacency matrix such as the Pearson correlation (Rodgers and Nicewander, 1988) or the Mahalanobis distance (Mahalanobis, 1936).

Finally vertex similarity measures can be related to the concept of vertex connectivity. In other terms, some measures are based on the number of possible paths which exist between each pair of vertices (Hartuv and Shamir, 2000). These measures are very close to the coefficients α and ß, which were proposed earlier in this work as direct tools to analyse the possible propagation phenomena within the project risk network.

VI.3.2.ii. Cluster fitness measures-based criteria and methodologies

Some clustering processes are based on cluster fitness measures, that is to say functions which assess the overall quality and relevance of a given cluster or of a given global clustering solution. The global objective of these methodologies is to identify clustering solutions which directly fulfil a certain property. For instance, methodologies based on graph density measures have been developed in order to partition the initial graph into subgraphs, the density of which should be inferior and/or superior to chosen values (Karp, 1977), (Kim, 2003). But other cluster fitness measures are used as a criterion for graph partitioning.

Indeed, as noticed by (Schaeffer, 2007), “one measure that helps to evaluate the sparsity of connections from the cluster to the rest of the graph is the cut size. The smaller the cut size, the better isolated the cluster”. Indeed, cutsize-based measures undoubtedly permit to quantify the relative independence of a subgraph to the rest of the graph and have been used in many clustering processes (Shi and Malik, 2000), (Kannan and al., 2004). Finding the partition which minimises cut-sizes (with restriction conditions on the orders of the subgraphs) permits to maximise the sum of the edges weights which are internal to the clusters. This cut-based measure seems very interesting in our case. In order to facilitate complex project risk management, one is likely to want to reduce interfaces in terms of number, and above all strength. Reducing interfaces is thus very similar to this problem of graph partitioning which aims at minimising the global cut size (since risk interactions are modelled and assessed thanks to edges and their weights).

VI.3.3 Problem formulation as a linear programming model

As a consequence, in order to facilitate project risk management and coordination, we propose to cluster risks in order to maximize intra-cluster interactions thanks to the use of the RNM. Let us consider a set of project risks (R_1, R_2, …,R_N). As seen before, due to project complexity, this set of risks is in essence a complex one, since interactions do exist between risks.

Let us suppose that the RNM of this set of risks is known (the former steps to build the RNM should have been followed by the user). Let K be the number of clusters of the optimal clustering solution, which maximises intra-cluster global interactions value. This INTRA value is defined by the sum of the values of all interactions between risks which belong to a same cluster. The INTER (Inter-cluster global interactions) value is defined by the sum of the values of all interactions between risks which are not paired inside a same cluster. The sum of INTRA and INTER values corresponds to the sum of all risk interactions values, which is constant. As a consequence, maximizing INTRA is equivalent to minimizing INTER.

The point is that K is not known in advance. However, some constraints may be elaborated for K. Namely, the goal is to assign project members to each cluster in order to manage the risks inside the cluster. People have a limited capacity to manage simultaneously numerous objects. We follow the hypothesis that in the end, the maximum size of a cluster should be 9, as some margin is left compared to the classical empirical rule of 7 objects to be managed simultaneously. This consideration permits to know a lower bound of K, which is $K_{\min} = INT(\frac{N-1}{9})+1$, where INT is the integer part of a real number. Upper bound is obviously N, the number of risks.

Here is the corresponding integer programming problem formulation. This problem is to be solved for each value of K which is superior to K_{min} and inferior to N. This problem belongs to the family of the graph K-partitioning problems (Schaeffer, 2007).

The decision variables of the problem are the following ones:

(1) $\forall i, 1 \le i \le N, \forall k, 1 \le k \le K, x_{ik} = 1$ if risk R_i belongs to cluster C_k.

The objective function, which is to be maximized, is given in equation 2

(2) $$INTRA = \sum_{k=1}^{K}\sum_{i=1}^{N}\sum_{j=1}^{N} x_{ik} x_{jk} RNM(i, j)$$

The reader should first pay attention to the fact that the values of the RNM are local judgements, which implies that risk interactions assessments are in essence relative. However, we do argue that a first clustering thanks to these values is useful, since it permits the user to focus on the most significant local risk interactions and since proportions between these relative judgements and proportions between real transition probabilities may be very similar (Vidal and al., 2009b).
Problem constraints are the following (equations 3 and 4).

(3) $\forall i, 1 \le i \le N, \sum_{k=1}^{K} x_{ik} = 1$ as we argue for clusters disjunction in order to permit easier management in practice.

(4) $\forall k, 1 \le k \le K, \sum_{i=1}^{N} x_{ik} \le 9$ since we want the maximum size of clusters to be 9 risks.

The reader should note at this stage that other conditions than Eq. 4 can be used to put a restriction on the size of clusters. Some conditions might be that the sizes of the obtained clusters may be equivalent or that the internal weights of each cluster may not be over a certain fixed size.
The condition given in Eq. 4 was chosen here because of the direct need for a restriction on the number of risks within any cluster, in order to facilitate for future management. Future research works may include the study of other constraints for the problem.
This problem is not linear but we can make it easily linear thanks to the introduction of new decision variables (equation 5) and new constraints (equation 6).

(5) $\forall i, 1 \le i \le N, \forall j, 1 \le i \le N, \forall k, 1 \le k \le K, y_{ijk}$ is a binary variable

We define y_{ijk} by adding the constraints:

(6) $\forall i, 1 \le i \le N, \forall j, 1 \le i \le N, \forall k, 1 \le k \le K, y_{ijk} \le x_{ik} + x_{jk} - 1$

This forces y_{ijk} to be equal to 0 if x_{ik} and x_{jk} are not both equal to 1, i.e. if R_i and R_j do not belong to the same cluster. All other constraints are kept for problem formulation. Note that the objective function can then be re-written thanks to these new decision variables, in equation 7.

(7) $INTRA = \sum_{k=1}^{K} \sum_{i=1}^{N} \sum_{j=1}^{N} y_{ijk} RNM(i, j)$

In the end, OPL (Optimization Programming Language) can be used in order to solve this problem. However, the complexity of it is high. The graph K-partitioning problems were proved to be NP-hard (Garey and al., 1976), (Falkner and al., 1994), (Sima and Schaeffer, 2006), which means that it is at least as hard as the hardest problems in NP. For all practical purposes, this means there are currently no known polynomial-time algorithms which can give the exact solutions of these problems. This remains true even if edge weights are one and the number of partitions (or clusters) K is 2. This was notably underlined in this work since problems over 20-21 risks appeared to be critical (impossibility to give solution because of resolution time) when testing them first.

The reader should note that if the number of partitions K is fixed and there is no restriction on the size of the partitions, then the problem is solvable in polynomial time $O(N^{K^2})$, where N is the number of vertices in the graph (Goldschmidt and Hochbaum, 1994). However, this is not interesting in the case of this work since clusters are built up for future management and restriction on their size is thus needed.

But the objective of this study is to give a tool which can assist project risk management through interactions-based risk clustering. It may not be worth the effort to find the best possible solution, but a not-too-bad solution is very likely to suffice. That is why some less consuming iterative algorithms can be written in order to approximate the optimal solution of the problem (see *VI.3.5*).

VI.3.4 Discussing the invariance of the results

The reader should notice that the AHP-based evaluation of the risk interactions in terms of possible precedence is an approximation. Indeed, the evaluation obtained is to some extent an approximation of transition probabilities, which is obtained through local expert judgment (as argued in (Chen and Lin, 2003). The clustering solution which is obtained is relevant since it is based on the relative evaluation of transition probabilities. However, the issue of the robustness and invariance of the clustering obtained is thus to be addressed. The problem which is studied answers the following question.

Let *P(i,j)* be the real transition probability from R_i to R_j. Assuming that a transformation function *f* exists and verifies *P(i,j) = f (RNM(i,j))* as a first approximation, then one could wonder if the clustering solution which is obtained varies when the coefficient vary from *RNM(i,j)* to *P(i,j)*. Two propositions are proved hereunder to give sufficient conditions on *f* so that the clustering solution is invariant regarding this transformation of the coefficients.

Proposition a. The solution obtained does not vary when the RNM varies according to an increasing linear function, which means that

- f is increasing
- $\forall(\lambda,\mu)\in\Re^2, \forall(x,y)\in\Re^2,\ f(\lambda x+\mu y)=\lambda f(x)+\mu f(y)$

Proposition b. The solution obtained does not vary when the RNM varies according to a function which respects the following conditions

- f is increasing
- $f(0)\geq 0$
- $\forall(\lambda,\mu)\in Z^2, \forall(x,y)\in\Re^2,\ f(\lambda x+\mu y)\geq\lambda f(x)+\mu f(y)$

PROOF

Proposition a.

Let us suppose that the RNM varies according to an increasing linear function *f* and that the optimal clustering solution of the initial problem is named S_1. The new objective function when performing the algorithm is

$$NEWINTRA = \sum_{k=1}^{K}\sum_{i=1}^{N}\sum_{j=1}^{N} x_{ik}x_{jk} f(RNM(i,j))$$

Then, the following calculations can be performed

$$NEWINTRA = \sum_{k=1}^{K}\sum_{i=1}^{N}\sum_{j=1}^{N} x_{ik}x_{jk} f(RNM(i,j))$$

$$= \sum_{k=1}^{K}\sum_{i=1}^{N}\sum_{j=1}^{N} f(x_{ik}x_{jk} RNM(i,j))$$

$$= f(\sum_{k=1}^{K}\sum_{i=1}^{N}\sum_{j=1}^{N} x_{ik}x_{jk} RNM(i,j)) = f(INTRA)$$

where INTRA is the objective function of the initial problem.

Knowing that S_1 permits to reach the optimum of INTRA, knowing that *f* is increasing, this proves that the clustering obtained in S_1 is still the best solution which can be obtained despite the variations of the RNM.

Proposition b.

Let us suppose that the RNM varies according to a function *f* which respects the conditions of Proposition b and that the optimal clustering solution of the initial problem is named S_1. The new objective function when performing the algorithm is still

$$NEWINTRA = \sum_{k=1}^{K}\sum_{i=1}^{N}\sum_{j=1}^{N} x_{ik}x_{jk} f(RNM(i,j))$$

Let S_2 be another clustering solution for the initial problem. Let INTRA(S) be the value of the objective function of the initial problem for a clustering solution S. We know that

$$INTRA(S_2) \le INTRA(S_1)$$

Let us now compare the two solutions S_1 and S_2 for the new problem.

$$NEWINTRA\ (S_1) - NEWINTRA\ (S_2) = \sum_{i=1}^{N}\sum_{j=1}^{N}(\sum_{S_1} x_{ik}x_{jk} - \sum_{S_2} x_{ik}x_{jk}) f(RNM\ (i,j))$$

$$\ge\ f(\sum_{i=1}^{N}\sum_{j=1}^{N}(\sum_{S_1} x_{ik}x_{jk} - \sum_{S_2} x_{ik}x_{jk})(RNM\ (i,j))$$

$$=\ f(\sum_{i=1}^{N}\sum_{j=1}^{N}\sum_{S_1} x_{ik}x_{jk} RNM\ (i,j) - \sum_{i=1}^{N}\sum_{j=1}^{N}\sum_{S_2} x_{ik}x_{jk} RNM\ (i,j))$$

$$\ge\ f(0)$$

$$\ge 0$$

which proves that the solution obtained in S_1 remains the best solution here. End of proof.

The invariance of the results regarding these two transformations makes the results obtained more robust, notably because of the interests of these conditions. For instance, the real transition probabilities may notably be considered as a first approximation as a linear function $f(x) = ax$ with $a>0$, which means that f is increasing. Indeed, let $RNM(i_o,j_o)$ be the maximum value of the RNM. Then, if one is able to assess $P(i_o,j_o)$, $P(i,j)$ can be evaluated thanks to the transformation

$$P(i, j) = \frac{P(i_0, j_0)}{RNM(i_0, j_0)} \times RNM(i, j)$$

since the proportions between relative local judgements may be considered as approximations of the proportions between real transition probabilities as a first approximation.
This transformation verifies the conditions of *Proposition a*, which means that the clustering solution does not vary when performing it. In other terms, results of the clustering algorithms are invariant if the values in the RNM vary according to relative uncertainties, and not according to absolute uncertainties. This seems to some extent relevant since the construction of the RNM values is partly based on relative evaluation of the values: proportional variations are thus more likely to appear than different absolute variations. Other transformations and invariance conditions might be studied in the future.

VI.3.5 Proposals of approximate iterative algorithms

Two approximate iterative algorithms are proposed for study. Both of these algorithms are iterative, but they use two different values for clustering conditions, as described in equations 8 and 9. The first iterative algorithm IA_1 is based on the maximum value between separate clusters. The second one IA_2 is based on global interactions value between clusters. In the two cases, these values are to be maximized at each step.

(8) $$Value_1(C_\alpha, C_\beta) = \max_{i \in C_\alpha, j \in C_\beta} RNM(i, j)$$

(9) $$Value_2(C_\alpha, C_\beta) = \sum_{i \in C_\alpha, j \in C_\beta} RNM(i, j) + RNM(j, i)$$

At the initial step, all risks are isolated, i.e. every initial cluster is a singleton. The maximum value is thus obtained for two isolated risks R_{i0} and R_{j0}, which are grouped into a first cluster C_1. At each following step, the previous value ($Value_1$ or $Value_2$) is maximized. This procedure is repeated iteratively until reaching a solution which respects all the constraints. In the case the maximum size of a cluster is reached before the end of this procedure, the second maximum value in the RNM is identified and the clustering operation is done on the corresponding interaction. It can be proved easily that the possible conditions which are proposed in to assure the invariance of the results when perturbing the RNM. These algorithms belong to the family of agglomerative clustering algorithms (Schaeffer, 2007). They correspond to the pair-wise nearest neighbours (PNN) method, and the merging criterion is based on the clustering measures which are given in

Eq. 8 and 9. The complexity of these algorithms is less high since it is $O(N)$ and can even be reduced, as shown by Fränti and al. (Fränti and al., 2006).

VI.3.6 Refining solutions through similarity-based clustering

Our goal here is to refine our results by identifying within clusters similar situations in terms of causes and effects, i.e. the less distant risks. Many distances (i.e. similarity functions) can be proposed in order to assess the proximity of two risks. To define them, we build up a symmetrical matrix thanks to the initial RNM (weighted adjacency matrix), the Risk Interaction Matrix (RIM), the i-j[th] term of which is given by

$$(10) \qquad RIM(i,j) = \frac{RNM(i,j) + RNM(j,i)}{2}$$

At this stage, note that any metric can be used in order to define this distance and indeed, many have been used (Johnson, 1967), (Morrison, 1967), (Hartigan, 1975), (Fowlkes and Mallows, 1983). One could firstly think of using the traditional Euclidian distance (note that as the RIM is symmetric, the Euclidian row distance is equal to the Euclidian column distance), defining

$$(11) \qquad \Delta_{ij}^2 = \Delta_{ji}^2 = \sum_{k=1}^{n} (RIM(i,k) - RIM(j,k))^2$$

However, as noted in (Hartigan, 1975), this distance has very poor properties. As for us, we claim for the use of the Mahalanobis distance (Mahalanobis, 1936) given by the formula

$$(12) \qquad D_{ij}^2 = D_{ji}^2 = \Re_{ij}.S^{-1}.{}^t\Re_{ij}$$

where $\Re_{ij}$ is the 1×n vector, the k-th term of which is equal to [RIM(i,k)-RIM(j,k)], where ${}^t\Re_{ij}$ is the transpose of $\Re_{ij}$ and where S^{-1} is the inverse of the variance-covariance matrix of the RIM.

The Mahalanobis distance corresponds to a weighted Euclidian distance (the weights being determined by the covariance matrix). The use of this scale-invariant distance permits to penalise the low cause and low effect project risks (which generate high values in the RIM), since their corresponding columns and rows in the RIM are likely to be sources of high values in the variance-covariance matrix S. The calculation of the Mahalanobis distance for each pair (i,j) gives a distance matrix. We then use a classical average-linkage clustering algorithm (Murtagh, 1983) to identify similar situations inside clusters. Such identifications of similar risks (in terms of interactions) within the obtained clusters permit to give relevant information to the person in charge of the management of the cluster. Indeed, two similar risks may be approached and handled with similar managing techniques and/or even the same preventive/curative actions. That is notably why this possible refinement thanks to the concept of project risk similarity permits to generate finer approaches when managing project risks thanks to the set of obtained interactions-based clusters.

VI.3.7 Looking at this issue through the eyes of the connectivity concept

It was noted before that the linear programming problem was NP-hard. Therefore restrictions appear on the sizes of the problem if one wants to obtain the optimal solution. In order to permit the analysis of larger problems and obtain still the exact solution of the problem, we suggest to use the concept of graph connectivity and connected components (Biggs and al. 1986), (Bang-Jensen and Gutin, 2007). This concept permits to isolate unconnected sub-graphs (which means no existing path can connect them), as shown on Figure 63.

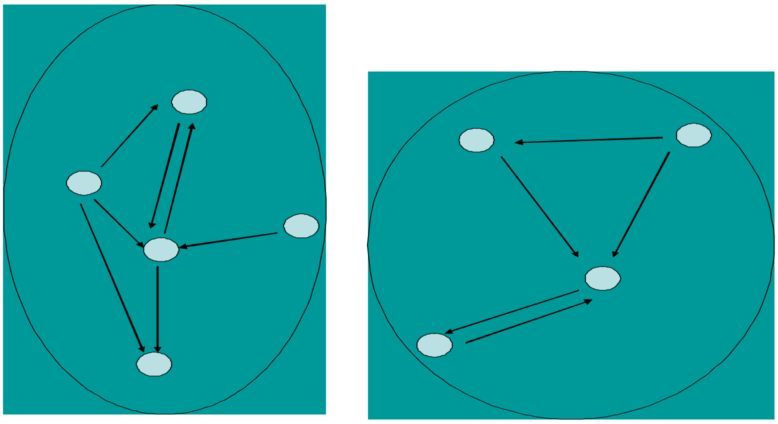

Figure 62. Digraph with two connected components

The following lemma can be proven.

Lemma

Looking for the optimal solution of the problem of the entire digraph is equivalent to looking for the optimal solutions of the problem for the subgraphs which are its connected components.

PROOF

This lemma can be proven by recurrence on C the number of connected components of the graph.

Initialisation

C = 1 is trivial. Let us explore the C=2 case.

Let $C_1 = (V_1,E_1)$ and $C_2 = (V_2,E_2)$ the two connected components of the graph G = (V,E). We have in essence $E = E_1 \cup E_2, V = V_1 \cup V_2$, $E_1 \cap E_2 = \emptyset$ and $V_1 \cap V_2 = \emptyset$.

The objective function which is to be maximized is

$$INTRA = \sum_{k=1}^{K} \sum_{i=1}^{N} \sum_{j=1}^{N} x_{ik} x_{jk} (RNM(i, j))$$

$$= \sum_{k=1}^{K} \Big(\sum_{(i,j)\in V_1^2} x_{ik} x_{jk} RNM(i, j) + \sum_{(i,j)\in V_2^2} x_{ik} x_{jk} RNM(i, j) + \sum_{(i,j)\in V_1 \times V_2} x_{ik} x_{jk} RNM(i, j) \Big)$$

But when R_i and R_j do not belong to the same connected component, they are not connected, which means that *RNM(i,j) = 0*. As a consequence,

$$INTRA = \sum_{k=1}^{K} (\sum_{(i,j)\in V_1^2} x_{ik} x_{jk} RNM(i,j) + \sum_{(i,j)\in V_2^2} x_{ik} x_{jk} RNM(i,j))$$

The two parts of this sum are mutually independent, which means that maximizing the whole function means maximizing the two parts of this sum. This exactly corresponds to the initial problem applied to the two connected components of the initial graph.

Iterations

Let us suppose the lemma is proven for C. Proving it for C+1 based on the same calculations as for the case C=2, with two subgraphs, one with C connected components, and one with 1.

The lemma is thus finally proved by recurrence. End of proof.

For all practical purposes, this permits to try to address larger problems since the size limitation becomes the maximum connected component size.

VI.3.8 Proposing performance measures for these algorithms

In order to compare different possible clustering alternatives, some performance indicators are needed. Given a problem with N risks and different possible clustering solutions, the first two indicators proposed in this work are:

- MPT = Mean Processing Time, which is the mean time to obtain the solution of the problem, functions of the methodology which is used. Note that drawing profiles MPT(N) for each methodology gives precious information in order to choose the methodology which is to be used for a given problem and situation.

- $\nabla INTRA(A,B) = \dfrac{INTRA(A) - INTRA(B)}{INTRA(A)}$, where A and B are two possible clustering solutions and INTRA is the value of the intra-cluster global interactions value which is obtained. $\nabla INTRA(A,B) \geq 0$ if the clustering solution obtained thanks to the A method is better than the one obtained with the B method. $\nabla INTRA(A,B)$ thus gives the user an idea of the relative improvement or degradation between two possible solutions.

Moreover, given a possible solution thanks to a method, a K × N matrix (M_{ki}), so that M_{ki}=1 if risk R_i belongs to cluster C_k in the final solution can be built. If ${}^T(M_{ki})$ is the transpose of this matrix, then:

- H=(M_{ki}).${}^T(M_{ki})$ is a K × K matrix, the diagonal terms of which correspond to the number of risks which are clustered in cluster K. MCS = Mean Cluster Size is then the average of the diagonal values of this matrix. This value can be taken into account in order to judge of the efficiency of the method used.
- L=${}^T(M_{ki})$.(M_{ki}) is a N × N matrix, the i-jth term of which is equal to 1 if R_i and R_j belong to a same cluster. As a consequence, the calculation of $\nabla M(A,B)$ which is the difference of

the two matrices L(A) and L(B), obtained thanks to methods A and B, permits to identify the similarity between two clustering solutions. Indeed, $\nabla M(A,B)$ is a N × N matrix, the elements of which are equal to 0 if and only if they face a same situation in the two clustering solutions (i.e., if and only if, they belong to a same cluster in A and B, or are not paired on the contrary). Let N_0 be the number of non-zero values in the $\nabla M(A,B)$ matrix. We propose the following indicator (equation 10) as a dissimilarity measure when comparing two clustering solutions. Note that mean cluster size is to be taken into account, since, if given a clustering solution, if one risk R_i is taken out of the cluster it belongs to, then MCS non-zero values are likely to appear (mean value) in the dissimilarity matrix for this risk R_i.

$$(13)\ \nabla(A,B) = \frac{N_0}{N^2 \times (\frac{MCS(A) + MCS(B)}{2})}$$

VI.4. Case studies

VI.4.1. A stage musical production project

VI.4.1.i Introduction

A first case study in the entertainment industry is carried out to test the validity of our approach and the confidence of the users in the result.

The chosen project is the production of a family stage musical in Paris. The project notably encompasses stage, costume, set, lightning and sound design, casting management, rehearsal management, fund raising and overall project management support activities, etc…

Staging duration target is 9 months at least. Target audience is family members aged 5 years old and more. Project duration is 6 months before staging. Project team is made of 6 permanent employees. Creative team is made of 7 people (lyricist/librettist, composer, director and choreographer, stage designer, light designer, costume designer, sound engineer).

The show is performed by a cast of 18 people, on the principle of alternating roles (9 on stage simultaneously). Overall budget is around 60000 € with salaries on a profit-share basis for cast and creatives, including an evaluation of the payment of the theatre for the whole staging period. Two financial investors and one media partner assist the project. The case study we present here is based on fieldwork and discussions which were conducted with 1 cast member, 2 creatives, and 1 production team member.

A list of 20 macroscopic risks was identified to perform the study. Traditional project risk management methodologies were applied for the identification and analysis process. This permitted to obtain a classification by nature and by value of the risks. An excerpt of this risk list is given in Figure 64.

Number	Risk name	Nature	Criticality	Potential consequences	Probability	Impact	P*I
1	Low budget	Cost & time	Unacceptable	2, 3, 4, 8, 10, 11, 12, 13, 14, 16, 17	8	7	56
2	Law and regulations infractions	Contracts	Unacceptable	4, 8, 10, 17	7	5	35
3	Low communication and advertising for the show	User / Customer	Unacceptable	7, 10, 15, 17	8	9	72
4	Unsuitable cast	Organization	Unacceptable	8, 10, 13, 15, 17	5	9	45
5	Unsuitable ticket price setting	Strategy	Unacceptable	1, 10, 15, 17	7	6	42
6	Unsuitable rehearsal management	Controlling	Acceptable	10, 17	3	8	24
7	Cancellation or delay of the first performance	Cost & time	Unacceptable	8, 10, 15, 17	5	8	40
8	Poor reputation	User / Customer	Acceptable	3, 7, 10, 17	3	7	21
9	Lack of production teams organisation	Organization	Acceptable	3, 7, 10, 15, 17	4	6	24
10	Low team communication	Organization	Acceptable	6, 8, 13, 17	3	6	18
11	Bad scenic, lightning and sound design	Technical performance	Neglectible	7, 8, 15, 17	2	7	14
12	Bad costume design	Technical performance	Acceptable	7, 8, 15, 17	3	8	24

Figure 63. Extract from the initial project risk list

VI.4.1.ii Results and discussions

The case study involves a list of 20 macro-risks. Initially, there were more risks but some were finally gathered under a common denomination. The construction process of the RSM was followed to identify project risk interactions. In the end, the risk graph was very connected, with a density of nearly 55%. In order to perform the case study, it was chosen to keep the values which represented 80% of the total values of interactions in the RNM (these ones represented about 35% to 40% of the values of the graph). The RNM of this problem is given hereunder in Figure 65.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	0,000	0,000	0,000	0,000	0,770	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,159	0,000	0,000	0,000	0,000	0,000
2	0,410	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
3	0,243	0,000	0,000	0,000	0,000	0,000	0,000	0,137	0,391	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
4	0,164	0,337	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
5	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
6	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,471	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,372	0,115
7	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,197	0,000	0,327	0,346	0,000	0,000	0,000	0,139	0,000	0,000	0,000	0,000
8	0,000	0,311	0,000	0,000	0,000	0,000	0,287	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,193	0,000	0,000	0,000	0,000	0,000
9	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
10	0,000	0,153	0,118	0,217	0,106	0,301	0,183	0,000	0,129	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,108	0,000	0,000	0,000
11	0,415	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,129	0,000	0,000	0,000	0,000	0,000	0,000
12	0,415	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,129	0,000	0,000	0,000	0,000	0,000	0,000
13	0,000	0,000	0,000	0,173	0,000	0,000	0,000	0,000	0,000	0,394	0,000	0,000	0,000	0,000	0,000	0,000	0,175	0,000	0,154	0,000
14	0,106	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,203
15	0,000	0,000	0,000	0,000	0,082	0,000	0,102	0,000	0,000	0,000	0,000	0,000	0,311	0,157	0,000	0,000	0,000	0,184	0,000	0,000
16	0,164	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
17	0,000	0,186	0,116	0,000	0,000	0,000	0,159	0,000	0,170	0,146	0,000	0,000	0,252	0,000	0,000	0,000	0,000	0,000	0,000	0,000
18	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,352
19	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
20	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000

Figure 64. RNM of the problem

Propagation phenomena were then analysed thanks to the identification of existing loops and a clearer analysis of propagation phenomena within the risk network thanks to the RSM and RNM. Indeed, some propagation curves are first to be drawn in order to understand the possible implications of the occurrence of a given risk. An example is given on Figure 66 for Risk 6, which is the macroscopic risk “bad rehearsal management”.

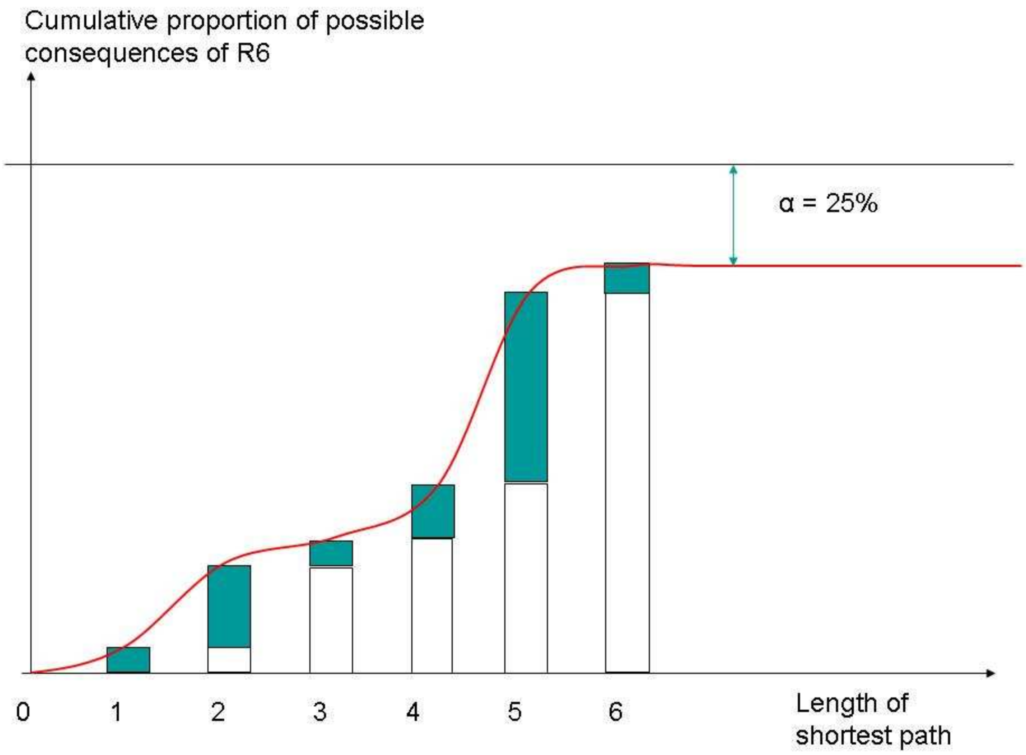

Figure 65. Possible propagation of risk R6 within the project risk network

Thanks to the powers of the RSM, this figure can be drawn. ASP and MSP can be calculated. In this case, MSP is 4.071 and ASP is 3.933. The proportion α of risks which cannot be reached by a path (of any length) from R6 is 25%. This percentage expresses that a great majority of risks are possible consequences of R6 over time, but the first level consequences (5%) and second level consequences (15%) appear to be very limited. Such indicators (α, β, MSP, ASP, first level consequences ratio, second level consequences ratio,…) are thus to be calculated in order to permit the effective comparison of project risks in terms of propagation possibilities.

Therefore, it is suggested to build up a global table which permits to address the issue of risk comparison regarding propagation given these indicators. In that case, here are the results of the risk propagation analysis (see Figure 67).

Such a table permits to give some insights on propagation phenomena. For instance, risk R5 can be stressed as a risk which may have many consequences in the project risk network (70% of first level and second level consequences). Risks R5 and R9 appear as origin risks since no path can lead to them. Risk R10 appears to be a node which may be at the confluent of many propagation chains. Indeed, 25% of the existing risks appear as first or second level consequences and 85% of the existing risks appear as possible origins for the occurrence of R10. Finally risks R6 and R10 appear to be involved in second order loops (minimal ones in), which means particular attention should be paid to a possible self-aggravation of the effects of these risks if occurring.

Risk	α (%)	MSP (ORCo)	ASP(ORCo)	FLR(ORCo) (%)	SLR(ORCo) (%)	β (%)	MSP(ORCa)	ASP(ORCa)	FLR(ORCa) (%)	SLR(ORCa) (%)	Min. Loop Order
5	25	1.409	1.867	15	55	100	0	0	0	0	0
6	25	3.833	3.933	5	15	0	1.875	2.500	15	40	2
7	25	1.875	2.267	20	20	0	3.333	3.700	20	10	4
8	25	5.071	4.600	5	10	0	1.778	2.450	15	45	6
9	25	1.875	2.600	20	20	100	0	0	0	0	0
10	25	5.071	3.067	15	10	0	1.222	1.800	40	45	2
11	25	2.875	3.000	5	20	0	3.250	2.700	10	15	4
12	25	2.875	3.000	5	20	0	3.250	2.700	10	15	4

Figure 66. Propagation comparative analysis of project risks

After this direct use of the RSM and RNM, the three interactions-based presented algorithms were processed. Their results can be seen next page in Figure 68. They only represent two graphs, since the second iterative algorithm (IA2) gave the same result as the linear programming (LP) algorithm. In this figure, they are compared to the two classical clustering results (by nature and value). The reader can also notably note that these results were refined. Indeed, the two risks R_{11} and R_{12} were analysed as very similar thanks to the Mahalanobis distance-based clustering method we use. The person in charge of the corresponding cluster should then think of handling these two risks with similar approaches (or at least be aware of the similarity of these risks inside the cluster).

In the end, interesting similarities and differences must be noted between the results which are obtained. As shown after in Figure 69 (synthetic indicators), it must be noted that interactions-based clustering give here much more efficient results in terms of interactions values within clusters, as expressed by the values of $\nabla INTRA$. The linear programming solving by OPL and the iterative algorithms which are used indeed give very interesting results and perspectives for project risk management since in all cases, more than 70% of the interactions values are kept inside the obtained risk clusters (nearly 5 times best than by nature, and 2 times best than by values). This appears all the more interesting than each cluster can then be dispatched to one project team member. In the end, coordination is facilitated in the project management risk process since interfaces are considerably reduced.

Moreover, in that case, the second iterative algorithm (IA2) and the linear programming solving give the same result, which underlines the possible efficiency of IA2. The first iterative algorithm gives us a slightly different result in terms of risks regrouping and intra-cluster interactions value.

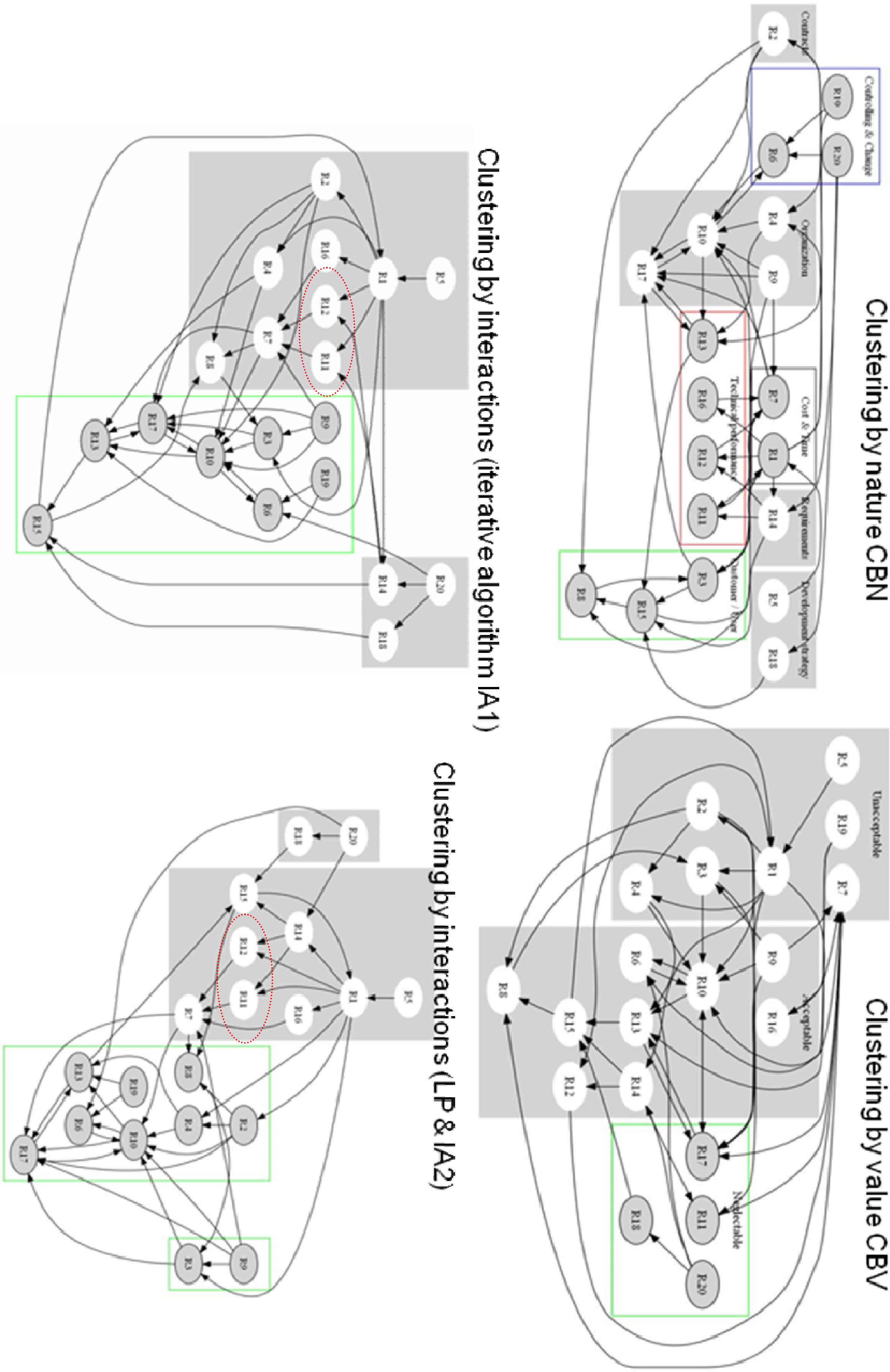

Figure 67. Results of the clustering algorithms

	Intra	MPT	MCS	Intra %
Clustering by nature	1,586	0 min	2,5	14,0%
Clustering by value	4,361	0 min	6,67	38,4%
Clustering by interactions PL	8,376	40 min	5	73,7%
Clustering by interactions AI 1	8,247	15 min	6,67	72,6%
Clustering by interactions AI 2	8,376	18 min	5	73,7%

$\nabla INTRA(A,B)$

	CPN	CPV	CPIPL	CPIAI1	CPIAI2
Clustering by nature	0,0%	-175,0%	-428,1%	-420,0%	-428,1%
Clustering by value	63,6%	0,0%	-47,9%	-89,1%	-92,1%
Clustering by interactions PL	81,1%	47,9%	0,0%	1,5%	0,0%
Clustering by interactions AI 1	80,8%	47,1%	-1,6%	0,0%	-1,6%
Clustering by interactions AI 2	81,1%	47,9%	0,0%	1,5%	0,0%

$\nabla M(A,B)$

	CPN	CPV	CPIPL	CPIAI1	CPIAI2
Clustering by nature	0,000	0,355	0,087	0,345	0,087
Clustering by value	0,355	0,000	0,072	0,400	0,072
Clustering by interactions PL	0,087	0,072	0,000	0,039	0,000
Clustering by interactions AI 1	0,345	0,400	0,039	0,000	0,039
Clustering by interactions AI 2	0,087	0,072	0,000	0,039	0,000

Figure 68. Performance of the clustering methods – First case study

The issue of the clustering methodology performance compared in terms of resolution time is thus to be addressed, since results do not differ much, whereas MPT can vary of around 275%. In order to address this specific point and to validate even more this overall approach, new tests are to be carried out on several projects. Another case study was notably carried out on a large infrastructure project.

VI.4.2. The case of a large infrastructure project

VI.4.2.i Introduction

The following case is the case of a large infrastructure project, which consists in the building of all the infrastructure and system which is dedicated to the future tramway of a 750 000 inhabitants city in a country C in the world by a French company.

This notably comprises:

- The construction of a depot to stock trains and execute their control and maintenance
- The installation of tracks throughout the city (the survey of which includes many changes in altitude)
- The construction of the corresponding trains.
- The establishment of a traffic signalling system, which gives priority to the tramway in order to assure a performance level in terms of future travel time. This point implies a particularly high level of complexity from the interconnected traffic signalling systems in the city.

An industrial partner realises the civil work which is to permit the installation of the tramway.

The project was initialized by the government of country C in 1995. The first selections of the firms which would execute the project occurred in 1999. The project contract was signed in 2002. After negotiations with banks, the government and the future operator (in which the French firm which executes the project holds shares), the final concession contract was signed in 2004. The project started in February 2005, with a practical start of the execution in 2006.Until now, a project risk management process has been carried out and led to the existence of 8 lists of risks which nurtured the successive risk reviews. We focus here on the System product line, which considers the integration of all the aspects of the project, and is thus to be one of the most complex ones, which motivated us to work on it with the firm. The corresponding risk list (42 risks) we have been working on can be seen afterwards on Figure 70. The 42 risks which are present in the list are very diverse and are classified according to six risk classes (risk nature). Risk ownership in terms of responsibility is dispatched to 12 actors in the project.

Actually, risk management presently receives moderate attention within the firm and the following issues are to be underlined:

- Risk lists are elaborated since they are to be done, but no real attention is paid to them and they are not used as much as they could be. Risk management is still too often considered as an academic work which in not necessary for day-to-day project management.
- Risk owners (in terms of responsibility) may sometimes be defined too quickly, since the examination of this list underlines that some ownerships should be rearranged. Indeed, risk owners belong to very varied hierarchical levels in the firm structure, and some risk owners are responsible for one risk while other ones are responsible for more than ten.

We hoped that our works though the consideration of risk interactions would create more inclination and confidence with the use of risk management approaches in the case of this project thanks to the underlining of neglected risks and risk interactions. The first remark is that when performing the study thanks to the iterative process of risk interaction identification, new risks appeared (since they were consequences / causes of some which were present in the initial list, or since they were seen as compulsory intermediary risks to explain the link between two risks which were present in the initial list). As a whole, 13 risks were newly identified for a lack of their presence in the list appeared (see Figure 71), which represents an increase of nearly 31% in the number of identified risk. Finally, 6 of the risks which were present in the initial list (R1, R8, R11, R15, R23, R34) were considered as poorly defined or possibly negligible.

	Review Session	RS8		IMPACTED			
	RISK IDENTIFICATION	PRODUCT LINE	RISK OWNER	QUALITY - SCOPE	DELIVERY (in months)	CLASS	INDIVIDUAL / COMMON
1	Safety studies	SYS	Actor A		0	Technical	Common
2	Liquidated damages on intermadiate milestone and delay of Progress Payment Threshold	SYS	Actor B		0	Contractual	Common
3	vehicle storage due to depot delay	SYS	Actor A	0	0	Contractual	Common
4	Vandalism on site	SYS	Actor C	0	0	Contractual	Common
5	Traction/braking function : behaviour in degraded mode on slope	SYS	Actor A		0	Technical	Common
6	Local laws and regulations	SYS	Actor A		0	Contractual	Common
7	Traffic signalling, priority at intersections	SYS	Actor D	0	0	Contractual	Common
8	Unclear Interface with the Client, for Infra eqt	SYS	Actor E		0	Contractual	Common
9	Delays due to client late decisions	SYS	Actor E		0	Contractual	Common
10	Travel Time performance	SYS	Actor D	0	0	Technical	Common
11	Limited Force majeure definition	SYS	Actor B		0	Contractual	Common
12	Operating certificate	SYS	Actor B	0	0	Contractual	Common
13	Reliability & availability targets	SYS	Actor D	0	0	Technical	Common
14	Permits & authorisations	SYS	Actor B		0	Contractual	Common
15	Insurance deductibles	SYS	Actor F	0	0	Financial	Common
16	Archeological findings	SYS	Actor B		0	Contractual	Common
17	Discrepancies Client / Operator / Concessionaire	SYS	Actor G	0	0	Contractual	Common
18	CW delay & continuity	SYS	Actor H		0	Contractual	Common
19	Responsibility of client on CW delay	SYS	Actor B		0	Contractual	Common
20	On board CCTV scope	SYS	Actor I		0	Technical	Common
21	Noise & vibration attenuation	SYS	Actor D	0	0	Technical	Common
22	Potential risks of claim from CW partner	SYS	Actor B	0	0	Contractual	Common
23	Harmonics level	SYS	Actor D		0	Technical	Common
24	Non compliance contractual Rolling Stock	SYS	Actor A		0	Technical	Common
25	Non compliance technical specs Rolling Stock	SYS	Actor A		0	Contractual	Common
26	Exchange risk on suppliers	SYS	Actor F		0	Financial	Common
27	Track installation equipment performance	SYS	Actor J		0	Client/Partner/Sub-contractor	Common
28	Tax risk on onshore	SYS	Actor F	0	0	Financial	Common
29	more poles	SYS	Actor D	0	0	Contractual	Common
30	Security requirements	SYS	Actor E	0	0	Technical	Common
31	Track insulation	SYS	Actor K		0	Technical	Common
32	Delay for energising	SYS	Actor D	0	0	Project Management, Construction site	Common
33	Fare collection requirements	SYS	Actor G	0	0	Contractual	Common
34	Construction safety interfaces	SYS	Actor C		0	Technical	Common
35	Electromagnetic interferences	SYS	Actor E	0	0	Technical	Common
36	Exchange risk	SYS	Actor F		0	Financial	Common
37	Risk of partial rejection of our request for EOT	SYS	Actor B	0	0	Contractual	Common
38	Interface rail / wheel	SYS	Actor E		0	Technical	Common
39	Risk on Certification of our equipement	SYS	Actor L	0	0	Country	Individual
40	OCS installation	SYS	Actor C	0	0	Project Management, Construction site	Individual
41	Banks stop financing the project	SYS	Actor B	0	0	Contractual	Individual
42	Costs of modifications not covered by EOT agreement	SYS		0	0	Contractual	Individual

Figure 69. Initial risk list of the System product line of the project

NEW RISKS	N°
Return profit	43
Extra trains	44
Pedestrian zones	45
Train performance	46
Waiting time at stations	47
Depot delay	48
Survey	49
Ticketing design delays	50
Track installation	51
Reengineering / Redesign	52
Slabs pouring	53
Initial specifications of CW	54
Available cash flow	55

Figure 70. Newly identified risk thanks to the risk interaction identification process

The identification of the existing risk interactions was thus performed and a direct evaluation on a 10 level Likert scale of the strength of interactions was executed. The feedback is that there were some difficulties while performing this step since:

- This step is to require the participation of several experts of the project for it implies a very wide view of the project elements and stakes.
- Some bias may be included in the evaluation of interactions since, even when trying not to do so, it appears that interactions are often thought at a first sight in terms of impact and not in terms of precedence. Great attention should thus be paid to that point in order to analyse the results.

In the end, a global Risk Numerical Matrix for the studied risk network was obtained. Compared to the musical staging project, this one's density was much lower and no feedback loops were present in it after the project risk interactions identification and evaluation steps. The corresponding RNM (on a 0 to 10 Likert scale) can be seen next page on Figure 72.

Even when separating in its connected components, the LP-problem was too large to be solved by OPL. The use of heuristics was thus necessary. The clustering iterative algorithm IA2 (which, on several tests, seems always better than IA1) was performed to obtain a first good approximate result for the clustering operation.

Before discussing the results, we must insist on a practical point when performing this iterative algorithm. Here, the values in the RNM are integer values, contrary to the ones of the former case study which had been obtained thanks to the AHP-based pair-wise comparisons. At some stage of the algorithm, some problems arise since equalities can be obtained and choices must be done between these equal maximum values inside the RNM. Operational tests seem to show that the final result is likely to depend on the order one decides to perform the clustering of these equal situations. In our case, the choice was performed thanks to a second criteria, which was that, in case of equality, then the clustering which was performed was the one which had the minimum interactions with the other risks or existing clusters.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55
1	1																																																						
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Figure 71. The RNM of the project

VI.4.2.ii Results and discussions

As a whole, the clustering algorithm IA2 was performed and the following clusters were obtained (Figure 73 and Figure 74). Several commentaries are to be performed:

- Some risks appear to be high accumulation risks, notably the budget related ones in terms of return profit (R43) or risk of rejection of extension of time EOT (R37) and liquidates damages (R2) (which can be seen visually on Figure 74 with two horizontal flows towards these risks). These ones are to be considerably watched over since many paths in the risk network are likely to lead to them. Same observation can also be made for travel time performance (R10).
- The obtained clusters seem to be quite consistent with the fieldwork as they form groups of risks which seem to be relevant in order to assist project risk management. Cluster C3 and C4 for instance permit to group possible chain reactions which could imply delay (respectively for the permits and authorizations, and for the depot construction and track installation). This appears to be all the more interesting than such chain reactions were not highlighted and managed before during the project. For instance, there were no discussions between Actor A and Actor E regarding the link between R3 (Vehicle storage due to depot delay) and R32 (Delay for energising), whereas this interface should have been particularly highlighted retrospectively.

RO Initial	Class Initial	C1
Actor B	Contractual	Liquidated damages on intermadiate milestone and delay of Progress Payment Threshold
Actor D	Technical	Travel Time performance
Actor J	Client/Partner/Subcontractor	Track installation equipment performance
Actor B	Contractual	Risk of partial rejection of our request for EOT
Actor B	Contractual	Banks stop financing the project
		Return profit
		Extra trains
		Waiting time at stations
		Available cash flow

RO Initial	Class Initial	C2
Actor B	Contractual	Potential risks of claim from CW partner
		Initial specifications of CW

RO Initial	Class Initial	C3
Actor E	Contractual	Delays due to client late decisions
Actor B	Contractual	Permits & authorisations
Actor G	Contractual	Discrepancies Client / Operator / Concessionaire
Actor G	Contractual	Fare collection requirements
		Ticketing design delays

RO Initial	Class Initial	C4
Actor A	Contractual	vehicle storage due to depot delay
Actor B	Contractual	Archeological findings
Actor H	Contractual	CW delay & continuity
Actor B	Contractual	Responsibility of client on CW delay
Actor D	Technical	Noise & vibration attenuation
Actor E	Project management, Construction site	Delay for energising
		Depot delay
		Track installation
		Slabs pouring

RO Initial	Class Initial	C5
Actor A	Contractual	New local laws and regulations
Actor D	Contractual	Traffic signalling, priority at intersections
Actor B	Contractual	Operating certificate
Actor D	Technical	Reliability & availability targets
Actor E	Contractual	more poles
Actor D	Technical	Security requirements
Actor L	Country	Risk on Certification of our equipement
		Reengineering / Redesign

RO Initial	Class Initial	C6
Actor A	Technical	Traction/braking function : behaviour in degraded mode on slope
		Train performance
		Survey

RO Initial	Class Initial	C7
Actor I	Technical	On board CCTV scope
Actor C	Project management, Construction site	OCS installation

RO Initial	Class Initial	C8
Actor A	Contractual	Non compliance technical specs Rolling Stock
Actor D	Technical	Interface rail / wheel

RO Initial	Class Initial	Isolated risks
Actor A	Technical	Safety studies
Actor C	Contractual	vehicle storage in Bellevue due to depot delay
Actor E	Contractual	Unclear Interface with the Client, for Infra eqt
Actor B	Contractual	Limited Force majeure definition
Actor F	Financial	Insurance deductibles
Actor E	Technical	Harmonics level
Actor A	Technical	Non compliance contractual Rolling Stock
Actor F	Financial	Exchange risk on suppliers
Actor F	Financial	Tax risk on onshore
Actor K	Technical	Track insulation
Actor C	Technical	Construction safety interfaces
Actor F	Financial	Exchange risk
???	Contractual	Costs of modifications not covered by EOT agreement
		Pedestrian zones

Figure 72. Results of the clustering operation

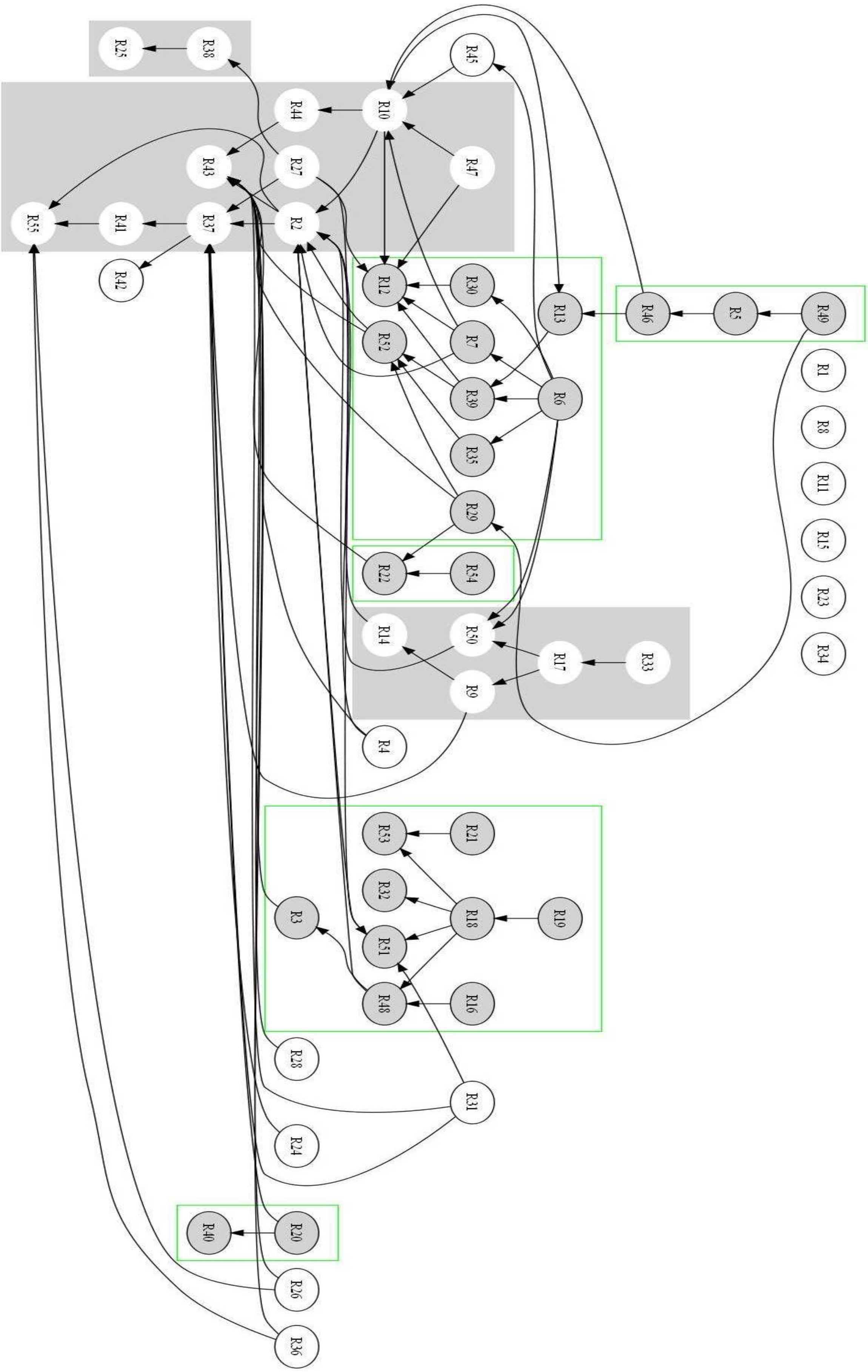

Figure 73. Clustered project risk network

- One commentary is that cluster C1 should however perhaps be separated into two parts by regrouping all financial risks in a sub-cluster. This appears all the more relevant than these financial risks are also linked to many other risks which exist in other clusters. Therefore, managing them as a complete cluster could for sure be very interesting.
- Another issue which arises is the question of risk ownerships. Indeed, it appears that within clusters, there are numerous risk owners, and often numerous risk classes. One question which is to be addressed is how such highlighted interfaces can be managed and how coordination can be facilitated since there seems to be some benefit to discuss with all the impact actors (risk owners) of a same cluster. One thing which was suggested is that a meeting with all the impacted risk owners of a cluster could permit to nominate / vote for a responsible for the cluster who could facilitate the coordination between the interrelated risks. One of the possible nominees for this cluster responsibility could be the least common boss in the hierarchical structure of the project.
- Moreover, new constraints might be added to perform more clustering solutions. For instance, new tests are to be conducted by varying the maximum possible size of a cluster. Another constraint which could be added would also be to add a maximum number of different risk owners within a cluster.
- As a whole, the feedback with this case study is that in order to obtain helpful results thanks to this methodology would be in the end to:
    - Perform pertinent risk identification and risk interactions identification and evaluation processes (in group) in order to obtain a good description of the situation and to have a same hierarchical level in the risk structure to study same level risks in the chain reactions.
    - Identify carefully during the initial step the correct risk owners, i.e. the actors which seems initially the most appropriate ones to hold the responsibility for each risk.
    - Perform the clustering operation thanks to the iterative algorithms or with OPL on the LP problem if processing time can be improved thanks to some operations.
    - Analyse the obtained results and identify possible chain reactions, possible accumulation risks and the actors which are to be responsible for each risk cluster in order to facilitate the global coordination of the project risk management process.

VI.5. Conclusions and perspectives

As a whole, this chapter presents innovative tools based on the integration of risk interactions in the processes of risk analysis and risk clustering for efficient project risk management. This is all the more important since some works in the literature show that, in the context of decision-making within some specific environments, project managers tend to deny, avoid, ignore and/or delay dealing with risks (Kutsch and Hall, 2005). For all practical purposes, the gap between expected and real risk management implementation is significant. As shown by the case studies, the tools which are proposed here permit greater communication on project risks and better confidence in risk management activities thanks to two aspects at least.

- First, the evaluation of risk interactions which is performed when building up the RNM implies a two-step process (looking in terms of causes, and then of consequences). Information can thus be checked and refined since one interaction should be listed twice (from cause to effect, and from effect to cause): this checking process permits a better confidence in risk identification and risk interaction identification. Even if theory is sometimes difficult to implement in real projects, we argue that the theoretical background of our models can easily be implemented and understood at a reasonable level. The fact that it relies on expert judgements, mainly qualitative, makes it a user-friendly and easily computable tool. The first case study indeed proved that, even in project contexts which are not used to working with tools issued from design engineering and industrial engineering theories, the whole approach is globally understood.
- Moreover, clustering risks in order to maximize intra-cluster global interactions value permits to facilitate the coordination of risk monitoring and controlling activities, as it underlines the need for cooperation and transversal communication within the project team. It permits greater communication between people, since it does not seek the identification ownership, responsibility and/or accountability, but the identification of risk interdependencies. After the clustering process, coordination is made by the person who is assigned to the cluster, but communication has been facilitated before, meaning we have less defensive phenomena.

However, this implies that a shift should be operated in the skills of project risk managers (or at least the team members who are in charge of the management of the obtained clusters). Such project team members should indeed be able to facilitate communication and to show great adaptability since they need to manage risks which are to be of different nature.

As a whole, this chapter permits to make a comparison between several possibilities for grouping risks in a project. Our aim is not to criticize the use of classical approaches: on the contrary, we refer to them as points of comparison and claim for the use of conjoint classifications which can all give powerful insights on reality. Our initial objective in this chapter was the improvement of coordination through the better recognition and handling of risks interactions. The research works and case studies have shown possible significant improvements regarding this specific objective. They also underline the need for a shift in the way project risk management should be approached. In the end, complexity-related possible effects can be caught more easily and as a consequence managed more effectively and efficiently. Project coordination is undoubtedly facilitated with this approach since interface problems are considerably reduced (for inter-clusters links global value is lowered). This new approach is thus a complementary one to traditional project risk management techniques.

Lots of aspects of this work and its results may however be discussed. We thus identify several research perspectives to consolidate this approach.

- Challenging the definition of risk interaction and trying to integrate other risk characteristics (than probabilities and precedence relationship) into the definition of risk interactions. For instance, one could say that a possible interaction between two risks R_i and R_j is that if R_i occurs, then the impact of R_j on the project system is higher, even if its occurrence probability remains the same. In other terms, when occurring, R_i is likely to make the project system more vulnerable regarding the occurrence of the triggering events related to R_j.
- Evaluating with more reliability the relative weights of risks. The sensitivity of this evaluation should first be explored. Then, a proper use of fuzzy pairwise comparisons could permit to reduce the subjectivity of the users' judgements. This gives important research perspectives and these points are to be addressed, notably thanks to the literature on fuzzy graphs and fuzzy linear programming.
- Exploring other graph partitioning algorithms. Indeed, this research work suggests the optimal solving of the linear programming model, which significantly constrains the size of the problems which can be possibly addressed (even though the concept of graph connectivity permits to address larger problems). When the problem is too large, this research work argues for the use of basic and non-consuming iterative algorithms in order to reach an approximate and acceptable clustering solution. However, some other graph K-partitioning algorithms are to be addressed and tested in the future in the case of complex project risk clustering. A particular look is to be given over the Kernighan-Lin algorithm (Kernighan and Lin, 1970), the Fiduccia-Mattheyses algorithm (Fiduccia and Mattheyses, 1982) and some spectral methods (Pothen and al. 1990), (Rendl and Wolkowicz, 1990), (Simon, 1991). Discussions about the final choice of a particular clustering algorithm in this context are to be held according to some criteria such as computability, understandability, user-friendliness, resolution time.
- Exploring new constraints to perform other clustering operations. For instance, the maximal size of the clusters may vary. One could think of asking for a density constraint or asking that the obtained clusters may as a whole be of a similar size. Statistical tests might in the end be performed in order to analyse how often some risks are clustered together.

- A final improvement of the results and algorithms thanks to the concept of strongly connected components of a graph (Pearce, 2005), (Bang-Jensen and Gutin, 2008) is also to be addressed as it can notably identification some possible accumulation zones within the project risk network.
- Finally, new case studies are to be performed in order to validate even more this approach and study both the practical applications (and improvements) thanks to these results and the future implications on project management processes and organisation.

Epilogue

Overall conclusion of this work

As a whole, this Ph.D. thesis can be partly synthesised thanks to the following paragraphs. We show how it permits to propose answers to the research questions which were raised in the overall introduction of this work (Prologue).

- **What is project complexity? What are its characteristics and sources? How can it be described?**

After describing what a project is (Chapter 1 – Prologue), Chapter 2 permits to explore the notion of project complexity. This chapter highlighted that, in spite of the lack of consensus existing about project complexity, a standard framework could be elaborated.

The project complexity framework proposed in this Ph.D. thesis claims for the description of project complexity as compounded of factors of four kinds (size, variety, interdependency and context-dependence), which can themselves be categorized thanks to Baccarini's traditional dichotomy into technological and organizational sides of project complexity.

Furthermore, an international Delphi study which was carried out over academic and industrial experts permits to underline the preponderance of organisational interdependency-related factors into complexity-driven phenomena. This study also permits to refine the framework into a smaller one, as needed in Chapter 3.

- **In order to manage, one needs to measure. The question is then how can project complexity be measured to assist decision-making in complex project management?**

The ambition of Chapter 3 is to assess project complexity and propose as a consequence a project complexity measure. In order to do so, the refined project complexity framework is used to build up an Analytic Hierarchy Process hierarchical structure in order to integrate all the compounding effects of project complexity in its evaluation. Such an evaluation is adapted to any kind of project but must be done in accordance with the specific context of any project.

Carrying out such an evaluation permits to identify particularly complex projects within a portfolio, or particularly complex project scenarios in the context of mono-project decision-making, or particularly complex zones one should focus on during a project.

- **What are the stakes of project complexity? What are its implications on project risk creation? What are the lacks of traditional project risk management methodologies regarding the integration of complexity?**

As Chapter 4 underlines it, such identification and understanding of complex projects or project zones is all the more interesting that many complexity-driven phenomena (ambiguity, uncertainty, propagation, chaos) are the causes of project risks.

Complexity is to be integrated in innovative ways to manage risks since traditional project risk management methodologies do not efficiently and effectively take into account project complexity (ambiguity, lack of confidence in the risk management activity, unsuitable for risk networks,…).

- **Can innovative methodologies and tools be developed to integrate better complexity related aspects into project risk management? Can these innovative approaches, whether systemic or analytical, permit to assist complex project risk management?**

That is why Chapters 5 and 6 permitted to study two different approaches.

Chapter 5 (systemic approach) suggested that, as a complement to traditional project management methodologies, project vulnerability management methodologies should be developed, notably to diminish the complexity-driven ambiguities. By focusing on project weaknesses thanks to the concept of vulnerability, one avoids possible usual reluctance and non-consensus regarding project risks (in terms of existence, management,...).

The identification of project tasks/elements the non-resistance and resilience of which (regarding possible negative triggering events) are high then permits to propose a conjoint approach to traditional risk management ones. Response plans to decrease the importance and the apparition of possible project damages may be improves thanks to these complementary approaches.

Another possible improvement was proposed in Chapter 6 (analytical approach) thanks to the integration of project risk interactions into the definition of project risk networks. One of the practical implications of this integration is to study better the possible propagation phenomena within a project (and thus identify origin risks, etc...).

Another one is the clustering of project risks functions of their interactions thanks to different clustering algorithms which can be adapted from graph theory. We hope that this analytical developments will permit in the end to propose innovative approaches which will complement the existing ones.

All these results are also synthesized hereinafter in Figure 75.

	Most notable academic results	Most notable industrial results
Chapter II	Construction of a project complexity framework which identifies possible project complexity sources thanks to a large literature review. Proposal of a definition of project complexity. Analysis and refining of the project complexity framework thanks to an international Delphi study.	Generic grid to identify project complexity sources: retrospective application to two automotive projects.
Chapter III	Critical selection of a multicriteria approach (the AHP) to measure project complexity. Proposal of a relative measure of project complexity to assist decision-making. Generic formulation of gradient sensitivity analysis of the proposed	Assistance to decision-making when selecting projects in a portfolio thanks to a measure of project complexity: prospective application to an entertainement industry start-up firm.
Chapter IV	Identification of the consequences of project complexity and their implications on project risks thanks to a critical analysis of the literature.	-
Chapter V	Proposal of a definition of project vulnerability. Proposal of a systems thinking-based project vulnerability management process which includes the phases of identification, analysis, response plan, monitoring and control.	A new way to identify the existing weaknesses of a project through the project vulnerability management process: present application to a software development project within the pharmacy industry.
Chapter VI	Introduction of matrix representations to model project risk networks. Proposal of a methodology to evaluate the strength of risk interactions. Proposal of matrix-based indicators for a first analysis of possible propagation phenomena within the project risks network. Proposal of an interactions-based clustering methodology to manage project risks and facilitate coordination. Proposal of corresponding heuristics, performance measures, etc...	Innovative ways to analyse project risk networks thanks to matrix representations and clustering operations: present application to a musical production project and a large infrastructure project.

Figure 74. Synthesis of the main results of this Ph.D. work

As a whole, the reader may have noted that several case studies have been used in this Ph.D. thesis.

- A retrospective case study about two Renault Multi-Purpose Vehicle development projects (Renault Espace and Renault Twingo) in Chapter 2.
- A prospective case study within a start-up firm the ambition of which is to produce stage musicals in Chapter 3.
- A diagnosis case study for the FabACT project, a software development project taking place in the health context in Chapter 5.
- Two diagnosis case studies in Chapter 6, one taking place in the stage musicals production industry, one about a tramway development project.

These different case studies permit to underline the extensiveness of the possible applications and implications of this work about project complexity identification, measure, management and integration into innovative project risk management processes. That is notably why we aim at extending our research works to other industrial cases and applications.

However, it must be noted that for the moment, no case study integrating the results of all the chapters was carried out on a single project. One of our research application perspectives is undoubtedly to work on a large complex project and:

- Use systems thinking as proposed in Chapter 1 to identify properly project values, project tasks and processes, and project elements (actors, resources, inputs).
- Use chapter 2 to identify existing complexity factors within this project.
- Use chapter 3 to identify particularly complex zones within this project in order to focus on them.
- Use chapter 5 to perform a project vulnerability analysis and compare it with traditional project management methodologies.
- Use chapter 6 to study the complexity of the project risk network in terms of their possible propagation. Practical implications in terms of propagation studies and clustering may be underlined.

This case study will in the end validate even more the works of this Ph.D. and show how they can be integrated in a global approach to study project complexity and improve complex project risk management.

Other research perspectives after this work are to be the following ones:

- Further statistical analysis on project complexity factors (such as correlation tests for instance, notably thanks to Kruskal-Wallis tests) may permit to explore more deeply project complexity and its impact on project management.
- Further research is to be carried out on project complexity measure and its implications, notably thanks to the three following issues:
    - Exploring the possibility to define some direct measures of some complexity factors.
    - Exploring the use of the Analytic Network Process to refine the project complexity index proposed in Chapter 3.
    - Proposing a typology of projects regarding the multiple aspects of complexity.
- We will explore how graph theory (notably around the concept of connectivity) can be integrated to the vulnerability approach in order to consider more efficiently how a project network (and its evolution) can be affected by the possible damages of its vulnerable processes or entities.
- Finally, some research is to be pursued around the clustering processes proposed in Chapter 6:
    - Exploring approaches to reduce processing time to solve the LP problem in order to address larger problems.
    - Testing the impact of the clustering constraints (maximum cluster size, gap with target mean cluster density, maximum gap with target mean cluster size, maximum number of risk owners,…). Defining different heuristics due to these

different constraints. Understanding the commonalities and differences between the clustering solutions which are obtained through these different approaches.

As an overall conclusion, we want to underline that all the propositions of this Ph.D. thesis around the notion of project complexity and its implications on project management are to coexist with existing traditional project management methodologies. Indeed, we do not suggest eliminating traditional approaches. On the contrary, we are undoubtedly building up new methodologies and tools on it and thanks to it.

For instance, as established by the conventional approach, each project must have a Work Breakdown Structure to define its work packages, a schedule, a budget, a traditional risk list, etc… and all of them need to be reworked and redefined during the project evolution over time. All these traditional methodologies and tools remain absolutely necessary steps to manage successfully complex projects. As Shenhar stresses it, traditional project management methods are "building blocks [which] will […] form the baseline to leading the project in a flexible way" (Shenhar, 2007).

As a whole, modern projects include a greater and greater deal of complexity and a larger and larger amount of complexity-driven risks, due to ever more demanding requirements under ever more pressuring constraints. The conjoint use of innovative systems-oriented / complexity-oriented methods and more analytical tools is to be a high potential evolution for project management, opening new perspectives for future research in this discipline.

As each project is to remain complex, temporary and unique, it will have to be managed it its own way thanks to the application and extension of these methods to the project's own characteristics. The managers', organisations' and teams' flexibility and adaptability around innovative and traditional project management methods and tools are thus to become some of the greatest stakes of modern complex project management.

Publications

International journals with scientific committee review

- *Chapter II:*
    - VIDAL, L.A. and F. MARLE, Understanding project complexity: implications on project management. *Kybernetes, the International Journal of Systems, Cybernetics and Management Science*, 2008. (Web of Science – ISI)

- *Chapter V:*
    - VIDAL, L.A., SAHIN E., MARTELLI N., BERHOUNE M. and B. BONAN. Using the AHP to select anticancer drugs to produce by anticipation. *Expert Systems With Applications*. (Web of Science – ISI) TO BE PUBLISHED (Submission Nov. 2008)
    - BONAN, B.., MARTELLI, N., BERHOUNE, M., VIDAL, L.A., SAHIN, E. and P. PROGNON. FabAct: a decision-making tool for the anticipation of the preparation of anti-cancer drugs. *Journal of Evaluation in Clinical Practice.* (Web of Science – ISI) TO BE PUBLISHED (Submission Apr. 2009)

International conferences with scientific committee review

- *Chapters I, II and IV:*
    - VIDAL, L.A., F. MARLE. and J.C. BOCQUET, Modelling project complexity. *International Conference on Engineering Design*. 2007. Paris, France.

- *Chapter II:*
    - VIDAL, L.A., F. MARLE, and J.C. BOCQUET, Project complexity understanding and modeling to assist project management. *PMI Research Conference,* 2008. Warsow, Poland. (Best student paper)

- *Chapter VI:*
    - VIDAL L.A., MARLE F. and J.C. BOCQUET, Interactions-based clustering to assist project management. *International Conference on Engineering Design*. 2009. Stanford, United States of America.
    - VIDAL L.A., MARLE F. and J.C. BOCQUET, Interactions-based risk clustering methodologies and algorithms for complex project management. *9ème Congrès International de Génie Industriel*, 2009. Bagnères-de-Bigorre, France.

- MARLE F. and L.A. VIDAL, Potential applications of DSM principles in project risk management. *Proceedings of the 10th Design Structure Matrix Conference*, 2008. Stockholm, Sweden.

National conferences without scientific committee review

- *Chapters II, IV and V:*
    - VIDAL, L.A., Management de projets complexes et vulnérabilité. *Séminaire des doctorants de l'Ecole Centrale Paris et du Laboratoire Génie Industriel*, 2007. Châtenay-Malabry. France.
- *Chapters II, IV and VI:*
    - VIDAL, L.A., Vers une meilleure intégration de la complexité projet dans le management des risques projets. *Journée jeunes chercheurs et jeunes ingénieurs – Institut de Maîtrise des Risques,* 2009. Cachan, France.

Working papers

- *Chapter II:*
    - VIDAL, L.A. and F. MARLE, Understanding project complexity : implications on project management. *Working Paper* – Ecole Centrale Paris, 2007
    - BOCQUET, J.C., A.F. CUTTING DECELLE, V. GINOUX-EZRATTY, J.L. GIORDANO, F. MARLE, A. SCHINDLER, J. STAL LE CARDINAL and L.A. VIDAL. La complexité dans les projets en entreprise Proposition d'une définition de la complexité et de méthodes pour sa détection et sa maîtrise, *Working Paper* – Ecole Centrale Paris, 2009.

Submissions to international journals ongoing the scientific committee review process at the time of publication of this Ph.D. thesis

- *Chapters II and III:*
    - VIDAL, L.A., MARLE F. and J.C. BOCQUET, Using a Delphi process and the AHP to evaluate project complexity. Expert Systems With Applications. **(Web of Science – ISI)** (Submission July 2009)
    - VIDAL, L.A., MARLE F. and J.C. BOCQUET, Measuring project complexity thanks to the Analytic Hierarchy Process. *International Journal of Project Management.* **(Web of Science – ISI)** (Submission August 2009).
- *Chapters IV and VI:*
    - VIDAL, L.A., F. MARLE and J.C. BOCQUET Interactions-based risk clustering methodologies and algorithms for complex project management *International Journal of Production Economics.* **(Web of Science – ISI)** (Submission September 2009)

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Résumé
Un projet est un effort temporaire et unique entrepris pour fournir un résultat. Ce résultat est toujours un changement pour l'organisation, qu'il prenne effet dans ses processus, sa performance, ses produits ou services. De nombreux manques ont été détectés tant dans le monde industriel que dans le monde académique dans la mesure où les paramètres usuels (délai, coût, qualité) ne sont clairement plus suffisants pour permettre de décrire et gérer le projet à un instant t. Dès lors, les méthodes actuelles ne sont plus suffisantes pour répondre aux enjeux grandissant de la complexité projet, source de nombreux risques. Cette thèse de doctorat propose de penser le management de projet dans ces contextes de complexité en cherchant à comprendre comment des aspects liés à la complexité peuvent être intégrés plus efficacement dans les pratiques de management de projet, et plus particulièrement dans le processus de management des risques projets. Elle commence par définir les concepts nécessaires puis vise à décrire dans un premier temps ce qu'est la complexité projet grâce à l'élaboration d'un référentiel de complexité projet. Ce référentiel est ensuite raffiné à travers la réalisation d'une étude Delphi internationale. Ce référentiel raffiné permet alors de construire une structure hiérarchique de type Analytic Hierarchy Process (AHP) et d'en déduire un indicateur relatif de complexité projet. En pratique cette approche permet notamment d'identifier les projets les plus complexes à l'intérieur d'un portefeuille ou les zones les plus complexes à l'intérieur d'un projet, afin d'assister le management de projets complexes. Ensuite, ce rapport a l'ambition de décrire les conséquences de la complexité projet et de comprendre en quoi les méthodes actuelles de management des risques projet ne permettent pas de prendre en compte convenablement certains effets de la complexité. Cette thèse de doctorat propose alors deux approches innovantes pour assister le management des risques des projets complexes. La première est une approche fondée sur la pensée systémique et qui repose sur l'introduction du concept de vulnérabilité projet. La seconde se fonde quant à elle principalement sur une approche analytique dont l'ambition est de regrouper les risques en fonction de leur niveau d'interaction potentielle (en termes de possibilité de relation de cause à effet) afin de faciliter la coordination. L'ensemble des résultats est testé et illustré grâce à des études de cas diverses (dans les secteurs de l'industrie automobile, pharmaceutique, du spectacle et de la construction).

Mots clés : Projet, Management de Projet, Complexité, Risque, Aide à la décision, Analyse systémique, AHP, Vulnérabilité, Partitionnement de graphe.

Abstract
A project is a temporary and unique endeavour undertaken to deliver a result. This result is always a change in the organization, whatever it is in its processes, performance, products or services. Limits and lacks have been detected in research as well as in industry about the project predictability, since usual parameters (time, cost and quality) are clearly not sufficient to describe properly the complete situation at a given time. As a whole, current methods have shown their limits, since they cannot face anymore the stakes of ever growing project complexity, which is an ever growing source of project risks. This Ph.D. thesis aims at thinking project management in the age of complexity and understand how complexity aspects can be integrated into project management practices, particularly in the case of the project risk management process. After defining concepts, this thesis aims at describing project complexity thanks to the elaboration of a project complexity framework, which is refined thanks to an international Delphi study. This refined framework is then the basis of an Analytic Hierarchy Process (AHP) hierarchical structure which permits to build a relative project complexity index in order to assist decision-making. For all practical purposes, it notably permits to focus on the most complex projects within a portfolio or on the most complex zones of a project in order to assist complex project management. Then, after describing the consequences of project complexity and understanding the limits of existing project risk management processes to cope with some complexity-related aspects, this Ph.D. thesis proposes two innovative approaches to assist complex project risk management. The first one is based on a systems approach through the introduction of the concept of project vulnerability. The second one is mainly based on an analytical approach which aims at clustering project risks according to the strength of their interactions (in terms of possible cause-consequence link). Diverse industrial case studies permit to test these proposals (automotive, pharmaceutical, entertainment and construction industries).

Keywords : Project, Project management, Complexity, Risk, Decision-making, Systems analysis, AHP, Vulnerability, Graph clustering.