Supporting the transformation of a company's project management by elaborating an invariant-based project management maturity model and a causal predictive model between maturity criteria and project performance

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LIST OF ABBREVIATIONS

AI: Artificial Intelligence

ANN: Artificial Neural Networks

ANRT: Association Nationale Recherche Technologie”,

APM: Agile project management

BN: Bayesian Networks

CIFRE: Convention Industrielle de Formation à la REcherche

IB2M: Invariant-Based Maturity Model

NES: Niveau d’Exposition Strategique

PM: Project Management

PMBOK®: Project Management Body of Knowledge

PMI: Project Management Institute

PMM: Project Management Maturity

PMMM: Project Management Maturity Model

RL: Reinforcement Learning

TPM: Traditional project management

CHAPTER 1

1. General Introduction

This report is a thesis on project management carried out in a particular industrial context, which is a partnership through an Industrial Convention for Training through Research CIFRE ("Convention Industrielle de Formation par la REcherche" - N° 2016/0778) founded by Sopra Steria and the ANRT funds ("Association Nationale Recherche Technologie", in English: National Research and technology association), begun in December 2016. Our scientific contributions are intended to be sufficiently generic to be applied in different contexts. However, our research is both based and focused on the elicitation of industrial issues and needs arising from the experience of Sopra Steria's consultants and applied to specific case studies.

This introduction will briefly present the research context before asking the research questions addressed. It will highlight the research goals, explain the working hypothesis and then summarize our scientific contributions.

1.1. Research context

The company in which I worked during my thesis period is Sopra Steria Consulting. This Sopra Steria's subsidiary carries out consulting activities to support the transformation of large organizations; it has an extensive experience in complex project management and audit.

The organizational entity in which my research was realized is a community called "*Excellence Practice in Industrial Operations*". Consultants meet in this community to share their knowledge and experience. One of the questions they address can be expressed as follows. Client organizations cope with problems due to their low level of expertise in project management. Most of their projects failing to achieve operational performances, *e.g*. quality, operational costs, lead-time, etc., they want to homogenize and improve their projects managers' practices. Thus, within these client organizations, the results can be very different from one department to another, from one project to another, etc. Moreover, Sopra Steria Consulting's experience shows that only one or two projects (that have problems) can significantly disadvantage the performance of the whole client organization, *e.g*. its margin or profitability in the case of a company. This means that there are projects within organizations that are more critical, and they need to be managed with particular attention.

When auditing project management of their client organizations, Sopra steria's consultants assess their level of expertise by using a project management maturity model (PMMM) they have elaborated. This PMMM is a tool comparing clients' project management routines with established best practices. The purpose of a PMMM is to help consultants to identify project management processes with poor maturity levels. Thanks to their expertise, consultants make hypotheses concerning the choice of the practices in each process that have to be improved in priority with the goal of increasing projects' performances. These hypotheses concern the impact of a change in criteria (and the related practices) in the PMMM on the evolution of a specific projects' performance (for instance, if you had better schedule in the project, you improve the chance of avoiding a cost overrun). **However, today there is no scientific model (and no methodology) that helps Sopra steria's consultants to justify their choice to their clients.** Providing such an innovative methodology to its consultants could lead to differentiation opportunities and competitive advantages for Sopra Steria compared to other consulting companies.

From Sopra Steria Consulting's point of view, the **operational goal of our research is to create an architecture of a data-based project performance prediction system based on the evaluation of project management maturity criteria.**

At the beginning of the thesis work, we searched for project management maturity databases available in Sopra Steria and in the literature. We found data concerning project management maturity audits performed by Sopra Steria's consultants. However, **the causal relationship with projects' performance could not be established because the maturity models contained many criteria.** A similar note was expressed when studying the project management literature. There are several project management maturity models with a lot of criteria but no workable database or relationship with projects' performance.

Therefore building this performance prediction system requires the formalization of feedback from previous consulting missions. This predictive system cannot be answered by quickly developing a ready-to-use solution. A conceptual and methodological detour is required. Therefore, this industrial problem raises real research questions.

1.2. Research Questions

Project management practices vary according to the type of projects, their industrial or cultural context, the routines of the organization within they are carried out, etc. The state of the art shows that existing PMMMs have several limits. For example, they ask too many questions (Ramirez, 2009; Torres, 2014), *e.g*. 183 items (Kerzner, 2017) or even more than 400 in the Project Management Body of Knowledge (PMI, 2013), they gather heterogeneous data (Vergopia, 2008), they are not based on standardized vocabulary (Lasrado, 2018), etc. More generally, it can be accepted that these models are not based on a sufficiently precise conceptual basis. Therefore, our first research question is:

Question 1:	*How to propose a general and concise method to build a PMMM and to evaluate project management maturity?*

Moreover, the current context of the Fourth Industrial Revolution (Industry 4.0) presents new challenges for project management (McAfee, Brynjolfsson, Boyd, Crawford, & Lohr, 2012; Westerman, Bonnet, & Mcafee, 2014), especially with the emergence of agile methodologies coming from Information Technologies (IT) sector (Scrum, Extreme, etc.) (Doug, 2004; Setpathy, 2016). Thus, our second research question is:

Question 2:	*How can we use our proposed PMMM to evaluate agile project management maturity? Moreover, how to help organizations to change their project management practices from a traditional method to an agile method?*

Furthermore, due to the diversity and fuzziness of projects' performance criteria and methods to assess them, it is not possible to clarify the causality and the correlation between project management maturity levels, defined under PMMMs, and past or anticipated projects' operational performances. Hence, our third research problem concerns the type of modeling techniques we can use to elaborate the causality between project management maturity and projects' operational performances. The difficulty is to choose good data input and good modeling techniques. In the field of project management, we have a limitation concerning the amount of structured data available to train a potential causal model based on artificial intelligence techniques. However, we can take advantage of the expertise of Sopra Steria's consultants or project managers. Hence we need to combine expert knowledge and experience with data coming from project management maturity audits. Consequently, our third research question is:

Question 3:	*How to choose the good modeling technique adapted to this context?*

The combination between expert knowledge and data is not so easy to implement. For example, experts' reasoning could be biased; they can use short cuts. We cannot request human experts to correlate a huge amount of input data (feedback from past projects) to several criteria (projects' operational performance). However, we can ask experts to build the structure of a causal network from a semantic point of view. During their missions, Sopra Steria's consultants are requested to solve specific problems when projects' operational performances are degraded and when their clients have troubles in their project management practices. When interviewing them, we discovered that their reasoning consists in identifying these possible dysfunctional points (here we call them drift factors) that generate a decrease in the projects' performance and then implementing either corrective or preventive actions before facing harmful consequences. Therefore, we recognize that experts are able to identify these drift factors, and to establish the causal relationships between project management maturity criteria (related to best practices) and each drift factor. Additionally they can estimate the probability of occurrence of these drift factors according to the maturity levels. However, it is not possible for them to quantify the consequences in the projects when these drift factors occur. This estimation should be based on historical project management database that associates the occurrence of a drift factor (or not) and the level of consequences on a particular projects' performance.

Consequently, we asked experts what are the causal relationships between best practices and project management drift factors, rather than to ask directly the relationships between best practices and project performance. Hence, the fourth research question in more precise terms is:

Question 4:	*How can we create a methodology based on interviews and historical project management data to predict projects' operational performance based on project management maturity evaluation?*

To sum up, the general research question of our work is then:

How to build a model elaborating causal relationships between project management maturity and projects' operational performances?

1.3. Research goals

Our research problem expressed in the four previous questions can be split into four research goals that are structured according to two features as displayed in Table 1.1: level of abstraction and field of study.

	Describe Project Management Maturity Evaluation (field of maturity models)	**Explain causal relationships within the project management (field of causal models)**
Abstract Level	**Goal 1** ***(related to question 1):*** Propose a general PMMM to evaluate project management maturity.	**Goal 3** ***(related to question 3):*** Evaluate and select the appropriated AI technique that could explain causal relationships within Project Management.
Specific Level	**Goal 2** ***(related to question 2):*** Apply the proposed model to projects of the specific industrial environment (agile project management).	**Goal 4** ***(related to question 4):*** Propose a methodology to explain how project management maturity can be linked to projects' performance for specific projects.
Operational goal (related to the general research question)*: Create an architecture of a data-based project performance prediction system based on the evaluation of project management maturity criteria.*		

Table 1.1 Distribution of research questions and goals

The left side of the table above concerns the field of project management maturity evaluation. This can be understood in two levels, abstract level *vs*. specific level. Abstract level (upper left) integrates the concepts and general properties characterizing project management maturity. Our research goals are thus to generalize existing PMMMs' concepts and to propose a generic or general model. The second level of the table is specific (down left). Under this level, we apply the general model previously elaborated to specific projects, *i.e.* traditional projects *vs*. agile projects. Moreover, the right column of Table 1.1 concerns causal models explaining how project management maturity drives projects' operational performances. Under the abstract level of analysis (upper right), we explore this question in general terms. We are focused on

Artificial Intelligence (AI) techniques that may be appropriate to establish the causal relationships between input data available in industrial context (causes) and expected results (consequences). Under the specific causal level (down right), we instantiate the causal modeling techniques to a specific industry and type of projects.

To fulfill these four research goals, we are departing from some ground-working hypothesis that are presented below.

1.4. Working Hypothesis

Research is usually based on key hypotheses that are being assumed for the inquiry.

The first assumption concerns the universe of project management. How do we conceive it? How are we involved on it? Indeed, inside project management universe, there are individuals acting and entering into transactions, *e.g*. clients, suppliers, top managers, project managers, project actors, supporters, etc. As engineers, our role is to bring them models, tools, methods, etc., to work more effectively. Derived from this ontological statement, we build models describing this universe (left column of table 1.1) without oversimplification or explaining key causal relationships in it (right column of table 1.1). Moreover, these models must be based on clear statements, explaining why we locate our engineer's point of view both as general (upper row of table 1.1) and specific (down rows of table 1.1).

The second assumption refers to the limitation of our knowledge about project management maturity (PMM). We must keep in mind that the literature presenting PMMMs has an implicit hypothesis, which is that PMM can be evaluated only for projects of the same nature, belonging to the same class or population. Our thesis preserved that specific hypothesis. In this report, we will then evaluate projects of the same nature, and we do not mix data from projects of different types, *e.g*. IT development projects *vs*. mechanical development projects. Whereas our proposed Invariant-Based Maturity Model (IB2M) describes project management in general, our more elaborated causal models evaluate only projects of the same type in order to have similar data (table 1.1., right column).

Other considerations explain why the proposed causal model is bounded.

The first one is that we have limited our sources of data to missions conducted from 2013 to 2017 by Sopra Steria's consultants. We are also constrained by the number of experts we have interviewed, even if some of them have more than 20 years of experience in the industry. Moreover, if we assume that project management maturity drives projects' operational performances, we also have good reasons to relativize the strength of this causal relation. Several sources of literature support this hypothesis (Lahrmann, Marx, Mettler, Winter, & Wortmann, 2011; Pöppelbuß et al., 2011), but we do know if it is true for all projects. We do not know if these performances depend solely on PMM. Therefore, we assume that we leave aside other causes, *e.g*. engineering process routines (core capabilities).

Our second causal hypothesis states that any type of project performance drifts (hypothetical causes) can be translated into cost overruns (consequence, here: a phenomenon stated by data). It is known that there are several indicators of project management performance (cost, quality, lead time, profitability, user experience, etc.). However, to simplify our proposed causal model (table 1.1, right column, third line), we assume that projects' key performance indicators can be translated into monetary terms. In other words, lead time, quality, etc., can be measured in cost overruns. We choose this indicator because it is largely used in project management literature and industry (Flyvbjerg, 2006).

To summarize, even if our description of the world of the project is intended to be as broad as possible, we are aware of the hypothesis above when building our contributions.

1.5. Research contributions

This thesis proposes four research contributions (table 1.1), each one is the subject of a chapter.

1.5.1. A generic model to evaluate project management maturity

(Question 1, Goal 1)

Chapter 2 explores the characteristics of project maturity models presented in literature (Young Hoon Kwak & Ibbs, 2002; Pennypacker & Grant, 2003; PMI, 2013; Software Engineering Institute, 2006). This second chapter has a conceptual model that explored each of the listed models and abstracted characteristics. This chapter proposes three criteria for evaluating a maturity model (or requirements): its concision (number of questions), its consistency on theoretical models, and its usability by auditors, *e.g*. Sopra Steria's consultants. Since most of the existing models do not respond adequately to these requirements (Albrecht & Spang, 2016; Ramirez, 2009; Torres, 2014; Vergopia, 2008), our research proposes a methodology to build a PMMM based on more clear and general statements. Our proposed model has a key constituent called invariants, that is, those characteristics that are transverse to different types of project management practices. This proposition simplifies project management tools and evaluation. The work is complemented by the inclusion in the model of the 70 best practices found in the literature (Besner & Hobbs, 2008, 2012; Fernandes, Ward, & Araújo, 2013b; Fortune & White, 2006; Fortune, White, Jugdev, & Walker, 2011; White & Fortune, 2001), and a series of interviews with Sopra Steria's consulting experts.

In addition, the second chapter presents a short case study where our generic model is applied to a series of industrial construction projects. Both Sopra Steria consultants' interviews and the case study validate the proposed methodology and generic model. The major contribution of this chapter is the evaluation model based on invariants, this model is also used in chapters 3 and 5 because it gives the characteristics to elaborate the causal relation and correlation between project maturity and performance. For example, the proposed conceptual model reduces the number of questions compared to the existing ones, then the number of causes to take into account when developing a causal model.

1.5.2. Applying the proposed PMMM to agile project management methodologies.

(Question 2, Goal 2).

Chapter 3 compares the characteristics of our proposed conceptual model in two specific cases, that is traditional project management (TPM) *vs*. agile project management (APM), which is supposed to be more suitable to the ''fourth Industrial Revolution'' framework. This second chapter will investigate the characteristics of TPM (such as those evaluated in chapter 2) and will compare them with APM's specificities. We compare the fundamental principles of each of these types of project management. Moreover, the chapter will propose three tools based on PMMM allowing the transition between TPM and APM. We call this organization dynamics: "*agilification''* process. We apply our agilification idea to industrial projects as a simple case study.

1.5.3. Evaluate and select the appropriated AI technique that could explain causal relationships within Project Management.

(Question 3, Goal 3)

Once the concepts for project evaluation have been defined, the next step is to select the technique that could be used to elaborate the causal relationship between PMM and projects' operational performance, more precisely: over run costs. Chapter 4 presents a concise state of the art of some machine learning techniques that were studied as candidate solutions. Among these techniques, we select those that could represent better the reality of project management maturity assessment, that is, those that are adequate with respect to the available data produced by the model detailed in chapter 2. Therefore, Artificial Neural Networks (ANN) (McCulloch & Pitts, 1943), Reinforcement Learning (RL) (Sutton, 1988), and Bayesian Networks (BN)[1] (Pearl, 1988), are compared. BN are chosen for its ability to integrate expert knowledge into predictions, reducing the amount of data needed to feed the algorithms (Neil et al., 2000).

We study the state of the art regarding its use in project management research (Al-Tabtabai, Kartam, Flood, & Alex, 1997; Demirkesen & Ozorhon, 2017; Ko & Cheng, 2007; Mir & Pinnington, 2014; Na, Simpson, Li, Singh, & Kim, 2007; Qazi, Quigley, Dickson, & Kirytopoulos, 2016; Wang & Gibson, 2010; Wang, Yu, & Chan, 2012). We make explicit the key parameters to take into account when building BN. In addition, we define requirements to evaluate the eligibility (well construction) of BN. Finally, we compare the networks created from the literature under those requirements (Constantinou, Fenton, Marsh, & Radlinski, 2016; Fenton & Neil, 2013; Sun & Shenoy, 2007). We find that none of the networks that could be built from the project management literature completely meets the requirements described above. Thus, we present the limits of literature, and the lines of improvement that are the basis of the next chapter.

[1] BN : Bayesian Networks is used in the plural form in the AI literature

1.5.4. Propose a methodology to explain how project management maturity can explain project performance for specific projects.

(Question 4, Goal 4)

In chapter 5, we propose a methodology for modeling the relation between project management maturity and projects' operational performances by using BN. We test it for a class of offshore Oil and Gas (*O&G*) projects that were evaluated over four years by Sopra Steria consultants, and in which their operational costs have dramatic deviations. In this case, BN's intermediate nodes will be the main causes of costs deviations, *i.e.* drift factors. For the construction of our BN, the parameters defined in chapter 4 will be taken into account. For example, our methodology meets the eligibility requirements defined in chapter 4.

In addition, the fifth chapter will demonstrate how our proposition can be used to choose which project management best practices (from chapter 2) should be improved in priority in order to reduce the probability of incurring in the large cost overruns.

1.6. Structure of the PhD Thesis

This current chapter (Chapter 1) introduces our research work. Chapters 2 to 5 correspond to contributions, each chapter detailing one contribution, as displayed in table 1.1. The last chapter (chapter 6) presents the conclusions and the perspectives. Each chapter, from 2 to 4, begins with a state of the art, then describes the gap in the literature, asks a research question, explains a research methodology, proposes a contribution, presents an application based on Sopra Steria requirements and backgrounds and finally discusses the interests and limits of this contribution.

Our research is at the intersection **of two fields: project management (maturity models) and AI techniques (causal models).** It is divided into four chapters that we can associate using the proposed block diagram displayed in figure 1.2, which derives from table 1.1. The first vertical axis of this diagram contains chapters related to project management conception; the second vertical axis integrates the chapters related to the causal models that will be used to answer our research problem. The red arrows represent theoretical inputs and outputs relating to each contribution. Blue arrows represent the information gathered in our research. Green arrows represent practical outputs.

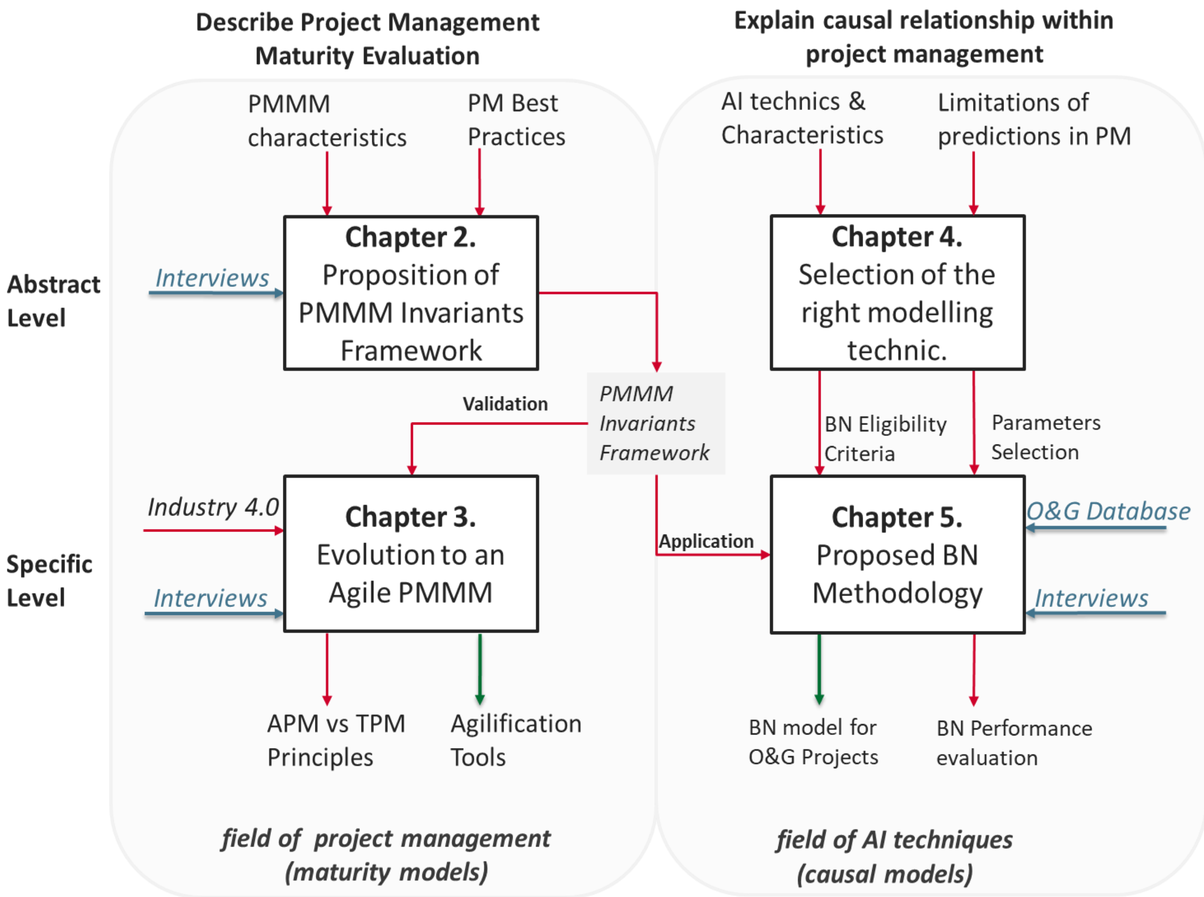


Figure 1.1 Structure of the thesis contributions

To sum up this introduction Table 1.2 presents the contents of each chapter.

	Chapter 2	Chapter 3	Chapter 4	Chapter 5
Main Research Question	How to propose a general and concise method to build a PMMM and to evaluate project management (PM) maturity?	How can we use our proposed PMMM to evaluate traditional project management (TPM) and agile project management (APM)?	How to choose the right modeling technique adapted to project management (PM)?	How can we create a methodology based on interviews and historical project management data to predict projects' operational performance based on PMMM evaluation?
Main Goal and Contribution	Propose a general PMMM, which is IB2M	Apply the proposed PMMM in two specific cases: TPM *vs.* APM	Evaluate and select the appropriate AI technique explaining causal relationships within PM	Propose a methodology to explain how PMM may be linked to projects' operational performance (cost)
Literature Review and gaps	PMMMs	Comparisons between TPM and APM	AI Techniques (ANN, RL, BN), BN principles, predictive models Applied to PM	
Gap in the literature	Existing PMMMs that have no clear conceptual statements and that cannot make predictions	Existing PMMMs only refer to TPM	Lack of accuracy in existing models in PM	There is no correlation model that links PMM levels and cost overruns
Specific Research Questions	How to generalize existing PMMMs? How to include the best practice of PM literature in our proposed PMMM?	How is it possible to instantiate a generic PMMM to TPM and APM? To define and to support agilification process?	How to choose an AI technique satisfying PM specificities and requirements? How to test the accuracy/precision of the models?	Are BNs good tools to model the causal relationships between PMM and project overcost? How to select the right hyper-parameter combination in the model? How to measure its performance?
Empirical backgrounds	Interviews with experts referring to 20 Projects and selection of best practices defined in the literature	Agilification scenario validated by interviewed consultants	Literature combining PM and AI	Interviews with experts referring to 15 Oil and Gas offshore projects and systematic data analysis

Table 1.2 Structure of the thesis by chapters.

CHAPTER 2

2 An Invariant-Based Project Management Maturity Model

About this chapter Project management maturity models (PMMMs) provide items to assess project management capability. Researchers and practitioners have proposed several PMMMS. Unfortunately, these models are heterogeneous; they have no clear conceptual statements. That explains why our first task is to create a generic PMMM. This second chapter puts forward the basic concepts and definitions in the literature of PMMMs and conducts several interviews to propose a new model based on common characteristics of project management, we call it Invariant-Based Maturity Model (IB2M). It should be capable of solving the main issues of project management maturity evaluation. This model is based on three categories: the project domain, the chronology, and the modality of project managers' tasks. The proposal of this model aims at reducing the number of questions to evaluate project maturity. The relevance of our IB2M is tested with 20 projects related to the energy industry.

2.1 Introduction

A project is *"a temporary endeavor undertaken to create a unique product, service, or result."* (Project Management Institute, 2016b). Projects are limited in time and budget; they exist to satisfy a unique request that cannot be solved with day-to-day operations. Today organizations are moving from operations activities to project type activities, those projects are set to develop new products or services, change internal structures or processes, and implement different business strategies (Elonen & Artto, 2003a). This trend is called "*projectification*" (Packendorff & Lindgren, 2014).

Academics and practitioners have built several bodies of knowledge collecting best project management (PM) practices (APM, 2012; IPMA, 2006; PMI, 2013; Project Management Association of Japan, 2005). Based on guidelines, they have developed project management maturity models (PMMMs) for auditing and assessing organization's project management capabilities, then designing the planning of actions that may result in an improvement of these capabilities. However due to the diversity of evaluation criteria and methods it is not possible to clarify the empirical correlation between project management maturity and the satisfaction of future project operational performance criteria such as achieve systems engineering measurement leading indicators (Zheng, Baron, Esteban, Xue, & Zhang, 2017), meet stakeholder needs, respect deadlines and avoid cost overruns (Jugdev & Thomas, 2002). In this chapter, we propose a new PMMM. This proposal is a first step allowing academics and practitioners to evaluate project management organizations with the same criteria, making possible to test how higher maturity implies higher probability of better operational performance for future projects.

PMMMs are helpful to identify, analyze and qualify project management tasks (T. J. Cooke-Davies & Arzymanow, 2003; Ramirez, 2009). Most PMMMs describe maturity in a perfection scale with five maturity levels (Christoph Albrecht & Spang, 2014). The first step represents informal project management, while the upper levels represent implemented and improving project management processes (Jugdev & Thomas, 2002). The assessment of project management organization is usually done by checking whether the actors accomplish best practices based on a defined Project management body of knowledge. Some of them are: the Association for Project Management (APM, 2012), The International Project Management Association (IPMA, 2006), The Project Management Association of Japan (Project Management Association of Japan, 2005) or the Project Management Body of Knowledge, PMBOK® (Project Management Institute, 2016a). We will specially focus on the last one because it is recognized as an internation reference for engineering projects by the Institute of Electrical and Electronics Engineers (IEEE standard 1490-2011).

After the analysis of several PMMMs, we came to the same conclusion as several authors: Each PMMM proposes a list of maturity criteria, but no conceptual statements are defined (Ramirez, 2009). Authors use diverse, heterogeneous and very large criteria to evaluate project management (Vergopia, 2008). PMMMs do not have any common language, concepts and methodologies (Torres, 2014), they cannot collect data from different projects to standardize the maturity evaluation (Albrecht & Spang, 2016). Transfer PMMM evaluation results in terms of another is complicated. Thereby, the main research question motivating this chapter is: How can we adapt existing PMMMs to create a generic project management maturity assessment model? Therefore, the objectives of this chapter are as follows:

- Highlighting the theoretical foundations, with some examples that illustrate their strengths and weaknesses,
- Exploring the common characteristics and generalizing the categories of the evaluating criteria and creating then an Invariant-Based Maturity Model (IB2M),
- Selecting the best practices in project management literature in order to check IB2M empirically,
- Demonstrating how to use this IB2M in a case study concerning 20 projects of the energy sector.

This second chapter is organized as follows. In section 2.2, we describe a literature review in maturity models. In section 2.3, we explain the problem and the methodology of this research work. In section 2.4, we develop the proposal IB2M and we compare it with the PMBOK® theoretical constructs. In section 2.5, we present the results of an industrial application where the project management maturity is evaluated with our proposed IB2M. Finally, in section 2.6, we discuss the results and in section 2.7, we give first conclusions.

2.2 Literature Review on Project Management Maturity Models

Academics identify three main phases of PMMMs over the last two decades.

From 1997 to 2003, an extensive body of literature proposed new PMMMs that are now commonplace tools (Andersen & Jessen, 2003; Cleland & Ireland, 2002; Goldenso & Gibson, 2003; Jugdev & Thomas, 2002; Y H Kwak & William, 2000; Young Hoon Kwak & Ibbs, 2002; Pennypacker & Grant, 2003).

From 2003 to 2014, firms or public institutions implemented these models, which allowed researchers to have sufficient hindsight to appreciate their effectiveness in different types of projects, organizations, sectors, etc. In this second phase, PMMMs were improved, and they were used to assess different types of organizations, especially those specializing in the development of Information Technologies (IT) (Andersen & Jessen, 2003; Becker, Niehaves, Pöppelbuß, & Simons, 2010; Pasian, 2014; Pennypacker & Grant, 2003; Schumacher, Erol, & Sihn, 2016; Yazici, 2009).

Third, since 2012 researchers have been showing an increasing interest in questioning the value of PMMMs. They are particularly exploring whether better maturity implies a higher probability of success in terms of satisfying project operational performances (Anantatmula & Rad, 2015; Ellis & Berry, 2013; Görög, 2016; Jonas, Kock, & Gemünden, 2013; Kampianakis & Oehmen, 2017; Lappe & Spang, 2014; Lasrado, 2018; McClory, Read, & Labib, 2017; Teller, Unger, Kock, & Gemunden, 2012). Nevertheless, this headlong rush towards the search for increasingly precise causal models should not prevent a return to an analysis of the conceptual foundations of PMMMs.

2.2.1 Basic concepts and definitions in PMMMs

We assume that PMMMs were constructed following common principles such as: Projects' success is described in terms of the achievement of Key Performance Indicators (KPIs). Projects' successes (*vs*. fails) are explained by the fact that project managers implement (or not) certain practices (T. Cooke-Davies, 2002). These practices are tasks producing well-defined outputs, *e.g*. Work Breakdown Structure (WBS), *"the major product that project managers should generate as an output product for the scope definition process is a Work Breakdown Structure (WBS) chart. These products were grouped according to the knowledge areas, identified by the* PMBOK®*"* (Zwikael & Globerson, 2006). A process is a collection of tasks (or practices, routines) and working rules that can be individually defined by project experts. Audit missions check the execution of the practices that enable the improvement of organizations' capabilities, *i.e*. their recognized ability to implement routines differentiating them from nearby organizations, *e.g.* competitors, followers, etc. There is a scale of perfection dividing the maturity levels from lowest to highest. Project management concerns distinctive separated domains (or knowledge areas). Project managers' work has then a wide scope; they must be aware of different aspects, implement various practices, *e.g.* technical specifications, team animation, cost reporting, etc., and produce several types of deliverables (Lasrado, 2018).

Literature recognizes three uses of maturity models in the organizations: assessing the current state of maturity, providing guidelines to reach higher-level maturity, and benchmarking with other organizations (Torres, 2014). It also assembles the values of the maturity models for organizations, such as strategic value: higher-level maturity is a competitive advantage, and benchmarking value: highlighting the needs for developing the maturity status.

2.2.2 Traditional PMMMs

Academics and practitioners have developed more than thirty different PMMMs (Grant & Pennypacker, 2006). The Software Engineering Institute of Carnegie-Mellon University was a pioneer in designing a PMMM called the Capability Maturity Model (Software Engineering Institute, 2006), assessing organizations' ability to deal with complex projects. At the first level, project managers improvise, and then strictly apply increasingly quantitative, complex, and shared tools, before being able to innovate in a very constrained model. Moreover, the PMBOK® breaks down a project into ten different areas, as does the *Berkeley Process Management Process Maturity Model* or $(PM)^2$ (Y.H. Kwak & Ibbs, 2000). Those areas are focused on scheduling, cost management, data integration, procurement, human resources (HR), deliverables, risk, etc. Furthermore, Kerzner's *Project Management Maturity Model* (Kerzner, 2017) lists 183 items to check concerning all these areas. The *Project Management Solutions Project Management Maturity Model* has a longer and more detailed list of items (Project Management Solutions Centers, 2006). PMI's *Organizational Project Management Maturity Model* (PMI, 2013) (OP3M) proposes the 600 best practices usable as benchmarks that auditors can utilize to compare existing practices to those references. Let us point out the main characteristics of the useful PMMMs.

• **Capability Maturity Model Integration CMMI** (Software Engineering Institute, 2006). The CMMI is a model composed by levels of best practices that are oriented to improve outcomes of the project such as products or services. It was created to integrate models from multidisciplinary organizations in order to reduce assessment and training costs in software related organizations. It decomposes the work into several process areas and evaluates its capacity. CMMI has two approaches: an organizational maturity approach and a process capability approach. It defines a roadmap to let organizations improve based on practices. On the one hand, (Goldenso & Gibson, 2003) reported the analysis of applying the model to 11 organizations in US, Europe and Australia. They showed that Boeing (Australia) decreased in average 33% the cost to fix defects. Lockheed Lartin decreased in 15% the cost of finding and fixing defects. General Motors decreased the average number of late times from 50 to 10, and Bosch Gasoline System improved in 15% internal on-time delivery. However, when applying the CMMI, SEI statistics (Software Engineering Institute, 2006) showed that an organization can take 18 to 24 months to go to one level to the next one. The CMMI is one of the main references in building several project management maturity models (Andersen & Jessen, 2003). It is complicated to apply since it has several components to evaluate.

• **Berkeley PM Process Maturity Model** (PM^2) (Young Hoon Kwak & Ibbs, 2002). This model is based on the practices of the PMBOK® and uses statistical techniques to evaluate process maturity level. This model is composed of five stages that show how organizations' improvement should be driven. This is the first model to adopt a software maturity model to any industry, it makes an assessment containing 148 questions (Vergopia, 2008). PM^2 evaluates how the organization can be classified in a certain maturity level, but it does not explain how an organization should move its project management process from one level to the other.

• **PM Solutions Project Management Maturity Model** (Pennypacker & Grant, 2003). This model uses the five levels of maturity of CMMI to separately evaluate the domains of project management in the PMBOK®. This model has a very long and detailed evaluation. A report from the Project Management Solutions Centers showed that in 2006, 67.9% of the organization using this model couldn't exceed level 1; the 21.0% were in level 2, 6.2% were in level 3, 3.7% in level 4, and 1.2% in level 5 (Project Management Solutions Centers, 2006).

• **Organizational Project Management Maturity Model** (OPM3) (PMI, 2013). This is the referenced model of the Project Management Institute (PMI). OPM3 aims at becoming a world referential in project maturity. This model considers around 600 best practices to evaluate the level of project management maturity in the organization; it is used in program and portfolio evaluation too. It helps organizations to identify areas that need improvement; it promotes organizational maturity among managers aligning projects with the organizational strategy. The assessment is long and complex; it is implemented in three main steps. First, one describes maturity in project management and explains how maturity in project management can be identified. Then one describes current methods, processes and evaluation procedures that an organization can use to make a self-assessment of its maturity. Finally, one provides a process to move from one level of maturity to another higher.

• **Portfolio, Program & Project Management Maturity Model** (P3M3) (Portfolio, Management, & Model, 2010). P3M3 applies the principles and best practices of project management to portfolio and program management. Every level describes how different process areas in portfolio management can be structured, so the organization can fix and accomplish its goals.

• **Project Management Maturity Model** (Kerzner, 2017). Kerzner had developed this model and created an online assessment tool of self-evaluation. This exhaustive tool has 183 multiple-choice questions that help participants to classify his/her project organization in one of the five levels of maturity. As an online tool, it allows the participant to compare his/her company with other companies in the same industry. This assessment evaluates the following areas: the communication within a common language, working with a common process, the knowledge and domain of standardized methodologies, the benchmarking of the "project management office" and the comparison with other companies and finally the focus on continuous improving through benchmarking with industry, analyzing lessons learned and transferring knowledge.

Moreover, classic PMMMs suggest a scale of perfection composed of several maturity stages, levels, or steps (these words are synonymous). The path of maturation is linear, whereby the organization improves in terms of project management capabilities while traversing this path (Lasrado, 2018). Existing models assess the maturity of project management often with the same five levels, synthetized by (Ramirez, 2009) as following:

- **Level 1:** There is no established project management practices, the project is first in its type in the organization (*ad hoc* project), and it does not have any defined team or senior management support.
- **Level 2:** There are some good practices in place and there is a small team engaged, also the organization has done some similar work before.
- **Level 3:** PM practices are standardized within the organization; there is a project team that has skills and training in project management.
- **Level 4:** There is a team with strength teamwork and formal training in project management, they benchmark best practices and formally report the information.
- **Level 5:** Individuals are involved in and dynamic, energetic and fluid organization. It continues to improve project management practices and processes; it transforms the whole company in a project-driven organization.

Project management literature has examined the empirical value of the PMMMs mentioned above. Several studies have been conducted to identify the most used practices in project management (Besner & Hobbs, 2008; Fernandes et al., 2013b; Fortune & White, 2006; Fortune et al., 2011; White & Fortune, 2001). White and Fortune (2006) listed 44 best practices and asked 236 interviewees how often they implemented them. Besner and Hobs (2008) selected 70 best practices and surveyed 753 participants about the implementation of practices based on a scale ranging from 1 (not used) to 5 (very extensive). More recently, Fernandes et al. (2013b) used the same practices to survey 793 practitioners over 75 different countries. Their results were consistent with those of previous authors: the most implemented practices are the same across different organizations worldwide. There is, therefore, a core of practices shared and implemented by almost all project managers throughout the world in all sectors and organizations.

2.2.3 Limits of PMMMs

Based on this review, we have pointed out limits of existing PMMMs:

1. Lack of concision: All the above-mentioned PMMMs are made of too many components and the principles guiding their design are not explicit (Vergopia, 2008). The detailed lists of criteria lead to long maturity evaluations that are often partially achieved (generating incomplete data) and make a quantitative impact analysis impossible (too many variables). In addition, the multiplicity of PMMM hinders the collection of a great amount of evaluation data that could be common to different projects. This causes a problem when researching the causal relationships between maturity in PM and project operational performance, due to the diversity of empirical data gathered from each maturity evaluation (Lahrmann et al., 2011; Pöppelbuß et al., 2011).

2. Lack of conceptual backgrounds: Literature points out PMMMs' lack of theoretical backgrounds and definitions: it is never indicated from which conceptual or theoretical foundations project knowledge areas, perfection scales, or even the concept of best practice are conceived (Ramirez, 2009). There is also a debate about the relevance of the notion of maturity stages, steps, or levels (Torres, 2014). Each maturity level displays different practices, evaluated differently to reach each state (Solli-Sæther & Gottschalk, 2010). There is no general model that could contain all the key concepts related to project management maturity evaluation.

3. Lack of usability: Authors pointed out that these exhaustive and very detailed models are too complicated to have any practical value for project management auditors (Renken, 2004). This heterogeneity in the assessment causes complications when transferring the results of the evaluation from one model to another (De Bruin, Freeze, Kaulkarni, & Rosemann, 2005).

Therefore, there is a large scope for future research for building and testing PMMs based on more clear conceptual and practical foundations. An analysis concerning the way PMMMs have been constructed allows us to highlight common principles, thus following Lasrado's proposals: first, use a standard vocabulary for project management evaluation; second, use a standard procedure for building the model (Lasrado, 2018). This author assumes that building better-defined PMMMs should improve the possibility to establish firmer foundations on the causal relationships between PMM and future projects operational performances. We consider this approach fruitful and will take it into account when building our models.

In synthesis, the elaboration of PMMMs lacks clear conceptual backgrounds applicable to different types of evaluation, that is, there is no consensus on the evaluation vocabulary, categories, and processes. Project management maturity audits produce a large variation of data collected to measure maturity. This data concerning a specific project cannot fit with the evaluation data to other projects. This implies that the development of empirical evidences proving the positive causal relationships (or not) between maturity and future projects' operational performance is not possible. In addition, the authors' tendency to multiply instances, *e.g.* projects dimensions, the list of practices, etc., leads to overly detailed, dense models whose practical values cannot be transferred from one to another.

Consequently, the next step of this second chapter is to propose an Invariant-Based Model for PMM assessment, solving a part of the conceptual challenges described previously, including the use of the best practices in project management accepted in scientific literature, and testing the model in several projects to evaluate its generality and adaptability.

2.3 Building an Invariant-based Maturity Model (IB2M)

The main research question underlying this work is: How can we adapt existing PMMMs creating a new project management maturity assessment model? Our first hypothesis is that it is possible to extract common characteristics of existing PMMMs, then building a model as Lasrado suggested (Lasrado, 2018). To solve this question, we have followed a four steps methodology. The step 1 and 2 explain how to build our proposed IB2M. The step 3 and 4 explain how to check the value of this model by qualitative and quantitative approaches. We have based our modeling methodology on two backgrounds: (1) a synthesis of PM literature highlighting best project management practices (Besner & Hobbs, 2008; Fernandes et al., 2013b; Fortune & White, 2006; Fortune et al., 2011; White & Fortune, 2001) and (2) 26 semi-structured interviews with 10 Sopra Steria's experts in the energy industry to check the relevance of our proposed generic model.

2.3.1 Step 1: Identify the most relevant results in PMMMs literature to extract invariants

Our first task was to identify and classify process groups and knowledge in project management areas. PMBOK® proposes 10 knowledge areas and 49 processes (Project Management Institute, 2016b). However, the groupings identified in a large-scale international survey with a sample of 2,339 practitioners participating, describe how processes vary in the reality of project management practice. They conclude that the groupings in the PMBOK® Guide are opinion-based conceptual groupings following an observable pattern. They affirm:

> "*This grouping is very effective since the management of project management practice in an organization is greatly simplified because instead of managing more than a hundred individual practices, they can manage practices in a much smaller number of groups of practices.*" (Besner & Hobbs, 2012).

Consequently, PMI suggests that project management is based on ten knowledge areas, *e.g.* scope management, integration management, cost management, quality management, etc. (Project Management Institute, 2016b). Areas with similar characteristics can be grouped into larger classes called domains. We propose to group project management knowledge and practices into four domains: *social domain, contract domain, results domain, interface domain*. Grouping knowledge areas into similar domains will reduce the number of questions when doing the maturity evaluation.

There is a consensus among researchers and practitioners: the PMBOK® terms and theoretical constructions, practices, tools, and techniques can be grouped by similar characteristics (Maylor, Vidgen, & Carver, 2008). For instance, the PMI proposes six process groups: Initialing, Planning, Executing, Monitoring, Controlling and Closing. However, the project management process groups can be divided into only three delimited time structures, called chronologies or chronological invariants under our approach. For each domain, we therefore define these time characteristics related to PMBOK® in three phases: *prepare, monitor, and valorize*. The reduction from six to three groups simplify the model without losing its generality.

The tasks inside the chronologies share common modalities, *i.e.* characteristics contextualizing the way these tasks are performed. They are doing so through individual or collective actors, possibly with tools (*resource involvement*), they are doing so with a repetitive manner (*frequency*) and their outputs can be described with different levels of detail (*activity granularity* – for instance, either macro-planning with a time step of one week or detailed planning with a time step of one hour). This grouping of the 49 processes tasks into three modalities would create communes axis of assessment, instead of a list of questions.

Table 2.1 displays the comparison between the categories in the PMBoK® and our proposed Invariant-based model.

PMBOK	IB2M
10 Knowledge Areas: ▪ Integration Management, Communications Management, Resource Management ▪ Schedule Management, Cost Management, Quality Management ▪ Scope Management, Risk Management ▪ Procurement Management, Stakeholder Management	4 Domains: ▪ Social Domain ▪ Results Domain ▪ Contract Domain ▪ Interface Domain
6 process groups: ▪ Initializing, Planning, ▪ Executing, Monitoring ▪ Controlling, Closing	3 Chronological Invariants : ▪ Preparation, ▪ Monitor, ▪ Valorize
49 Processes, each one with several tasks to evaluate.	3 Modalities of tasks on which the practices to check are performed (or not) and then assessed: ▪ Frequency (F: how many times?), ▪ Resource involvement (R: how much?), ▪ Activity Granularity (G: At what level of detail?)

Table 2.1. PMBOK® categories vs. IB2M categories**.**

In synthesis, by building an IB2M, we aim to create a consensus on PM evaluation vocabulary, categories, and processes. PM maturity audits produce a large variation of data collected, because they are excessively detailed. Audits outputs cannot be transferred from one model to another. Under our proposed IB2M, data of a project under study can fit with the evaluation data of other projects. This implies the development of evidences proving the positive causal relation between project management maturity and projects' operational performance, as we will present in chapter 5.

2.3.2 Step 2: Integrating the best practices of PM in our proposed IB2M

Figure 2.1 presents the Invariant matrix that maps the three basic categories, namely the domain, chronology, and modality of project managers' tasks to check. These tasks were considered as instances and placed in the cells of the matrix below. It shows the three chronologies (columns), the three invariants nature (columns) and the four domains (colored boxes)

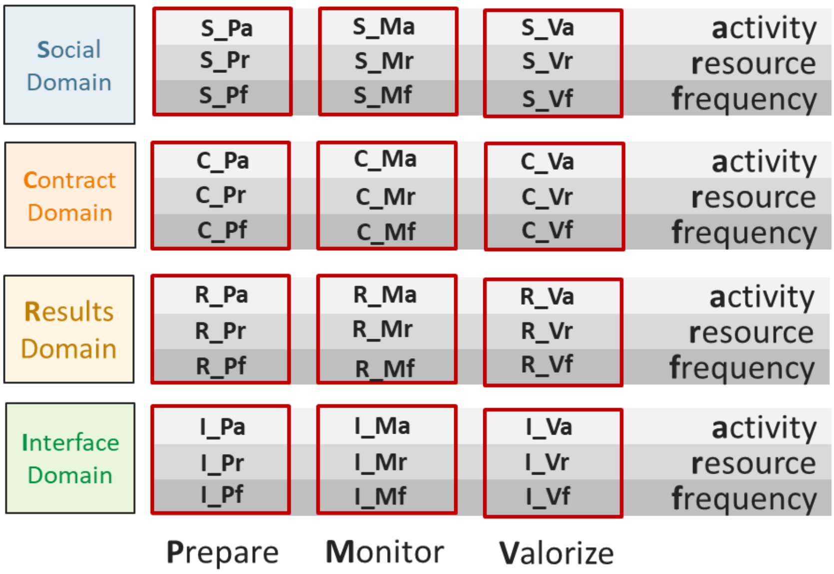


Figure 2.1. IB2M Matrix

We can detail each item of the above matrix.

1. Domains. Each domain (boxes inside Figure 2.1) integrates specific outputs that project managers are expected to produce. Thus, *the Social domain* describes the characteristics created by human interactions in the project. It corresponds to the PMBOK® knowledge areas of communication management (COM), Human Resources management (HR), and integration management (INT). The center of social configuration is the project team, the manager, and the relationships between them. Project management literature has shown that project manager's relationships with their team have a positive impact on the project results (Crawford, 2005; Jonas et al., 2013). Therefore, the maturity assessment will estimate whether the team is being managed correctly, and whether the required resources are available to let the team members feel they can work effectively. *The contract domain* corresponds to the PMBOK® knowledge areas of scope management (SCO) and risk management (RIS). This domain includes all inputs relevant to the contract definition, the risk management, and the scope management. The *Results domain* mirrors the PMBOK® knowledge areas of cost management (COS), quality management (QUA), and schedule management (SCH). Projects would need safeguards and a contingency plan. Project managers should foresee overruns, and estimate contingency reserves (referred to as buffers) to anticipate for schedule uncertainty. Finally, *the Interface domain* corresponds to the PMBOK® knowledge areas of procurement management (PRO) and stakeholder management. (STA). The Interface domain includes reviewing the horizontal integration, the data quality exchange between stakeholders and knowledge management repository.

2. Project Chronology. Chronology is a category, which distributes events and occurrences of different project management tasks on the time axis. Our proposed chronology has three segments:

- **Prepare:** Activities performed before the start of the project execution and updated at least, at each milestone, to prepare the work during the next phase(s) of the project.
- **Monitor:** Activities performed during the project execution to follow the progress of the project.
- **Valorize:** Activities performed at least at each milestone, and in the closing of the project. These activities will increase the value of the project, or improve future projects.

3. Modalities. In addition, for each chronology we define project managers' tasks' modalities as follows:

- **Resource:** concerns the actors' allocation (for instance, the project manager, the team, the stakeholders) and the tools necessary to complete their activities. Who is involved in the activities? Which tools does this actor need to perform his/her activity?
- **Granularity:** concerns the level of detail that may be used to describe the outputs of project management activities. It may depend on the chosen period of description (for instance, one hour, one day…) or on the aggregation of resources allocated to a project activity (for instance, at the member level or at the team level).
- **Frequency:** concerns the temporality of PM activities: Is there a unique execution of the activity? Is it repetitive? When? How often? How to measure important variations? This includes time plans, cycles, deadlines, etc.

4. Scale of maturity. By stating if the best practices or routines are implemented or not, the auditors can check the maturity level obtained on the evaluated project. Going from one level (n) to the next one (n+1) means that the best practices in (n) is fully accomplished and (n+1) is in the process of being accomplished. Classic PMMMs assess the maturity of project management often with scales consisting of five levels. We inspire our proposition in the existing scales, but also in the work from (Belkadi, 2006):

- **Level 1: Absent/Discover** Non-implemented process: the project organization has defined only some activities; their processes are carried out on an ad hoc basis,
- **Level 2: Define and implement:** *"this level corresponds to the minimum technical knowledge necessary to understand the characteristics of an entity, or a problem to be solved"* (Belkadi, 2006). The project manager and the project team define which are the best practices of project management that are need to be used in the project,
- **Level 3: Measure and Analyze:** *"this corresponds to a minimum level of control to be able to manipulate knowledge and apply it to solving the current problem"* (Belkadi, 2006). In this level, the project manager and the team take data from several sources (software, historical data, etc.) and analyzes it to make better decisions,

- **Level 4: Manage gaps and interdependencies: "***this level of expertise allows an actor to adapt and combine existing knowledge in order to apply it to new cases in the field."* (Belkadi, 2006). In this level the project manager and the team can manage complexity and uncertainty produced by interdependencies among different projects running at the same time,
- **Level 5: Capitalize and improve.** *"It is the highest level meaning a perfect mastery of a technical knowledge on an entity or a domain."* (Belkadi, 2006). In this final level, the project manager and his team capitalize activities and rapidly adapt to the changes in the environment. They manage complexity and extends the process learned to the whole organization.

The previous scale can evaluate the proposed invariants better than the scale proposed by classic PMMMs (in the section 2.2.2) because we are including the interdependence between projects (on level 4) and we are focusing on the capitalization and continuous improvement (on level 5). This new scale simplify maturity evaluation since the auditor needs only to evaluate the level of perfection of the best practice instead of evaluating a different best practice in each maturity level.

5. IB2M Grid. Auditors can synthesize the data in a tool called a maturity grid. This scored grid helps managers to formulate expectations in terms of practices' improvements, for instance, figure in the annex displays a simplification of the maturity evaluation process adapted from the Berkeley PMMM (Y H Kwak & William, 2000). The full model has several criteria; and it has more than 400 assessment questions. Similarly, our proposed IB2M can be represented with a maturity grid (Figure 2.2). This figure shows how each domain have three chronologies, and how each chronology have three modalities. For the IB2M we use 26 invariants to check maturity. The invariants evaluate project management best practices.

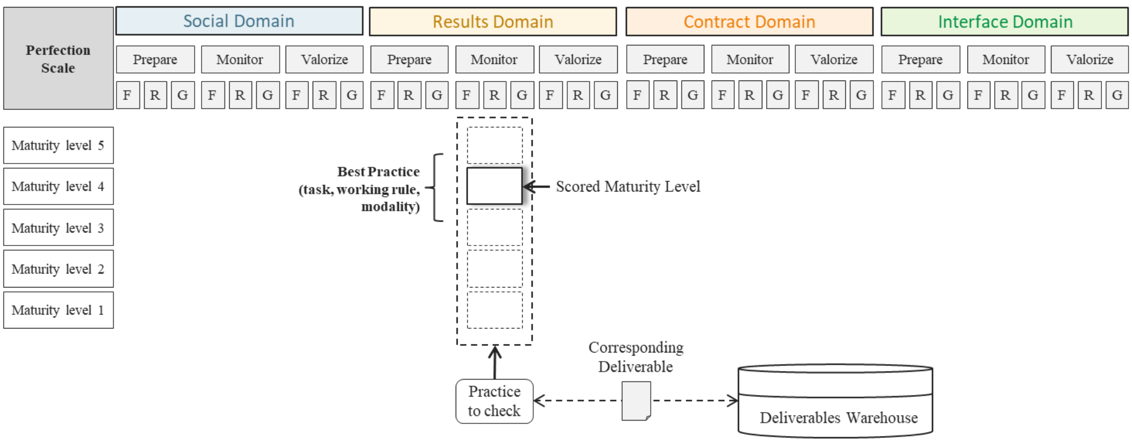


Figure 2.2 Invariant-Based Project Management Maturity Grid

The IB2M we proposed has been described. In the next section, an empirical assessment with experts' interviews and the selection of best practices in project management (Besner & Hobbs, 2008; Fernandes et al., 2013b) will be elaborated to refine the model, and finally a quantitative assessment will be described demonstrating the applicability of this model.

2.4 Industrial Assessment

IB2M assessment was conducted following two parallel inquiries: a first one during which we asked experts to check the value of the structure and the semantic content of the proposed model, and second one based on data related to 20 industrial projects.

2.4.1 Step 3: Check IB2M's qualitative value by interviews

Our proposed IB2M is very general. The main challenge is now to assess if it has a qualitative value for consultants practicing daily project management audit missions. We have then associated illustrative interviewees' responses to each invariant to check by experts.

This section aims at explaining how it is possible to create an PMMM based on the admitted best practices in project management (Fernandes, Ward, & Araújo, 2013a). Here we show how these practices can be classified in our model. Next, we explain in detail how invariants are developed in each proposed domain. We associate illustrative interviewees' responses to each invariant. The current research results are based on an empirical measure of the used practices, tools, and techniques as reported by practitioners through interviews.

Social domain

First, the Social domain describes those characteristics created through human interactions in the project. The center of social configuration is the project team, the manager and the relationships between them. Research has shown that the project manager's relationships with his/her team has a positive impact on the project results (Crawford, 2005; Jonas et al., 2013). Therefore, the maturity assessment will show whether the team is being managed correctly with efficient relationships between the manager and the team.

In general, interviewees affirm that it is highly important to check how social interactions are established in the beginning of the project. For example, interviewee 1 explains: "*analyzing the starting phase of the project (i.e. the preparation phase) it is imperative to know if the project has a communication plan in place (S_Pf), or if all key stakeholders have been identified (S_Pa)."* Moreover, interviewee 8 affirms: "*We are interested in knowing whether the project has enough resources, but also if those resources are adequate for the project.*"

The *monitoring* phase describes how the plan is implemented during the project, and how it is monitored. It is important to propose checkpoints to qualify if the project is meeting organizational standards. According to interviewee 4, a question to assess the maturity of a project organization in this phase is "*Does the project team have the necessary tools, skills and processes to undertake the project successfully*? (S_Mr). As pointed out by other researchers, a good practice in team management includes: conducting efficient meetings, making effective use of stakeholder time (S_Ma), and accurately documenting the business process behind the application and describing the information flow (Ellis & Berry, 2013). For this reason, it is essential for the project manager to track the progress in reports (S_Mr)

Experts will tend to examine the learning curve of the organization at the end of the project's execution (valorize phase) and in order to improve future projects (S_Vf). According to interviewee 3, "*we ask if the project organization has a training plan in place or if there is enough time to produce training materials, valuating learned experience and creating feedback*".

Table 2.2. shows how the best practices in the social configuration domain issued from Besner and Hobbs (Besner & Hobbs, 2008) and Fernandes et al. (Fernandes et al., 2013b) are classified with the proposed Invariant-Based Maturity Model. This table underlines the relationships between invariants we have proposed and their selected best practices.

Chronology	Nature	Invariant	Most common practices in Project Management
Prepare			
	Activity	S_Pa	Resources scheduling
	Resource	S_Pr	Responsibility assignment matrix
	Frequency	S_Pf	Kickoff meeting
	Frequency	S_Pf	Communication plan
Monitor			
	Activity	S_Ma	Team-building event
	Activity	S_Ma	Self-directed work teams
	Activity	S_Ma	Progress communication meeting
	Resource	S_Mr	Progress Report
Valorize			
	Activity	S_Va	Customer satisfaction surveys
	Resource	S_Vr	Team member performance appraisal
	Frequency	S_Vf	Team Learning Curve

Table 2.2 Classification of best practices in Social domain.

Contract domain

The Contract domain takes into account practices relevant to the contract, risk and scope definition of the project. According to interviewee 2 "*Some of the most important signs showing how mature is a project comes from the definition of the contract*". Practitioners as well as literature agree about the importance of requirements definition (C_Pa). In order to detect an issue with requirements it is necessary to know if requirements are well documented, and even if the organization has implemented a system for tracking requirement changes. As declared by the interviewee 5, "*The contract must describe project objectives in concise, clear, and unambiguous terms*", for example, project managers should work facilitating cross-functional group sessions where requirements can be discovered easily.

During the preparation phase, the project Manager should be able to confirm that the scope is well defined at the start of the project (C_Pa). Additionally, as shown by interviewee 6: "*contracts should take into account the risk definition of the project, this includes the contingency risk plan* (C_Pf), *and even if there are strategies to mitigate risks*".

Furthermore, in the monitor phase, the practitioners should consult if the mitigation strategies are in place and monitored, and risk reviews are undertaken to measure and control variations such as configuration reviews (C_Ma). In addition, the project manager should be capable of identifying the cumulative impact of scope variations, including cost and quality effects. The whole team and key stakeholders may be able to track and estimate the impact of variations. From this analysis, practitioners propose that another important practice to be checked is the frequency of change in the scope (C_Mf). Project management literature declares: "*the manager must assure that the scope of the project neither significantly changed nor had major activity functions that may be moved to the following phases of the project*" (Ellis & Berry, 2013)

Table 2.3. shows how the best practices in the contract domain issued from Besner and Hobbs (Besner & Hobbs, 2008) and Fernandes et al. (Fernandes et al., 2013b) are classified with our Invariant-Based Maturity Model. This table underlines the relationships between invariants we have proposed and their selected best practices.

Chronology	Nature	Invariant	Most common practices in Project Management
Prepare			
	Activity	C_Pa	Requirements analysis
	Activity	C_Pa	WBS Work Breakdown Structure
	Activity	C_Pa	Project charter
	Activity	C_Pa	Feasibility study
	Activity	C_Pa	PBS: Product breakdown structure
	Activity	C_Pa	Activity list
	Frequency	C_Pf	Contingent plans
Monitor			
	Activity	C_Ma	Ranking of risks
	Activity	C_Ma	Configuration review
	Resource	C_Mr	Scope Statement
	Frequency	C_Mr	Change Request
Valorize			
	Resource	C_Vr	Client acceptance form
	Resource	C_Vr	Graphic presentation of risk information
	Resource	C_Vr	Database of contractual commitment data
	Resource	C_Vr	Database of risks

Table 2.3 Classification of best practices in Contract domain.

Results domain

The results domain is related to the key performance indicators of the project: cost, time and quality. In this area, projects would need safeguards and a contingency plan. Project managers should forecast overruns, and develop *time buffers* in the planning to avoid (bigger) losses. For example, project recovery managers (interviewees 6 and 7) inquire: "*Is the project* *manager aware of the plans' impacts? What is the timeframe to put this plan in practice? How long can contingencies can last until the plan is broken?"*

The schedule management process is highly important. Interviewee 8 affirms: "*it is necessary to know if a suitably schedule plan was in place* (R_Pf). *Was the plan up to date* (R_Pf)? *Does it reflect the defined scope of the project and with a solid and realistic proposal for the remaining work* (R_Pa)?" Furthermore, interviewee 3 affirms that a good assessment of schedule in the project should include questions such as: "*How is the use of milestones in the project, are they regular enough to track progress?"* (R_Mf). Some processes are globally defined within the quality systems. This system is defined within the quality plan (R_Pr).

Table 2.4. shows how the best practices in the results domain issued from Besner and Hobbs (Besner & Hobbs, 2008) and Fernandes et al. (Fernandes et al., 2013b) are classified with the proposed Invariant-Based Maturity Model. This table underlines the relationships between invariants we have proposed and their selected best practices.

Chronology	Nature	Invariant	Most common practices in Project Management
Prepare			
	Activity	R_Pa	Task Scheduling
	Activity	R_Pa	Cost/benefit analysis
	Activity	R_Pa	Critical path method analysis
	Activity	R_Pa	Cost estimating, Parametric Estimating
	Activity	R_Pa	Probabilistic duration estimate (PERT)
	Activity	R_Pr	Top-down / bottom up estimating
	Resource	R_Pr	Network diagram, Critical chain method and analysis
	Resource	R_Pr	Monte-Carlo analysis
	Frequency	R_Pf	Milestone Planning
	Frequency	R_Pf	Quality plan
Monitor			
	Activity	R_Ma	Monitoring schedule
	Activity	R_Ma	Monitoring of cost
	Activity	R_Ma	Quality inspection
	Activity	R_Ma	Resources leveling
	Resource	R_Mr	Control charts: Gantt, S-curve, Cause-and-effect diagram
	Frequency	R_Mf	Baseline plan
Valorize			
	Activity	R_Va	Earned value Management
	Activity	R_Va	Quality function deployment (QFD)
	Resource	R_Vr	Financial measurement tools
	Resource	R_Vr	Database for cost estimating
	Frequency	R_Vf	Re-baselining

Table 2.4 Classification of best practices of Results domain.

Interface domain

Interface domain includes questions such as those expressed by Interviewee 7: "*Are documents centralized? Is that centralization organizing, secure, and easy to locate? Is there a proper version control? How are main documents constructed, including, for example, minutes of key meetings? Is there a complete decision register*?" (I_Pr).

PMMMs' assessment focuses then on the nature of the project's interface with suppliers and other external stakeholders. The procurement strategy is a part of the interface domain. As explained by Interviewee 5, "*the assessment should note how the impact of the business process of the organization is in the project, and how it is implemented. In addition, it is important to check whether the project has a make or buy strategy and what kind of negotiation was necessary"* (I_Pa).

Therefore, it is critical to review terms of the negotiation with stakeholders to understand timeframes and details built within the plan. Interviewee 3 states: "*The relationships with internal stakeholders have an important impact on the development and result of the project. The information concerning unhappy/disinterested stakeholders and steering committee members is an early sign that the project is not going well, as well as other causes such as continuous criticism by stakeholders, changes in stakeholders without any warning, or high-tension meetings with the team and stakeholders*" (I_Pa).

Table 2.5. shows how the best practices in the interface domain issued from Besner and Hobbs (Besner & Hobbs, 2008) and Fernandes et al. (Fernandes et al., 2013b) are classified with the proposed Invariant-Based Maturity Model. This table underlines the relationships between invariants we have proposed and their selected best practices.

Chronology	Nature	Invariant	Most common practices in Project Management
Prepare			
	Activity	I_Pa	Stakeholder analysis
	Activity	I_Pa	Bid/seller evaluation
	Activity	I_Pa	Bidders conferences
	Resource	I_Pr	Bid documents
	Resource	I_Pr	Project Web site
	Resource	I_Pr	Database of historical data
	Resource	I_Pr	Life-cycle costs (LCC)
Valorize			
	Activity	I_Va	Lessons Learned/Post-mortem
	Resource	I_Vr	Database for lessons learned

Table 2.5 Classification of best practices of Interface domain.

2.3.2 Step 4: Check IB2M's quantitative value by data related to past projects

In order to understand better the advantage of the proposed IB2M, we have conducted a quantitative data analysis. The proposed model has been used to assess 20 projects grouped into five programs (here called "service centers"). These projects correspond to the assembly of the parts of steams generators for nuclear power plants. Table 2.6 includes a detailed description of each service center (SC).

Characteristics	SC1	SC2	SC3	SC4	SC5
Number of projects	3	3	5	4	5
Project costs (EUR millions)	~ 5	~ 5	~ 5	~ 1	~ 10
No. of employees	~ 100	~ 100	~ 100	~ 50	~ 250

Table 2.6 Characteristics of assessed projects.

In order to execute the data analysis, we have transformed the database developed by the consultants in their auditing mission in order to adapt it with the proposed invariant-based maturity model. To envisage this transformation, we have chosen respectively the common and specific characteristics of this model. The raw database contained a group of criteria extracted from several PMMMs models, such as the PM2, OMP3 and P3M3.

Main findings from the Quantitative Assessment

The best practices can form a maturity grid as displayed on table 2.7. This table presents the maturity of each of the invariant (and its respective best practice) for clients' five service centers. Due to confidentiality reasons, we only present the evaluation of the results domain. Table 2.7 also displays statistical measures (min, average, max, std. deviation) in this domain. They were calculated in order to compare the overall maturity of each service center.

Invariant	Best Practice Evaluated	Maturity Level				
		SC1	SC2	SC3	SC4	SC5
R_Pa	Cost/benefit analysis	2	3	2	2	2
R_Pr	Top-down / bottom up estimating	2	2	3	3	2
R_Pf	Milestone Planning	1	4	3	2	1
R_Ma	Monitoring schedule/cost	4	5	2	2	1
R_Mr	Control charts	3	3	1	1	2
R_Mf	Baseline plan	3	4	3	3	1
R_Va	Quality function deployment (QFD)	1	5	3	3	1
R_Vr	Financial measurement tools	2	3	3	2	1
R_Vf	Re-baselining	2	3	3	3	2
	Minimum Maturity Value	1	2	1	1	1
	Average Maturity Value	2,22	3,56	2,44	2,33	1,33
	Maximum Maturity Value	4	5	3	3	2
	Standard Deviation	0,74	0,84	0,74	0,59	0,59

Table 2.7 Project Management Maturity Evaluation for the Results Domain across all service centers

The quantitative assessment aims at comparing different maturity audit missions in a unified format. Table 2.8 displays the statistics measures of the maturity levels reached by each Service Center, that is, how each service center is performing:

- Min and Max are the minimum and maximum maturity values reached in each service center.
- Mean represents the average maturity level.
- The last column of table 2.9 represent the Standard Deviation of the maturity for each service center.

Maturity Levels by Domain		Min	Mean	Max	Std. Dev
Social	SC1	2	2,89	5	0,59
	SC2	1	2,11	5	1,04
	SC3	1	1,56	4	0,84
	SC4	1	1,78	4	0,96
	SC5	1	2,78	5	1,41
Contract	SC1	1	2,78	4	0,91
	SC2	1	2,44	4	1,51
	SC3	1	2,00	5	1,56
	SC4	1	1,44	3	1,16
	SC5	1	1,78	4	1,75
Results	SC1	1	2,22	4	0,74
	SC2	2	3,56	5	0,84
	SC3	1	2,44	3	0,74
	SC4	1	2,33	3	0,59
	SC5	1	**1,33**	2	0,59
Interface	SC1	2	3,78	5	0,91
	SC2	1	2,22	4	1,14
	SC3	1	2,11	5	1,04
	SC4	1	1,78	3	0,91
	SC5	1	2,33	5	1,85

Table 2.8 Results of the application of the model in five service centers

Table 2.8 displays how it is possible to evaluate project management maturity of 20 projects under homogenous criteria (here called Invariant-Based). The data collected demonstrates that it is possible to use similar categories in best practices to evaluate maturity. The proposed IB2M allowed us to evaluate the maturity of PM domains for different projects and compared them with the same categories. This assessment enables the experts and auditors to focus their effort in those areas where project organization need more attention. For example, the result domain shows a low maturity level in the service center 5 (mean of 1,33), showing that the project organization was having problems within this area; additionally, the standard deviation of this domain is the lowest (0,59), confirming the relevance of the data within this assessment.

To explain the results of the model in more details, Figure 2.3 displays the data for the Results domain maturity assessment in two service centers (SC1 and SC5). These service centers were selected because they exhibited a clear example of high and low maturity in project management. The first three columns in Figure 2.3 shows the maturity for those activities evaluated before the project (R_P). The activities are grouped by criteria of the same class, i.e. R_Pf (Results, Preparation, and Frequency), R_Pr (Results, Preparation, Resources), R_Pa (Results, Preparation, Activity granularity).

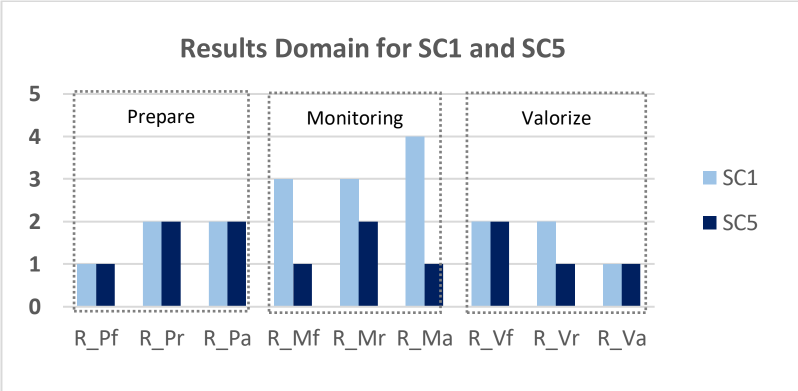


Figure 2.3 Results domain invariants maturity levels for SC1 and SC5

The first three columns (**preparation invariants**) show that SC1 and SC5 had low maturity for the frequency related task (*R_Pf level 1*) demonstrating how these projects did not define milestones correctly to prepare the project for future gaps and allowances. Auditors could also see that the evaluated SCs defined their cost structure completely (*R_Pr level 2*) and they completed all the necessary cost/benefits estimations (*R_Pa level 2*).

The next three columns demonstrate the project management maturity level of the routines during the execution of the project (**monitoring invariants**). Figure 2.3 displays how, in the SC1, the project team uses control charts (*R_Mr Level 3*) and a baseline plan (*R_Mf Level 3*) to measure and execute the actions in the correct timing. However, SC5 did not have any baseline plan (*R_Mf Level 1*). In addition, it is important to note that the schedule of all of the interconnected projects in SC1 were monitored (*R_Ma level 4*). Project organization in SC5 still needed improvement in the use of control charts (*R_Mr Level 2*) and it was not doing control activities such as cost monitoring (*R_Ma Level 1*).
The last three columns (**valorize invariants**) characterizes the evaluation for those activities needed to close the project and to further improve similar projects. SC1 defined and used financial tools (*R_Vr level 2*) such as PM software, they were executed at the right moment (*R_Vf level 2*); however, there is still a gap to improve the quality function deployment (*R_Va level 1*). Similarly, SC5 was not using financial tools to control the end of the project (*R_Vr level 1*). In SC5, the projects did not have a quality control in the end of the project (*R_Va level 1*).

Figure 2.3 shows that projects implementing systematic monitoring activities obtain significantly better PMM, as also shown in Table 2.8, where it is possible to compare the results of SC1 and SC5. In this table, for each domain SC1 has higher maturity levels than SC5. This could be explained by the nature of the assessed projects; they are very complex engineering projects.

2.5 Discussion

In the literature review we have pointed out some limitations of existing PMMMs. In this section, we explain how our proposal gives answers to these limitations. We included several suggestion proposed by (Lasrado, 2018): PMMMs could be too complicated and have large assessment processes. To solve this issue we proposed an Invariant-Based Maturity Model with fewer criteria. Furthermore, PMMMs lack operationalization in maturity measurement. To solve this concern, we proposed to check the most common 70 best practices found in project management literature. Finally, we tested our proposed Invariant-Based Maturity Model in 20 industrial projects and we asked feedback from experts belonging to a community of practice in project management.

In the literature review we have pointed out some limitations of existing classic PMMMs. In this discussion, we explain how our proposed IB2M goes further to these limitations.

1. Concision and conceptual backgrounds: In our point of view, the lack of concision of existing PMMMs is a consequence of the absence of clear conceptual backgrounds. All the above-mentioned PMMMs are made of too many constituents and the principles guiding their design are not explicit (Vergopia, 2008). The detailed lists of criteria lead to long maturity evaluations that are often partially achieved (generating incomplete data) and make a quantitative impact analysis impossible (too many variables). PM literature recommends the use of a standard vocabulary and procedure for building PMMMs (Lahrmann et al., 2011; Pöppelbuß et al., 2011; Renken, 2004). Following this recommendation, we have defined in this second chapter a concise and standard vocabulary, as displayed in Figure 2.1. The standard procedure for building the model was described in section 2.4. Our proposed model (IB2M) is based on 36 invariant criteria only. These criteria were justified by correlating them with the 70 best practices in PM shared by project managers across the world (Besner & Hobbs, 2008; Fernandes et al., 2013b; Fortune & White, 2006; Fortune et al., 2011; White & Fortune, 2001). We classified these practices in our categories in Table 2.2 to Table 2.5. This implementation allowed our proposed IB2M to be aligned with the current literature.

2. Lack of usability and evidence: We have tested our IB2M empirically. We have shown that the proposed model can group the information gathered from other PMMMs, facilitating then the usability. Moreover, we have look for empirical evidence. We have tested our IB2M across 20 complex industrial projects. We obtained an effective project management evaluation and normalized results. Given the proposed IB2M, other projects could be evaluated similarly. We also improved the assessment process, and we helped experts discover the best actions for improving PM practices. For example, if PM maturity is led by monitoring-frequency tasks for some projects, the experts should improve first those monitoring-frequency practices. Consultants have found the model easy to use and we corroborated the findings for the projects evaluated.

The proposed invariants model can be used to build maturity grids by different ways. For example, for each proposed invariant, it is possible to elaborate one question by maturity level; however, this action would increase the number of questions. These several question can be ambiguous for the project management auditor. That is the reason why, in the case study presented in this chapter we used one best practice by invariant, and we evaluated them regarding the characteristic of maturity levels defined in section 2.4.2.

2.6 Conclusion

This chapter addresses the following research question: How can we create a model overlapping the lacks of existing classic PMMMs? To answer to this question, we have proposed an Invariant-Based Maturity Model (IB2M). Our proposed IB2M clusters PM practices in classes, referred to as invariants. Moreover, consultants in PM reviewed this model. They agreed with its concise structure and semantics; they can include the best practices they check in the cells of our models. A second evaluation was based on empirical data related to 20 projects in complex product development. Data models derive from our conceptual model, and data shows the capability of our IB2M to evaluate several projects (and programs, called service centers) under the same criteria. Subsequently, this evaluation is a step to demonstrate the generality and adaptability of our model.

Our proposed IB2M is related to the conceptual basis of the PMBOK®, and more generally to the Traditional Project Management (TPM) framework of reference. Nevertheless, since the 2000s, new practices have been developing, called Agile Project Management (APM). The main challenge is then to check if our proposed IB2M is compliant with this new framework. The proposed invariants could be extended in further research to several project management methodologies following the V cycle (for traditional project management) or in short cycles (for agile project management). Consequently, how to adapt the proposed invariant-based project management maturity model to different types of project management, particularly agile approaches? The study in chapter 3 addresses this question.

In addition, the proposal of the IB2M is a first step to check the causal relationships between PMM and project performance. A key interest of this contribution is to provide the basis for the normalization of project management maturity assessments. Once PMM evaluation is normalized (standardized), it would be conceivable to collect statistics of project management maturity evaluation for a significant number of projects. They would share similar evaluation criteria, and the collected data will be of the same nature. The research approach in ***chapter 5*** is based on IB2M to build a causal model between PMM and operational performance.

CHAPTER 3

3 Applying Invariant-Based Management Model to traditional and agile project management

About this Chapter: In the previous chapter, we proposed an Invariant-Based Management Model (IB2M) to describe the domain of project management maturity and to audit or assess management process maturity. In this third chapter, we explore the possibility of either using or adapting IB2M to evaluate traditional project management practices (TPM) and agile project management (APM) rules. Our comparison between TPM and APM will be based on the key principles used in these two cases. Then, based on our IB2M, we will propose three tools to manage agilification, *i.e*. the transition process from TPM to APM: a conceptual model, a maturity grid, and an activity diagram displaying scenarios agilification. The contribution of this chapter will be tested with a case study related to the schedule management audit carried out by consultants.

This chapter will explore the characteristics of two types of project management, Traditional Project Management (TPM) vs. Agile Project (APM), with a focus on "*Scrum*" (Setpathy, 2016). It will compare its key principles to highlight their main differences and similitudes. An organization can move from TPM to APM, implementing then a process we called ''agilification''. Agilification is a key issue for large companies, especially if they implement Industry 4.0 solutions, as it is the case of clients of Sopra Steria Consulting. We will then use our proposed Invariant-Based Management Model (IB2M) to analyze agilification. Our conceptual results will be test on a case related to schedule management process.

Therefore, the objectives of this third chapter are:

- explaining why APM is important in the context of Industry 4.0,
- highlighting the key principles of TPM and APM,
- testing our IB2M in these two cases,
- creating new tools to improve agilification management.

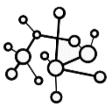
This chapter is structured as follows: in section 3.1, we will describe how Sopra Steria consultants conceive Industry 4.0. In section 3.2, we will present a brief view of TPM and APM, with a focus on Scrum, considered as an archetype of APM. In section 3.3, we will explain why IB2M is not fully compliant with APM. In section 3.4, we will go off the blocking points to propose a conceptual model coherent both with TPM and APM. In section 3.5, we will present three new tools facilitating agilification: a conceptual model depicting the context of TPM and APM, a maturity grid related to APM, and an illustrative tool displaying agilification scenarios. In section 3.6, we will discuss the results, before concluding this third chapter.

3.1 Industry 4.0: Sopra Steria conception

In practice, digitization challenges business or organizational models in many cases. Established organizations frequently fail to embrace opportunities offered by IT; they also struggle to adapt their business models (Westerman et al., 2014) or routines. Many missions of Sopra Steria consultants concern digitization, and one declination in industrial sector, that is Industry 4.0. TPM aim at developing a detailed planning or scheduling, managing project cost, locking in contracts, etc. Nevertheless, TPM can lead to situations where the plan has succeeded, but the customer is not satisfied. By contrast, recent APM coming from IT sector seems sometimes more relevant. The key issue is then to develop with agility Industry 4.0 projects.

For Sopra Steria consultants, project related to Industry 4.0 are based on four pillars: data-driven activities, openness, focus on operational performances, and agility as a key performance driver. Achieving the goals of these pillars supposes to implement APM.

Data-driven activities – TPM tends to bureaucratize project management. For example, each project management domain is always highly documented. Moreover, TPM is based on a hierarchical organization control: the higher the maturity is, the more the project management is excluded from the projects' life. In contrast, with the Industry 4.0 paradigm, data-driven collective and reactive decisions are replacing hierarchical decisions (McAfee et al., 2012).



Openness - Smart factories are supposed to facilitate the reindustrialization by bringing design, fabrication and distribution closer to the customers. On the contrary, TPM is usually based on introvert tools which only focus on internal practices (see PMMMs presented in chapter 2). The only opening towards organizations' external environment is reduced since it concerns only benchmarks of best practices. Industry 4.0 is by definition an open concept. It integrates several stakeholders (customers, suppliers, etc.), it is based on cross-functional teams, and it recognizes that everything changes because of continuous flows of opportunities, threats, innovations, etc.

Operational performances – Smart factories are supposed to be extremely reactive and flexible. On the contrary, under TPM, key performance indicators are reliability and efficiency. TPM's main idea is to make project managers' practices safer and more cost-efficient by detailing what they have to do. By acting efficiently and safely, project managers reduce the unexpected loops slowing down the planned progress of the project. However, the literature shows that APM improves delivery times and customer satisfaction (Budzier & Flyvbjerg, 2013). In the new context of Industry 4.0, we found new variables to measure projects' performance, *e.g.* customer involvement, brand penetration, data acquisition, goodwill, etc. Consequently, a new PMMM should not only evaluate the project manager's practices, but also other actors' practices interacting during an agile project.

Agility – Nowadays, agility is a key word, and even a buzz word… It can concern the capability to adapt quickly and with astuteness to any new situation. Key leverages of agility are cooperation, IT implementation, feedback, iterations, actors' involvement, etc. For example, under APM, designers are expected to prototype a solution as quickly as possible in order to iterate with the clients, customers, end user, etc. This modality appears in start-up companies implementing a continuous "*build-measure-learn*" loop (Blank & Dorf, 2012). This way of conceiving the progress of the project seems to be incompatible with TPM or manufacturing practices based on planned schedules and sequences. The literature on agile processes presents few assessments only to check firms' digital maturity (Schumacher et al., 2016), which supposes that every use of IT is intrinsically agile.

Few articles highlight the complications of existing PMMMs and TPM compared to Industry 4.0 paradigm. Nevertheless, we have no clear distinction between TPM and APM, and no clear idea of the location of the border between these two project management archetypes. We do not have any guideline or rule explaining when moving from TPM to APM (T. J. Cooke-Davies & Arzymanow, 2003; Jugdev & Thomas, 2002).

3.2 Background on project management methodologies

Agile Project Management (APM) is supposed to replace the Traditional Project Management (TPM). However, literature shows that there is a spectrum of project management approaches between these two (Doug, 2004). In this section, we do a brief literature summary and we present several types of project management methodologies. For example, Wysocki (2006) proposes a classification of project management types based on two criteria: (1) the nature of the goal of the project (clear or well-defined *vs*. not clear or ill-defined) and (2) the nature of the process to achieve this goal (clear or planned *vs.* not clear or ad hoc). Inspired by this author, we can highlight four potential types of project management (Table 3.1, adapted from (Wysocki, 2006)). A concrete project management practice or a project methodology belong to at least one of Wysocki's types.

		Solution Process	
		Clear (planned process)	**Not Clear (*ad hoc* process)**
Goal	**Clear (well-defined)**	Type 1	Type 2
	Not Clear (ill-defined)	Type 3	Type 4

Table 3.1 An Interpretation of Wysocki's Typology of project management types.

Type 1. Linear methodology (e.g. heavy construction projects): this project methodology consists in sequential phases with no or very few feedback loops. The project solution is not released until the final phase is reached. This strategy is characterized by a clearly defined goal and requirements, few requests for changes in the scope, routine and repetitive processes, and the use of pre-established formula and templates. Table 3.2 displays the main strengths and weaknesses of this type of project methodology. In his work, Wysocki explains largely the strengths and weakness. We summarized the main points under the form of a table.

Strengths	Weaknesses
➢ The project's schedule is done in advance. ➢ It is not mandatory to have high skilled resources. ➢ It is usually implemented in very large projects ➢ It has been largely used, then its techniques and tools are mature	➢ It is difficult to adapt planning and schedule to changes. ➢ Cost tends to be higher than expected (i.e. building projects) ➢ Time can be longer than expected ➢ Changes can make project time even longer ➢ It requires detailed planning ➢ It is structured with a strict pre-defined process ➢ It doesn't ensure value for the customer/user

Table 3.2 Strengths and weaknesses of a linear methodology, adapted from (Wysocki, 2006)

Type 2. Incremental methodology (e.g. Feature-Driven Development): In this project methodology type each phase releases a partial solution; the valuable solution has then to be delivered before the final step. Table 3.3., adapted from (Wysocki, 2006), draws the main strengths and weaknesses of incremental methodology type.

Strengths	Weaknesses
➢ Equilibrium between planned process and value delivery ➢ The scope is fixed, and the solution is incremental ➢ Change request can be established between increments and adapted through intermediate solutions ➢ It focus on customers' value	➢ The team may not remain intact between increments ➢ You must define increments based on function and feature dependencies rather than business value. ➢ Partitioning the functions may be problematic. ➢ Difficulty defining feature dependencies ➢ It needs more customer involvement

Table 3.3 Strengths and weaknesses of an incremental methodology, adapted from (Wysocki, 2006)

Type 2. Iterative methodology (e.g. Scrum): this project methodology type encourages iterative decision-making**.** For example, under Scrum, the primary focus is on delivering products that satisfy customer requirements in small iterative increments. It is similar to an incremental strategy, but iterative methodology repeats the loops after a group of short-run tasks are completed. A loop stops since customers are satisfied (stop rule). The iterative methodology type uses several intermediate solutions as a pathway to discover how the final solution should be (Table 3.4, adapted from (Wysocki, 2006)).

Strengths	Weaknesses
➢ Customers can review the current solution in order to suggest improvements. ➢ Scope changes can be established between iterations. ➢ Strategy can adapt to business conditions. ➢ Based on just-in-time planning	➢ It requires highly active customer participation. ➢ There is a risk of losing team members between iterations ➢ Subject to losing priority between iterations

Table 3.4 Strengths and weaknesses of an iterative methodology, adapted from (Wysocki, 2006)

Type 3. Adaptive methodology (e.g. Adaptive Project Model or Adaptive Software Development): under this project methodology, for each iteration the feedback will adjust the future of project managers' strategy. The solution is only partially developed by/for the customer, so the success depends on the ability to allocate frequent changes (Highsmith, 2000). An iteration may create a partial solution to the customer (called MVP: minimum viable product) (Table 3.5, adapted from (Wysocki, 2006)).

Strengths	Weaknesses
➢ It avoids non-value added work ➢ It provides maximum value given time and cost constraints. ➢ It is focused on generating business value ➢ Clients review partial solutions and they get improvement	➢ It must have meaningful customer involvement throughout the project ➢ Implementation of intermediate solutions can be problematic ➢ The final solution may not be the same as described by the customer at the project kickoff.

Table 3.5 Strengths and weaknesses of an adaptive methodology, adapted from (Wysocki, 2006)

Type 4. Extreme methodology (e.g. Research & Development projects): under this project methodology, the goal (scope) of the project must be (re)discovered in each iteration or feedback, and the project will converge upon it. Under this type, both the goal and the solution process are unknown. Therefore, this type refers to projects within exploration is more important than exploitation. The level of uncertainty of projects leads to high levels of complexity and uncertainty. Usually the final product is very different from what may be expected in the original intent (Table 3.6, adapted from (Wysocki, 2006)).

Strengths	Weaknesses
➢ It allows to keep options open as late as possible ➢ It offers an early look at a number of partial solutions	➢ It may be looking for solutions in all the wrong places. ➢ It is not possible to identify a priori what will be exactly delivered at the end of the project

Table 3.6 Strengths and weaknesses of an adaptive methodology, adapted from (Wysocki, 2006)

In the next section we will focus only on two types of Wysocki's project management methodologies types, linear methodology (type 1, labeled as TPM) and incremental and iterative methodology (types 2 and 3, labeled as APM). This selection is justified because both are frequently used in the industry 4.0 (Pedro Serrador & Pinto, 2015).

3.3 Agile Project Management as a challenger of Traditional Project Management

Traditional Project Management (**TPM** - also called classic, heavy, linear or bureaucratic project management, etc., depending on the authors) is based on a sequential conception of the project's dynamics. This temporary organization is then driven by fully defined requirements, deliverables, scheduling (Boehm and Turner, 2003), tools, mandatory roles and processes designed by experts belonging to the "*technostructure*" (Mintzberg, 1980). Project managers are expected to implement the processes as strictly as possible and auditors check whether their ways of managing projects comply with standards. By contrast, Agile Project Management (**APM**) (Conforto, Amaral, da Silva, Di Felippo, & Kamikawachi, 2016; Dalcher, 2011) derives from and iterative conception of the project (L. Lee, Reinicke, Sarkar, & Anderson, 2015; Rose, 2010), corresponding to methodologies types 2 and 3 in Wysocki's typology. Project's dynamics depend on teams or communities exhibiting daily reactivity, quick communication, creativity and flexibility. Project actors work autonomously by acting iteratively and by using a shared pool of resources or specific IT (Henriksen & Pedersen, 2017). Under APM, project managers play a key role as enablers facilitating the spontaneous team work (Elonen & Artto, 2003b).

APM and TPM seems to be two opposite ways of conceiving and managing projects. Nevertheless, it is possible, for organizations that wish to change their routines, to shift from one methodology (TPM) to another (APM). According to Conforto et al. (Conforto et al., 2016), agility is *"the ability to change project plan as a response to customers or stakeholders needs, market or technology demands, in order to achieve better project and product performance"*. We define then '*agilification'* as the process by which organizations make this shift effective. Agilification qualifies thus the ability of an organization to gain agility, thus to behave quickly, with celerity, promptness, astuteness, reactivity, flexibility and dexterity.

Project management specialists may conceive agilification as a disruption. On the contrary, we assume that agilification can be considered as an incremental process. One of the theoretical reasons explaining our conception comes from the work of theorists of "*organizational ambidexterity*" (Tushman & Nadler, 1978), who explain that organizations combine "*exploitation of old certainties*" and "*exploration of new possibilities*" (March, 1991). In the case of project management, ambidexterity has a specific meaning: this type of management balances the implementation of planned processes (exploitation, as TPM highlights it) and the guidance of improvisation (exploration, as APM mentions it). Moreover, empirical works show the complementary between APM and TPM. For instance, whereas APM has a significant impact on projects' efficiency, stakeholders' satisfaction, and internal perceptions (Pedro Serrador & Pinto, 2015), it does not concern all areas of the project management (Whyte, Stasis, & Lindkvist, 2016). In large companies designing complex and potentially hazardous products, TPM remains thus dominant in risk or contracts management. Therefore, one issue arises: What TPM parts can be adapted to make agilification effective? We defend that a TPM's key instrument, which is the Project Management Maturity Model

(PMMM) presented in chapter 2, can be sufficiently flexible to be adapted to APM. Nevertheless, existing PMMMs involve substantial improvements and changes that we will present in this chapter.

3.3.1 Identification of Traditional Project Management (TPM) principles

In this section, we give more details about TPM principles (type 1 in Wysocki's typology). Project management experts aim at rationalizing working activities. That explains why, since the beginning of the 2000s, they have been developing more than thirty instances of PMMMs, as described in chapter 2. Despite their differences in detail, these models share common principles that we point out hereafter.

Principle 1 (**P1.T**, 'T' for 'Traditional): The achievement of Key Performance Indicators (KPIs) describe the success of projects. These KPIs are supposed to drive projects' reliability and efficiency.

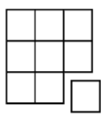
P2.T: Projects' successes (*vs*. fails) are explained by the fact that projects' managers implement (or not) certain practices (Cook-Davies, 2002).

P3.T: These practices are tasks producing well-defined outputs and working rules. For example, a Work Breakdown Structure (WBS) is a well-defined output and create the WBS once the Product Breakdown Structure (PBS) is defined is a working rule.

P4.T: Project experts can defined a process as a collection of well-defined events, mandatory tasks (or practices, routines, etc.) and working rules.

P5.T: Several process audit missions enable to identify the best practices improving organizations' capabilities in project management, *i.e*. their recognized ability to implement routines differentiating them from nearby organizations, *e.g.* competitors, rivals, followers, etc.

P6.T: There is a scale of perfection dividing the maturity levels from lowest to highest. Process maturity depends on a Confucian vision of learning: without any predefined process, the project managers improvise harmfully, and then they gain maturity by conforming to a detailed pattern created by experts, creating improved ways of performing processes.



P7.T: project management concerns different separated domains (or knowledge areas). Project managers' work has then a wide scope; they must be aware of different aspects, implement various practices, *e.g.* technical specifications, team animation, cost reporting, etc., and produce several types of deliverables, *e.g.* bill of requirements, scheduling charts, scorecards, contracts, meeting reports, etc.

IB2M we have presented in chapter 2 concerns many sectors and types of organizations; does it remain relevant when managers require more agile projects? To answer this question, we need to clarify APM basements.

3.3.2 Identification of Agile Project Management (APM) principles, the case of Scrum

Experts in software engineering have identified that projects based on TPM often fail to develop applications in a timely manner and to satisfy clients' needs. Therefore, these experts have proposed a model which emphasizes agility (Conforto et al., 2016). We point out APM principles in a mirror with TPM basements:

P1.A ('A' for 'agile'): Agility drives to projects' success; especially in terms of customer's value (usability, price, etc.) and lead-time (reactivity).

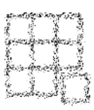
P2.A: Projects' successes are explained by the fact that the project managers and the teams implement collective and time-focused practices and working rules. Moreover, the project manager is not a conductor alone. Responsible for the "*roadmap*" definition and planning, s/he collaborates with the "*product owner*", who is the customers' spokesperson, and the "*scrum masters*", who leads teams' meetings. In addition to using commonplace tools, these actors rely on a pool of resources made of working environment, *e.g.* rooms for stand-up meetings ("*daily sprint"*), visual management tools, *e.g.* "*scrum board*", rapid or virtual prototyping, etc.

P3.A: Agile practices enable teams to develop in short times intermediary prototypes satisfying prioritized requirements ("*sprints*"). Scrum is then based on the assumption that the bill of requirements can be breakdown into *"user stories".*

P4.A: Scrum atom is not a task, but a loop occurring in a very constrained period ("*time boxing*"). The feature of this loop is not elaborated by Scrum creators. Nevertheless, we can assume that it is made of "*ad hoc processes*" or explorations; it is based on the continuous collaboration between projects' actors, and its control is autonomous, *i.e.* made of self-organization and "*mutual adjustments*" (Mintzberg, 1978).

P5.A: Scrum experts identify APM's best principles and resources.

P6.A: there is no predefined perfection scale of agility. However, every agile project requires "*core roles*", *e.g*. project manager, scrum master and product owner; when an organization's projects portfolio reaches a certain size, APM also requires "*non-core roles*", *e.g*. "*Scrum Guidance Body*" and "*Chief Scrum Master* [who] *is responsible to coordinate Scrum-related activities*" (Setpathy, 2016).



P7.A: there is no clear mention of the project's domains supporting the loops or iterations on which agile methodologies are based on.

Despite its very marked IT character, agile project methodologies are now recognized as a reference by many organizations whose core business is not software development. (Dijksterhuis & Silvius, 2017)

> *"- Individuals and interactions over processes and tools*
> *- Working software over comprehensive documentation*
> *- Customer collaboration over contract negotiation*
> *- Responding to change over following a plan"*

Agile Manifesto for Software Development (Beck et al., 2001)

There are different APM methodologies; the one we will focus on in this chapter is "*Scrum*" (type 3 in Wysocki's typology). Scrum creators propose a body of knowledge based on clear principles. The method they promote is supposed to be "*an adaptive, iterative, fast, flexible, and effective methodology designed to deliver significant value quickly and throughout a project* […] *A key strength of Scrum lies in its use of cross-functional, self-organized, and empowered teams who divide their work into short, concentrated work cycles called Sprints*" (Setpathy, 2016). Whereas Scrum targets the project, it is clear that its principles differ from those of the TPM. Once the agile pattern has been illustrated in the case of Scrum, it is now possible to compare TPM's principles about project management maturity *vs*. APM's ones.

3.3.3 Terms of comparison

Now we can compare TPM and APM principles.

P1.T *vs*. P1.A (Success definition) – The definitions of KPIs are the first differences between TPM and APM. Under TPM, the process conformity or compliance is supposed to guarantee by itself the achievement of other KPIs. Moreover, as part of the bureaucratic organization, practices are supposed to be safer and more efficient since they are detailed as precisely as possible. By acting conformably, project managers would reduce unwanted and time-consuming loops slowing down the planned progress of the project (P Serrador, 2013). This conception contrasts with APM, which is more focused on customer's value, lead-time, and teams' dynamics than on conformity with predefined processes. Under APM, projects are supposed to be extremely intensive; the project organization would develop the most valuable deliverables as soon, and as frequently, as possible (Conforto et al., 2016).

P2.B *vs*. P2.A (Project Manager Role) – Both TPM and APM assume that projects are manageable entities, explaining why the implementation (or not) of certain practices leads to success (*vs*. fails) (Gillard, 2009; Ramazani & Jergeas, 2015). However according to the project management methodology, the project manager role (with its rationale, knowledge, and practices) is quite different. The rationale of TPM and APM is not the same: exploitation and standardized process implementation for TPM *vs*. exploration and improvisation for APM. In both cases, experts and theorists build and improve, as the years pass, a body of knowledge, the *Scrum BoK* being currently less mature than the *PMBOK®* .

P3.T *vs*. P3.A (Requirements and Target Outputs) – The temporal and spatial scales that are taken into account in TPM differ from those targeted by APM. Scrum has a finer granularity than TPM; it is focused on weekly work, with sprints and scrums management, and even daily work, with stand-up meetings animation. APM is therefore closer to its operational actors and its monthly, weekly or even daily projects' dynamics.

P4.T *vs*. P4.A (Processes) – TPM states that the best practices (and the working rules) are atoms, which are assessed independently and be replicated as series parts. On the contrary, Scrum refers to loops, which have more complex behavioral features. Furthermore, Scrum experts point out the key role of shared resources, IT included, and then organization's digital maturity (Schumacher et al., 2016). Another cleavage concerns the conception of openness. Under TPM, it concerns only the benchmarks of best practices to apply as such (see P5.T). *PMBOK*'s maturity level 5 mentions another term referring to openness, which is innovation (see P7.T). APM is contradictory with this conception: project members are creative and empowered individuals, improvisers, not agents executing mandatory detailed procedures.

P5.T *vs*. P5.A (Auditing) – Both TPM and APM explain a part of the organizations' capabilities by the way their projects are managed. However, the capabilities under study differ according to these two project management methodologies. Under TPM, the capability concerns the ability to implement mandatory practices and processes. On the contrary, APM theorists are attentive to the stakes, to the opportunities, but also to temporal constraints or the ones derived from collaboration, creation, etc., referring then to organizational openness.

P6.T *vs*. P6.A (Perfection Scale Definition) – The perfection scale in the case of TPM is based on work initiated since the 1990s on Quality Management, and then process maturity assessment. The maturity of agility is clearly a point to develop, as we will see in section 5.

P7.T *vs*. P7.A (Domains) – Under TPM, tasks are atoms, *i.e*. organizational elements that can be distinguished and then checked separately, and process domains (or knowledge areas) are groups of tasks of the same nature. Scrum does not mention domains.

It is also possible to compare TPM and APM concerning PMMMs presented in chapter 2, and more precisely about the domains presented in the PMBOK®.

Results Domain: The Results domain mirrors the PMBOK® knowledge areas of cost management, quality management, and schedule management. Traditional project management focus on exhaustive planning. TPM focuses on detailed scheduling, hence project management practices must be compliant to project managers' plan. If a change occurs, it should be managed through a change control process, which is highly documented and slowly implemented. The value of the project may be delivered within the final product. On the contrary, APM does not rely on an extensive planning and scheduling before project execution. Planning is done iteratively in each sprint. Nevertheless, APM defines more strictly the expectations about intermediate results since value-driven delivery prioritizes the good enough deliverables that are valuable for the customer, the client, the end user, etc. Since the first iterations, Minimum Viable Products (MVP) with minimum marketable features are built; even if a project is unexpectedly stopped, some benefits have been created.

Social Domain: The Social domain describes the characteristics created by human interactions in the project. It corresponds to the PMBOK® knowledge areas of communication management, HR management, and integration management.

Traditional project management defines. TPM is based on clear definitions of roles and hierarchies; it even produces managerial tools to clarify the position of each individual in the organization, *e.g.* Organizational Breakdown Structure chart (OBS). However, agile project management defines three core roles: Product owner, Scrum Master and Team members and, in addition, several non-core roles. The interactions between these roles are not hierarchical. The teams use open meetings (daily scrum), and serious games to develop a horizontal communication. Conversely, under TPM, the communication is vertical; it is mostly under project managers' responsibility.

Contract Domain: *The contract domain* corresponds to the PMBOK® knowledge areas of scope management and risk management. This domain includes all inputs relevant to the contract definition, the risk management, and the scope management. As we mentioned, TPM has a static approach of requirements, which are parts of well-defined contract established before projects' execution. On the contrary, APM conceive requirements as dynamic entities; they are discovered, defined, prioritized as the sprints goes along. Therefore, clients' value is created early in the first deliverable products and it continues to increase in each iteration. Moreover, under TPM, risk is defined as "*uncertain event(s) that could positively or negatively affect the achievement of project objectives"* (Project Management Institute, 2016b). Risks are then clearly conceived as harmful perturbations disturbing a very detailed plan or schedule. That explains why risks are monitored continually, and why specific organizations, *e.g.* steering committees, and roles, *e.g.* risks managers, are focused on these negative events. Contrariwise, under APM, each team member can identify risks, the product owner update them in the product backlog in order to prioritize tasks that dismiss higher risk; cumulative risk will tend to decrease as the project advances. In each iterative step, the project team can identify and monitor new risks. Therefore, risk monitoring is both collective and implemented on an operational level. The Scrum board.

Interface Domain: *Interface domain* corresponds to the PMBOK® knowledge areas of procurement and stakeholders' management. TPM is based on well-defined contracts. Clients have a complete knowledge of their needs, expectations, constraints or requirements, and project managers or purchasers know precisely what suppliers will provide during the project. Conversely, APM believes that clients, team members, suppliers, etc., can offer much more than just their technical expertise; they can cooperate and discover together the precise content of the project.

This section has compared TPM with APM (defined under Scrum) concerning each principle or project area. Table 3.7 sums up this comparison. When reading this table, it is easy to note that we are in the case of an existing managerial tool (TPM) which is not fully consistent with a historical situation, *i.e*. expectations of managers in large organizations in terms of agilification. This situation is not exceptional; the literature has still emphasized the importance of selecting a suitable model for each historical context (T. J. Cooke-Davies & Arzymanow, 2003; Jugdev & Thomas, 2002). The main issue is then to elaborate a reference model for an agile PMMM based on one TPM's component, which is the Project Management Maturity Model (PMMM).

TPM: Traditional Project Management	**APM: Agile Project Management**
Focus on the PMBOK®	Focus on Scrum
Processes are introvert entities that can be considered as mandatory and detailed procedures. They should be replicated as series products. Project managers are the core actors of the projects implementing these predefined processes (exploitation).	Processes have irreducible *ad hoc* features (exploration). Project management is performed by different individuals playing separated roles: project manager, scrum master, etc. Agile projects involve actors with creative potential and empowerment (exploration).
KPI is process conformity or compliance guaranteeing by itself projects' efficiency and reliability.	KPI is agility, with a focus on customer's value and lead-time (project reactivity).
The perfection scale ranges from improvised practices to standardized ones, then innovative ones improving processes	There is nothing about a perfection scale in the current literature about Scrum.
The practices to check are atoms, *i.e*. separated tasks with a single well-defined deliverable, and working rules expressed by a proposition (If… Then…).	The practices to check are loops with complex behavioral features: creativity, exploration, collaboration, autonomy, etc. These loops are controlled by lead-time (reactivity). *The current literature about Scrum does not elaborate the content of the loops.*
Process specialists are part of the techno structure; they are not involved in concrete projects. We have then a clear dichotomy between project design and project execution.	APM experts play a peripheral role: the operational and practical project context is more important than the aboveground processes.
Only resources for project managers are taken into account and IT plays a secondary role	Projects suppose a pool of shared or common resources, and IT is a key advantage to APM.
TPM sometimes fails to produce in a satisfying lead-time acceptable deliverables. Moreover, it cannot be used to give details about project's daily life.	APM seems not to be adapted to develop complex products. Its scalability is questionable when the project is not just about the software sector.

Table 3.7 TPM vs APM

3.4 Steps towards an Agile Project Management Maturity Model

The goal of this chapter is to apply the proposed model in projects of the specific industrial environment. We have found that during on their missions, were consultants worked on making agile the schedule management, they have detected several challenges, *e.g*. the requirements were continuing to change due to the concurrent design; and the obsolescence of the schedule was accelerating. It was decided to "*agilify*" the schedule management. Several derived challenges occurred then, *e.g*. How to reorganize teamwork? How to train personnel in APM, especially in terms of sprints implementation (see P3.A) and resources sharing (see P2.A)? How to align sprints to the PBS, defined before the realization of the project, and then to prioritize the requirements in monthly backlogs (see P3.A)? How to convince and involve top managers in this first APM experience to change theirs organizational routines, *i.e*. TPM?

Under TPM, project management tasks belong to separated areas (see P7.T). On the contrary, we found that this disaggregation is harmful: tasks, processes, and then areas are interdependent and clustered. We proposed then to break down these silos; auditing one project area (for instance, schedule management) requires to audit other connected areas, *e.g*. scope management, integration management, quality management, etc. As we proposed in the domains definitions on chapter 2, section 2.3.2.

While TPM differs to APM, we assume that there is a process, we called agilification, to move from one to the other. The first issue is then to analyze if Project Management Maturity Model (PMMM) presented in chapter 2 can describe the universe of APM. Therefore, in this section, we will propose a PMMM integrating some characteristics of TPM and APM defined above. The proposed PMMM will be elaborated in three phases: set a specific conceptual model of the project management domain, which is a first step to have a behavior ontology of this domain, and then build the maturity grid, to conclude with the presentation of the roadmap for agilification.

3.4.1 Step 1. Build a Project Management Conceptual Model

Our first assumption is that every PMMM should be based on an ontological basis, *i.e*. an explicit conception of the project's domain made of specific entities (projects, actors, process, practices, deliverables, resources, etc.), properties (conformity, agility, reactivity, maturity, etc.) and relations (is a, is part of, drives, etc.). We suggest that these ontological fundaments can be based on a generic entity called '*behavior*'; project management ontology is then no more than an instance of behavior ontology. The behavior is an entity with the following characteristics: (1) It is labelled with an action verb describing what is done. (2) It is related to an individual or collective actor with a well-defined role in an organizational structure. (3) It is triggered when a given event occurs (stimulus). (4) It produces an observable output (response). (5) It occurs in a given context made of alters and resources. (6) It drives by internal variables (goal-oriented). (7) It follows some given modalities, maturity included.

We develop Figure 3.1 as a concept map based on our proposed Invariant-Based Management Model (IB2M). The grey T defines TPM's instances of interest. The first instance we can derive from the behavior ontology is the perfection scale. Made of maturity levels (see P6.T), it refers to modalities of the behavior to check. A level of the perfection scale qualifies how project managers should behave. Do they improvise? Do they conform to an existing pattern? Do they improve the ways of performing processes? We have also instances of the behavior when we mention project domains (see P7.T). Any of them defines the content of the behaviors projects managers realize: operations vs. transactions, *e.g*. PBS definition vs. procurement. The domains also mention the results of their behaviors, e.g. deliverables, contracts, interpersonal relationships, etc. The behavior has a third instance referring to the types of roles individuals play. They exhibit specific behaviors by managing organizational structures, managing projects, auditing processes, etc. The behavior concepts may be structured according to the levels of decision in projects. The strategic level concerns the development of the organizational structure's capability; the tactical level refers to the improvement of process maturity; the operational level corresponds to the way projects are led, and the practical level concerns the way tasks are performed in projects.

Finally, the right side in figure 3.1 shows who is concerned by the ability to implement best practices defined by experts (Project Manager, Process Auditor, Team). In addition, this figure is useful to understand the evaluation process as it displays how maturity evaluation is driven by process conformity and Project KPIs.

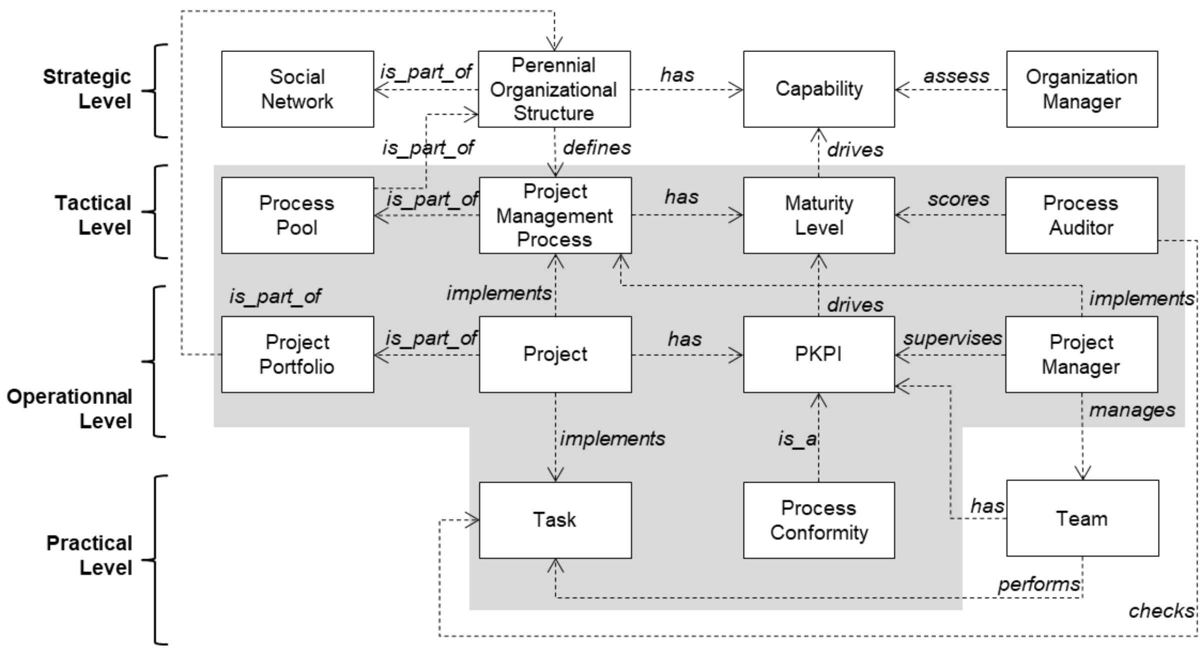


Figure 3.1 TPM Maturity Conceptual Model.

3.4.2 Step 2. Build a Maturity Grid

We propose the building of a maturity grid similar to Figure 2.2. However, in this chapter the same invariant-based maturity grid would have a different perfection scale.

The perfection scale has a specific content since it refers to agility. We propose then five maturity levels in agility inspired from PMMMs, our IB2M and (Wysocki, 2006), following the same construction logic as in chapter 2 (section 2.3.2, *invariant-base scale of maturity*)

- **Absent agility**, agile methodologies are not implemented, and then absent (lack of agility, maturity level 1),
- **Adaptive agility**, agile methodologies consist in local variations of an existing well-defined model (maturity level 2), *e.g*. clients collaborate with designers in requirements definition, then they are not involved in the development of solutions,
- **Proactive agility**, agile methodologies are implemented in the project under study (maturity level 3), *e.g*. the project scope or roadmap is redefined after the sprints,
- **Complex agility**, interdependencies between agile projects are managed at the portfolio level and experts in APM, *e.g.* Scrum Chief Masters, are usually required (maturity level 4),
- **Global agility,** agility is a key capability of the organizational structure; no more processes are hierarchical. All projects belonging to the agile organizational structure's portfolio (maturity level 5). *"It is the highest level meaning a perfect mastery of a technical knowledge on an entity or a domain."* (Belkadi, 2006).

3.4.3 Step 3. Define the Roadmap for Agilification

The behavior ontology described above concerns TPM (Figure 3.1). What happens in the case of APM? If the conception of agilification as an incremental process is accepted, then parts of the TPM pattern **can be reused** to create a roadmap for agilification. Hence, we have derived the previous figure in the case of APM (Figure 3.2). In comparison with figure 3.1, we note that: new individuals are added (scrum master, product owner) (see P2.A), KPIs are not the same since they concern agility (see P1.A), and the bottom of the diagram is elaborated, corresponding to finer granularity by which APM describes the projects (see P3.A). The practice to check is not a separated task, but a collective and time-constrained iteration or loop, that is, an agile scenario (see P4.A). Finally, the shade area indicates the instances of interest under APM.

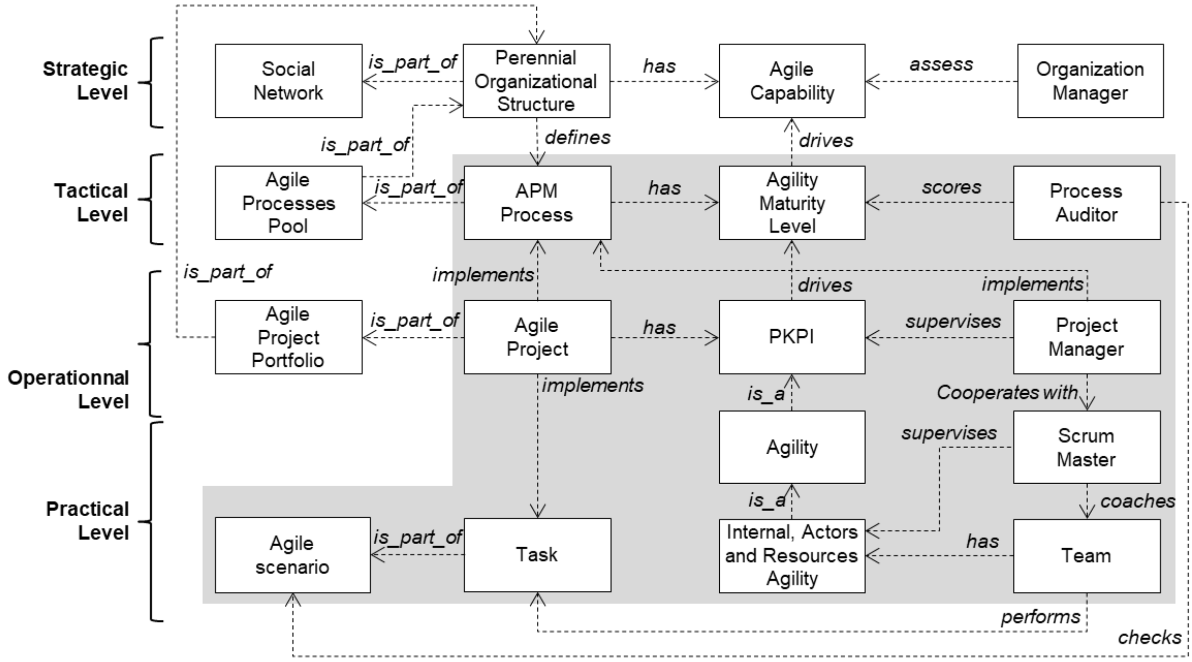


Figure 3.2 APM Maturity Conceptual Model.

Our presentation of TPM and APM was conceptual; the next section will illustrate the types of tools required to implement project management agilification in a real scenario.

3.5 New Tools for Enabling Projects' Agilification

In 2017, we interviewed, with open-ended questions, ten experts specialized in project management audits, with 6 to 20 years of experience. We collected their knowledge about the way they and their clients conceive TPM, APM, and agilification. We explored their consulting missions and results. Most of the consultants and their clients know and put into practice the *PMBOK®*; they consider TPM as a reference even though they have an overview of APM. In the present case study, we will focus on a specific project management process, which is schedule management. A part of our data materials came from an audit mission performed for a department of a large company in charge of the development of complex capital goods, *e.g.* steam generators.

3.5.1 Step 1. Set a Project Management Conceptual Model

Starting from this rough material, we instantiated the APM model as displayed in figure 3.3. This diagram was presented to the experts. After this, they validated the fundamentals of the ontologies displayed in figures 3.1 (*The TPM Maturity Conceptual Model)* and 3.2 (*The APM Maturity Conceptual Model*). Subsequently, the right column figure 3.3 displays who are the members concerned by APM, i.e. the project's Team. It also shows how these actors can acquire an agile capability, such as doing the "*agile task*" which is going to be the basis of the agilification scenario. This instantiation is useful for the auditor to identify how to implement the agilification scenario, e.g. how to score the agility maturity level?

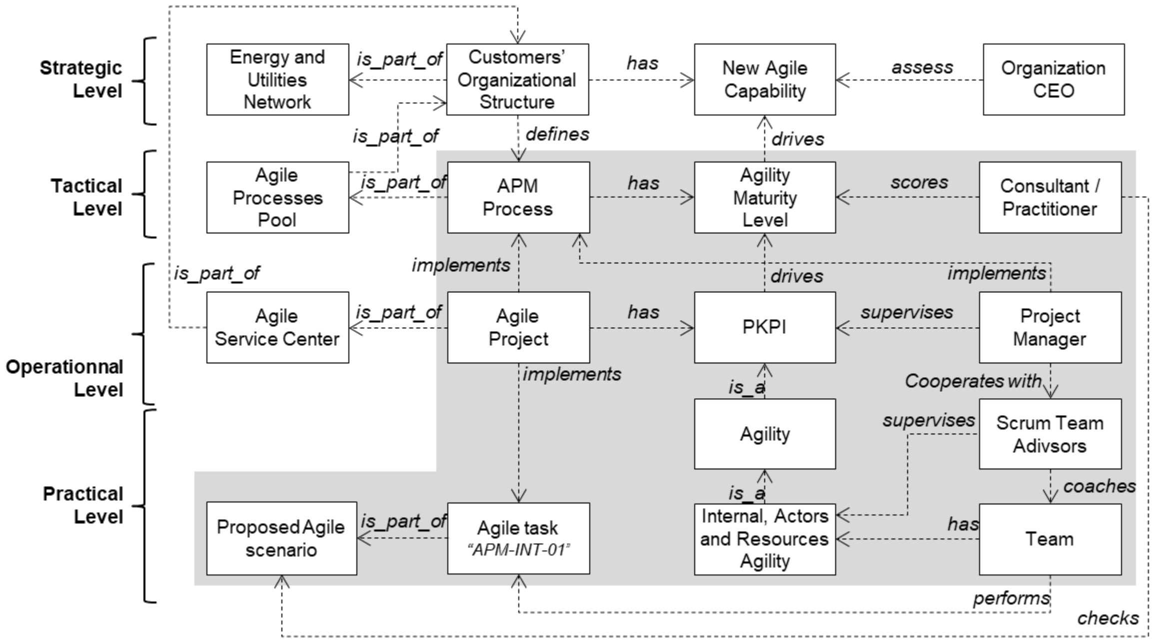


Figure 3.3 APM Conceptual Model applied to the Case Study.

After developing the conceptual clarification, we focused on a project management process, namely schedule management. Both TPM and APM mention it. They use standard tools like the Gantt chart, but the content of the chart changes: it is a single task under TPM vs. a sprint under APM. We began the elaboration of a maturity grid consistent with the TPM. To achieve this task, we used the generic model displayed in Figure 3.3 (Conceptual Model applied to the Case Study) to depict properties concerning the project schedule, i.e. for frequency (F, how often the planning is updated or changed?), for resource involvement (R, who is updating the planning?) and for activity granularity (G, what has been done to elaborate the planning?).

3.5.2 Step 2. Build a Maturity Grid

To help consultants to overcome some challenges, we created a new maturity grid consistent with APM. The grid displays the milestones to be achieved to obtain higher levels of maturity in agile schedule management (Table 3.8). Under TPM, project management tasks belong to separated areas (see P7.B). On the contrary, we found that this disaggregation is harmful: tasks, processes, and then areas are interdependent and clustered. This matrix tool reduces the number of items to check from 400 (PMI, 2013), to 44, reducing then the audit time (6-7 weeks). It enables the consultants to act then in accordance with P1.A.

Next, we instantiate a specific perfection scale derived from our proposition in section 3.4.2. (Build the Maturity grid). The refinement and validation of the proposed model and the content of the following maturity grid were performed with meetings with the interviewed consultants. The grid displays the tasks to be achieved to obtain higher levels of maturity in agile project management (Table 3.8). In order to make explicit how the characteristics of TPM are also present in the APM but in different means, we compare the classic domains defined in the PMBOK® and the characteristics of agile methods. This result, classified by domain can be found in the Annex 2.

SCHEDULE MANAGEMENT		Level 1		Level 2		Level 3		Level 4		Level 5	
		Absent agility, i.e. TPM monopole		*Adaptive agility inducing variations of an existing well-defined framework*		*Proactive agility creating a new project scope*		*Complex agility taking into account different projects*		*Global agility characterizing every projects belonging to the organizational structure's porfolio*	
Preparation	Frequency										
	Resources Involvement	Make a list of resources	APM-INT-01	Build the user stories by agile team: link ressources and activities	APM-INT-02	Build a flexible schedule by agile team	APM-INT-03	Build the schedule by agile team consistent with all organization strategy	APM-INT-04	Improve cycles of co-building stories with all stakeholders	APM-STK-5
	Activity Granularity	Make a list of activities				Define a prioritized product backlog measure and analyze its activities	APM-QUA-03			Improve schedule preparation in whole organization each sprint	APM-INT - 5
Monitor, Control & Follow	Frequency			Update burdown chart in the end of several sprints	APM-SCH-02	Update burndownchart several times in the sprint	APM-SCH-03	Update the burndown every inter project milestone	APM-SCH-04	Capitalize and improve the burndown chart for evolving with the	APM-SCH-05
	Resources Involvement			Follow the sprint review involving scrum master	APM-RH-02	Follow the sprint review involving scrum master, product owner and customer	APM-RH-03	Follow the sprint reviews in coherence with other projects' schedule	APM-RH-04	Manage sprint reviews at the managerial and operational levels	APM-RH-05
	Activity Granularity			Identify planning gap and schedule risks in user stories	APM-RIS-02	Build a Risk Burndown chart	APM-RIS-03	Take corrective actions according to inter project schedule risk	APM-RIS-04	Capitalize lessons learned from actions: risk predictions	APM-RIS-05
Valuation and Share	Frequency			Communicate product backlog every sprint	APM-COM-02	Communicate sprint review results	APM-COM-03	Communication actions according to the gaps and risks	APM-COM-04	Do real time communication with a sharing tool in whole organizational structure	APM-COM-05
	Resources Involvement	Present the schedule to stakeholders	APM-INT-01	Communicate the schedule to the scrum master and team		Communicate the planning to the teams of the other projects (inter projects)		Communicate actions according to gaps to all stakeholders	APM-STK-04		
	Activity Granularity	Identify customer contract milestones	APM-SCO-01	Define minimum viable product and main constraints	APM-SCO-02	Define and record minimum viable product and deliverables	APM-SCO-03	Establish deliverables and constraints of different levels: contractual, method; and interface with other projects	APM-SCO-04	Improve the process of generating deliverables for whole organization	APM-SCO - 05

STA: Stakeholders	**HR:** Human Resources	**RIS:** Risk	**INT:** Integration	**SCO** Scope	**COM:** Communication	**QUA:** Quality	**COS:** Cost *(not present)*	**SCH:** Schedule	**PRO:** Procurement *(not present)*

Table 3.8 Example of APM Schedule Management Maturity Grid.

3.5.3 Step 3. Define the Roadmap for Agilification

This concludes with technical and managerial recommendations to improve agile maturity. In the present case, the issue was: what actions should be performed to *agilify* Project Management? Answering this question requires the development of action-focused tools. The first we developed is a two axes map combining: (1) the criticality of the tasks under study (axis Y), that is, the expected influences of the task on the results of the project, and (2) their accessibility (axis X), that is, the difficulty in performing this task (Figure 3.4). Usually, when auditors and their customers conceive an improvement plan, they should take into account the risks, challenges and opportunities to execute each task. The evaluation of these criteria for each task was performed by the interviewed project management consultants. The resulting map is correlated with the fact that upper level maturity tasks (level 05) have more impact on the whole organization (high criticality). The more the task is on the left; the more difficult it is to perform it.

Once the 'tasks cloud' displayed, the last step is to sort them and to elaborate agilification scenarios. We used the graphical notations of BPMN (Business Process Model and Notation, 2006) specified by OMG (Object Management Group). Figure 3.5 displays an agilification scenario of schedule management. In the studied case, project management consultants guided the scrum team managers through this agilification scenario. They followed the proposed path until getting the desired maturity level for the concerned organization.

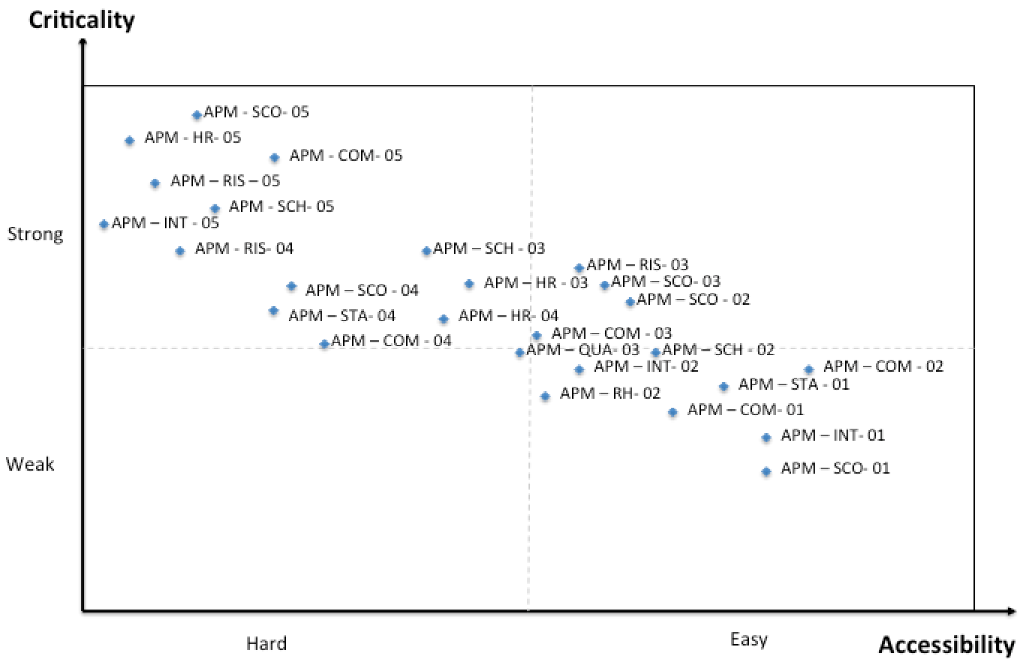


Figure 3.4 Candidate Tasks Distribution for Agilification

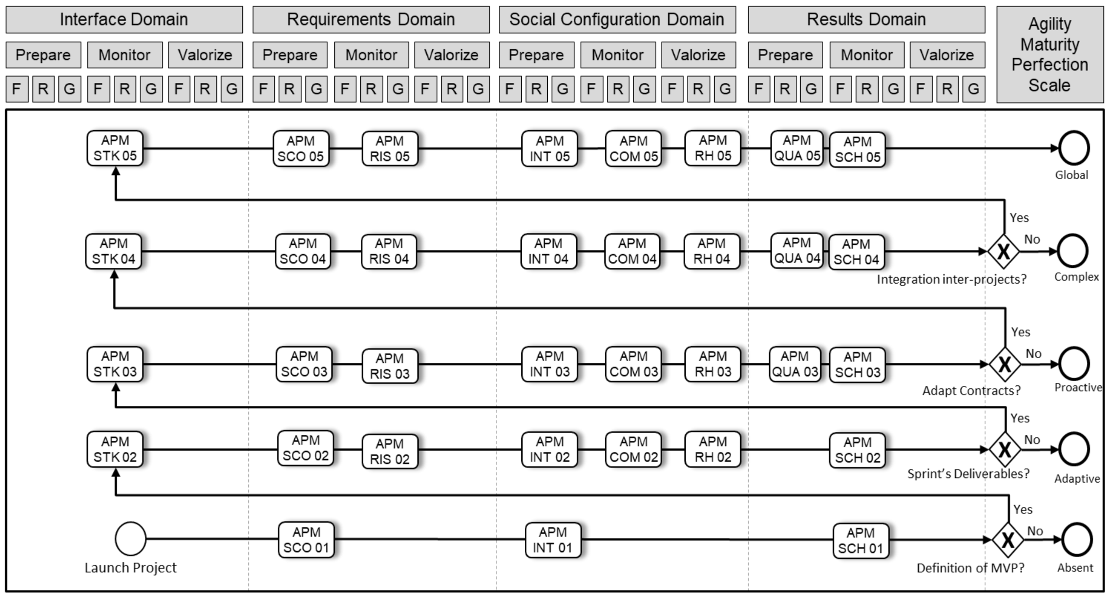


Figure 3.5 Schedule Management Agilification Scenarios.

Following the proposed agilification scenario of scheduling, design updates were planned and implemented with additional sprints rather than handling each one separately; teams' members improved their ability to anticipate sprint backlogs; the implementation of daily review meetings increased schedule reactivity; parallel teams gained understating on the importance of software integration to coordinate their schedules, etc. Finally, the successful implementation of local and short time experiences in APM was a good way to convince top managers to adopt this type of project management and extend its uses for future projects, the whole organization developing a new capability in terms of agility.

3.6 Discussion

The models and tools proposed in this chapter are supposed to satisfy both "*theoretical goals*" (How to use a behavior ontology to model the field of project management? etc.), and "*practical goals*" (how to facilitate agilification?). Our work suggests then two types of discussions, theoretical and practical.

3.6.1 Theoretical learnings

From the theoretical perspective, prior work documented the importance of project management maturity models (Grant & Pennypacker, 2006; Kerzner, 2017; Young Hoon Kwak & Ibbs, 2002; PMI, 2013; Software Engineering Institute, 2006). These models focused on Traditional Project Management (TPM) only. However, the irruption of Agile Project Management (APM) makes obsolete the mentioned maturity models according to surveys and testimonials concerning project managers (Conforto et al., 2016). Therefore, in this study, we have identified and compared TPM and APM principles (P1.T-P7.T in section 3.3.1 and P1.A-P7.A in section 3.3.2). The existing literature emphasizes the differences between them (Pedro Serrador & Pinto, 2015). Nevertheless, our results are much less clear-cut; there are both divergences and convergences between these two conceptions of the project management (Section 3.3.3). These findings extend current literature (Dijksterhuis & Silvius, 2017; McClory et al., 2017; Silvius & Schipper, 2015) demonstrating where it is possible to establish a common model of project management maturity assessment.

We noted that existing project management maturity models often lack a clear conceptual model (T. J. Cooke-Davies, Crawford, & Lechler, 2009; Pasian, Sankaran, & Boydell, 2012). This work helps to bridge this gap. In the present chapter, the second theoretical contribution concerns a common conceptual model of project management maturity evaluation based on behavioral categories shared in both project management types (TPM vs. APM).

3.6.2 Practical learnings

From the practical perspective, the analysis of the common model led us to propose managerial tools to measure maturity in project management. In this way, our theoretical work became the starting point of practical contributions. Those tools were tested by experts in project management audits, contributing to extending the limitations of PMMM literature such as described by (Görög, 2016). Practical contributions of this chapter correspond to a maturity grid that complies with APM fundamentals (Table 3.8) and the candidate tasks distribution for agilification (Figure 3.4). Practitioners need to classify the importance of each task for choosing the most critical and accessible tasks that will enhance agilification. The third practical contribution is the conception of an agilification scenario, where practitioners create the order of tasks they have to implement for reaching the agile maturity level (Absent, Adaptive, Proactive, Complex, Global) that is required by the organization depending on the industry's needs, projects' uncertainty levels, duration, complexity, etc.

Referring to the limits of our work, we did not take into account all the literature about traditional and agile methodologies. We focused on Scrum methodology for APM because it is largely used in the industry. Our choice was to go further, using few concepts, and aiming at a comprehensive panorama concerning the comparison between TPM and APM. The auditors pointed out that these conceptual models are more heuristics than ready-to-use tools. The definition of the content of the boxes in the maturity grid can give rise to infinite debates. Even if the idea of process interdependence is mentioned, reasoning by task clusters is an interesting way of not being focused on the precise content of each cell, but on a global picture. We have focused our work on the practical and operational levels as shown in the grey area of Figure 3.3. Consequently, the strategic level is outside of the scope of this chapter, for example, the research did not explore why TPM are hierarchical while APM organizations become more horizontal, or which are the roles in charge to facilitate this change.

3.7 Conclusion

Agility seems the horizon of project management; new Agile Project Management (APM) is then supposed to replace Traditional Project Management (TPM). Whereas TPM and APM are based on contradictory statements, project management in large organizations requires ambidexterity, *i.e*. exploitation (process conformity) *vs.* time and value-constrained exploration (APM): future project management tools should combine these two facets. This chapter gives an example related to a TPM key issue, which is the process maturity evaluation, with a focus on schedule management. The same conceptual model is proposed to describe and evaluate the process maturity under TPM and under APM; agilification being conceived as an incremental and smooth transition from this former type of project management to APM. Finally, three tools, validated by consultants, were proposed: a conceptual model depicting the TPM or APM domain, a process maturity grid consistent with TPM and APM, and a BPMN diagram displaying agilification scenarios. Whereas the results may be of interest to the project management community, there are at least two weaknesses to bear in mind: the conceptual basis may be incomplete (only the CMMI, the PMBOK® and Scrum are mentioned) and there is no data-driven approach implemented by consultants auditing project management processes.

Agilification is not completed; further research should then concern it. The APM ontology we sketched should be elaborated more formally. Moreover, according to the contextual characteristics of the project, the required maturity level should not be the same. Some projects will require higher maturity to improve their performance and others are 'good enough' with a lower agile maturity level. These characteristics concern the impact of the project under study on the strategy. Existing models do not take into account these key characteristics. Finally, under TPM maturity models, the levels of the perfection scale are defined by setting rules related to the assessment of the practice execution or not. Nevertheless, there is no practical way to measure whether it is necessary to stop in one level of maturity for a specific project and for a specific organization, or if it is necessary to keep improving up to level n+1, or n+2 in order to get maximal project performance.

CHAPTER 4

4 Selection and use of the appropriate technique to solve the research problem.

About this chapter. Our main research problem is to establish a proven causal relation between the maturity of project management processes and projects' operational performances. Several PMMMs collect heterogeneous data, hence it is not possible to create an immediate correlation between maturity and performance. In chapter 2, we have proposed an Invariant-Based Maturity Model (IB2M) standardizing project management categories, then data derived. Nevertheless, conceptual clarification is a first step for causal modeling, not its end. The next phase is to select an appropriate causal modeling technique given the context and the available data of Project Management (PM). In this fourth chapter, we explore several Artificial Intelligence (AI) techniques fitting with our main research goal. We present the strengths and weaknesses of Artificial Neural Networks (ANN), Reinforcement Learning (RL) and Bayesian Networks (BN).

This analysis leads us to select Bayesian Networks (BN), we explain their theoretical background, and we demonstrate how to build these networks and under which configuration of parameters they have the capacity to solve our research problem truthfully. Finally, we use knowledge developed in this chapter to create BN based on the information of the project management literature. We point out their characteristics and their limits. This is important because we discover that none of them could solve our research problem. As a result, this chapter provides all theoretical constructs to propose the methodology that will deal with our research problem in the next chapter.

4.1 Introduction

Project Management (PM) produces data that are generated, captured and stored during the project planning, execution and closing processes. These data provide many details about projects' goals, actors, processes, outcomes, performances or fails, etc. Lessons can be learned from this material. In the best case, these data can be used to identify or verify best practices, to explain past projects' failures or successes (diagnosis) or to predict their future performances (prognosis). To model a causal relation between project management process maturity and projects' operational performances, we have the choice amongst several Artificial Intelligence (AI) and Machine Learning (ML) techniques combining knowledge representation, data analysis and probabilistic inferences (Krizhevsky, Sutskever, & Hinton, 2012) and learning. AI and ML techniques fit with PM because large organizations have series of projects; data are thus constantly produced and updated, enabling causal hypothesis refutation or verification.

In the specific domain of PM, authors have still established statistical correlations between PM factors (processes implementation, team management, etc.) and past projects' performance (Ko & Cheng, 2007; Wong, Lai, & Lam, 2000). More generally, we assume that AI and ML techniques are valuable solutions for PM; they facilitate the systematic exploitation of projects data to have clearer about the relevance or the strength of causal relations. One of the main issue is to choose a good AI and ML techniques because this very active domain including various and numerous statistical methods that could achieve automatic decision-making, predictive modeling, data classification, and data clustering (Al-Tabtabai et al., 1997; Demirkesen & Ozorhon, 2017; Ko & Cheng, 2007; Mir & Pinnington, 2014; Na et al., 2007; Qazi et al., 2016; Wang & Gibson, 2010; Wang et al., 2012). That explains why this fourth chapter is focused on a choice of an AI technique fitted to the specificities of PM and then our research goal. Therefore, the goals of this chapter are as follows:

- Reviewing briefly some AI and ML techniques that can solve our research problem,
- Comparing them under the data-focused criteria and select the technique that is the most suitable, Bayesian Networks (BNs) in our case,
- Proposing BNs' modeling parameters, modeling rules, and evaluation rules,
- Pointing out limits of BNs in existing PM literature,
- Proposing building rules to elaborate well-formulated BNs in PM.

In section 4.2, we will then present briefly three AI and ML techniques that are frequently used, i.e. ANN, RL and BNs. We will explain what are the most relevant data-focused criteria to compare these techniques, and which of them would have the best scope to solve our research problem (section 4.3). Once a technique will be selected, i.e. BNs, section 4.4 will present BNs' theoretical foundations and key parameters to build well-formulated BNs (section 4.5). Then we model the project management literature (section 4.6) in a manner that let us identify what are their limits, and where it is necessary to work on when developing a new methodology (section 4.6). We will state that these BNs are not rigorous enough, explaining why it is required to define building rules to elaborate them (section 4.7).

4.2 Review of Artificial Intelligence techniques used in PM literature

Originally, AI techniques aims to ''computerize'' processes characterizing Human cognition, knowledge, reasoning, etc. The main challenges of AI are: identify a type of process that can be computerized, then computerize it and verify its relevance or efficiency. ML research is focused on a specific process, which is learning. The main challenge is to give minimal knowledge and data to computers to train them. Moreover, ML requires interactions between Humans, selecting data and verifying machines' results, and computers, with the idea of giving them a greater autonomy in decision. Since 1990s the synergy between large data sets, especially labeled data, and the augmentation of computer power using graphics processor units, more powerful technique applications upraised. Technologies and reasoning logic enabled to achieve several goals, for instance reducing word error rates in speech recognition, processing image recognition (Krizhevsky et al., 2012), beating a human champion at Go (Silver et al., 2016), and translating images into natural language (Karpathy & Fei-Fei, 2017).

In project management, some of the most used AI techniques are: bi-variate correlation and multiple regression tests (Mir & Pinnington, 2014), data mining (Ahiaga-Dagbui & Smith, 2014), artificial neural networks (Al-Tabtabai et al., 1997; Ko & Cheng, 2007; Wang & Gibson, 2010; Wang et al., 2012), reinforcement learning (Mao, Alizadeh, Menache, & Kandula, 2016; Tesauro, Jong, Das, & Bennani, 2006; Ye & Li, 2018), genetic algorithms and multi-criteria decision making (Baron, Rochet, & Esteve, 2006) and Bayesian Networks (Qazi et al., 2016) and even hybridation methods of Bayesian networks and evolutionary algorithms (Pitiot, Coudert, Geneste, & Baron, 2010).

This is why, in order to solve our research problem, we have explored three modeling techniques that can be familiar for PM researchers:

- Artificial Neural Networks (ANN), because we have now proofs of the accuracy in their results in several domains (Wang & Gibson, 2010),
- a type of ML called the Reinforcement Learning (RL), because it has similarity with our conception of maturity,
- Bayesian Networks (BNs), because these dynamic tools combine experts' knowledge and data, causal reasoning and correlation.

4.2.1. ANN Foundations

Initially we explore the use of artificial neural networks to predict performance based on project management maturity. Neural networks are used to extract patterns that are too complex to be perceived by humans because of their remarkable ability to obtain trends from complicated data (Castillo & Melin, 1999). They have a wide use in business applications (Wong et al., 2000), especially to evaluate risk management practice (Kampianakis & Oehmen, 2017). In this section, we introduce them, and then we explain how this technique could be used in our research work.

Inspired by the human brain, the neurophysiologist Warren McCulloch and the logician Walter Pits proposed a first neural network consisting of connected function nodes. The network was trained by iteratively modifying the weights of the connections (McCulloch & Pitts, 1943). Later, also inspired by neuroscience, Rosenblatt (Rosenblatt, 1958) developed the perceptron, a simple function for learning. It mapped the output of each neuron to one or zero. It took as input a vector of criteria **x**, the weight vector **w** and it evaluates whether their scalar product overcomes a threshold **u,** that is $f(\mathbf{x}) = \{ 1 \text{ if } \mathbf{wx} > \mathbf{u} \text{ ; otherwise } 0\}$. In a simple layer neural network, this function was not very useful because binary classification is limited. However, it was more useful in multi-layer networks, called multiple layers perceptron (MLP) (Rumelhart, Hinton, & Williams, 1986). Developed in the 1980s, MLP includes back propagation, *i.e.* algorithms assigning the good weights for which the neural networks have lower errors in its learning. One of the most used of back propagation methods is the Stochastic Gradient Descent (SGD), which minimizes the error rate by using the chain rules of partial derivatives. SGD propagates all derives, or gradients, starting from the top output and goes to the bottom, then it straightforward computes the respective weight of each link.

Since the implementation of MLP and SGD, there was no relevant progress in solving neural networks until 1997, when another method of back propagation, called Long Short Term Memory LSTM, was proposed by (Hochreiter & Schmidhuber, 1997). LSTM shortens SGD; it introduces also the concept of recurrent network to learn long-range dependencies. LSTM learns then faster than SGD and it solved complex artificial long-time-lag tasks.

Neural networks are applied in many sciences and industrial sectors. We need then to bound the type of neural networks useful for PM. Moreover, in our particular case, a neural network must have: (1) as input, the criterion characterizing the maturity of project management, and (2) as output projects' operational performance. According to the common practice, the use of several layers may be necessary for creating a causal model (see Figure 4.1). However, even if neural networks have shown high accuracy, in PM, we cannot access the amount of data needed to build a sufficiently efficient network. Our proposed IB2M having 36 criteria and 5 maturity levels, we fulfill a very important number of input parameters to train an accurate ANN. We do not have enough projects under these criteria to train the network. ANN's need for data increases exponentially with the amount of input criteria (Figure 4.2). Despite their intrinsic limitations, ANNs are still used in some business applications (Wong et al., 2000), e.g. to evaluate risk management practice (Kampianakis & Oehmen, 2017).

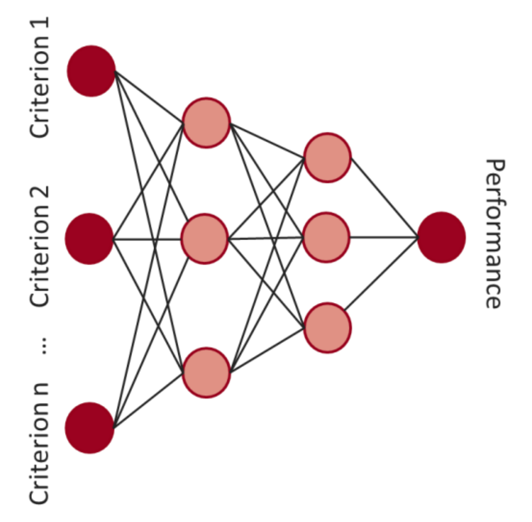


Figure 4.1 PMMM based Neural Network

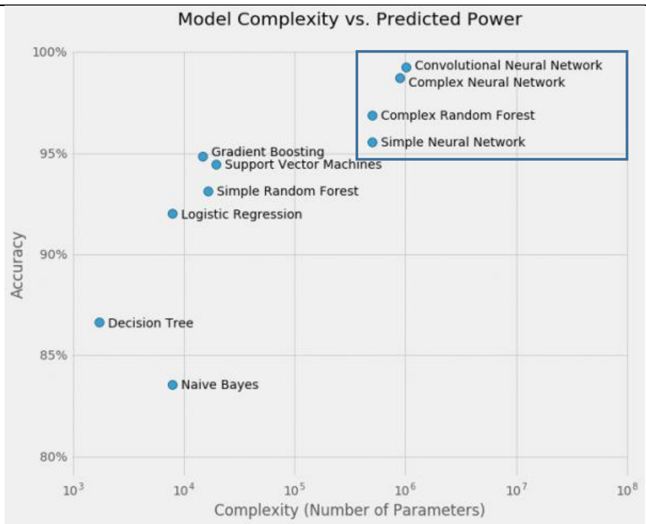


Figure 4.2 Accuracy vs Complexity of algorithms

ANNs are very interesting, or even fascinating. We sum up, in Table 4.1, their strengths and weaknesses related to PM's point of view.

Strengths	Weaknesses
➢ The relationship between input and output data is created automatically by using considerable amount of data ➢ This technique provides good performance: 96-98% accuracy in train/test predictions. ➢ Once the architecture of model is fixed, the designer just needs to do a parameter optimization to improve its accuracy.	➢ They need numerous quantities of data to learn an quite accurate model ➢ The required amount of data increases exponentially with the number of evaluation criteria ➢ They cannot represent the uncertainty present in real life projects ➢ They are a black box type model. It is not possible to explain how the model makes a decision, to a project management expert.

Table 4.1 ANNs' Strengths and Weaknesses following PM's point of view.

The second technique we would like to present is the Reinforcement Learning (RL).

4.2.2. Reinforcement learning (RL): a brief review

Reinforcement learning algorithms were developed from Markov Decision Processes (MDP). Which are mathematical models for decision-making in the stochastic situation where *each event depends only on the state attained in the previous event (the Markov Property).* In 1957, Bellman (Bellman, 1957) proposed a recursive formula optimizing the sum of all rewards along a MDP. Solving this equation means finding the optimal policy. However, Bellman's equation was not possible to solve analytically because it involves the maximization of a function, which cannot be derivative. The problem lets RL without any relevant advancement until 1995, when Watkins proposed the Q-learning algorithm (Watkins, 1995). This algorithm helps to solve the challenge of the exploration-exploitation dilemma: a computer agent spends the optimal time exploring the solutions and getting rewards, not enough to be trapped in a local optimal, but maximizing the general reward.

As an example, in Figure 4.3, the orange square agent tries several paths to maximize the long term accumulated rewards and to reach its goal: the green position with +1 reward. Under RL, this agent does not have direct instructions of which decisions to make or which are the immediate consequences of its decisions. Nevertheless, each decision will cost *-0.04 points*. The agent completes all steps (from its starting point, to the green square); it has then cumulative rewards in the end of its decision-making process. Then it would simulate several paths until maximizing accumulated rewards (Sutton, 1988).

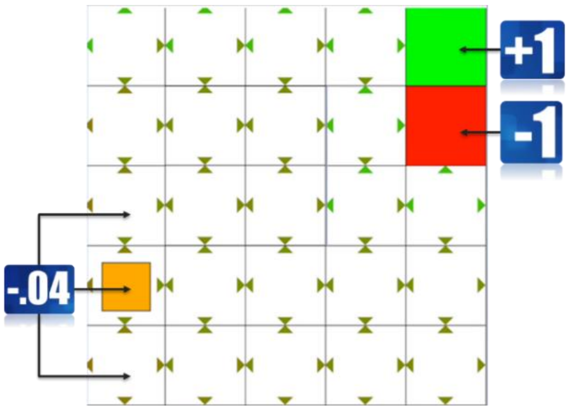


Figure 4.3 RL algorithm for a two-dimensions problem.

Very surprisingly, RL is based on a conception of learning that is closed to those of process maturity. PMMMs have been designed to classify and rank organizations according to the number and type of best practices implemented (or not) (see chapter 2). Similarly, under RL, improvement is based on successful repetitions of something, which is similar to best practices implemented. RL uses computer agents who learn how to make decisions directly from their interactions with a simulation environment. RL aims to maximize rewards signal from experience; this is, to maximize a reward utility function (similar to project performance) by creating an optimal policy (similar to project management advices). Under RL, a computer agent begins by not knowledge about how to deal with the external environment; as it gets more mature, it achieves its tasks in a more efficient manner, as in maturity process perfection scale (Table 4.2).

Process Maturity Conception	Reinforcement Learning (RL)
Maturity levels based on best practices implemented	**Steps** : based on best practices to accomplish
Project performance based on projects' KPI: cost, lead time, quality, reliability, etc.	**Rewards** points based on the selected step
Maturity path : selection of practices to gain projects' performance	**Politic**: chain of steps
Recommendations to obtain best performance	**Optimal politic**: result of the simulation

Table 4.2. Congruence between process maturity conception and RL.

Moreover, for PMMMs presented in the second chapter, maturity levels can be defined in two axes for two maturity criteria (Figure 4.4), while the agent – the system aiming at improving its maturity – is moving in each direction. It would get rewards from the environment. A project management assessment agent would explore states (that is, it satisfies criteria to move to the next level in each axis) and it will obtain reward points (gain in projects' operational performance). RL model will produce a corresponding policy based on the steps of passage through different levels of maturity while producing a better performance. Using RL requires the creation of a simulation including several project management criteria and the definition of "reward" points as the agent fulfills these criteria.

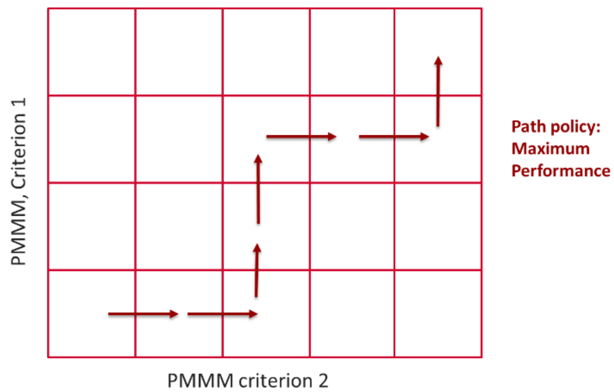


Figure 4.4 Gain in maturity under RL.

Despite its value, in PM included, RL is not easy to implement. Many parameters must be defined *ex ante*. Unfortunately, in our research inquiry, we do not have enough data to create robust RL scenario. Table 4.3 displays the strengths and weaknesses of RL.

Strengths	**Weaknesses**
➢ It learns how to optimize the behavior given a system of rewards and punishments ➢ It can graphically represent an optimal path, which implies to improve some actions in an axis before in another ➢ *The model can make recommendations to improve performance based on a set of criteria (project management practices)* ➢ *It has interesting similarities with our research problem*	➢ It is not easy to implement ➢ It needs a lot of data to qualify actions (elementary rewards) that cannot be acquired from past project management maturity audits ➢ The simulation needs many data to simulate a PMMM ➢ *A maturity evaluation uses too many criteria.*

Table 4.3 Strengths and weaknesses of RL

The combination of ANNs and RL is the basis of Deep Reinforcement Learning (DRL). In that case, the computer agent in a state uses a deep neural network to learn a policy. With this policy, the agent takes an action in the environment and gets rewards from the specific states it reaches. Rewards feed the neural network and generate a better policy. This was developed and applied in a paper named *"playing Atari with deep reinforcement learning*" in which they learn a machine to play Atari games directly from pixels, and after training, the machine produces excellent results (Mnih, Silver, & Riedmiller, 2013). The authors learn a computer to play Atari games directly from pixels, and after training, the machine produces excellent results. RL was also used, in 2016, to play Go, which is a very complex game, defeating the world champion (Silver et al., 2016). After this works, RL developed more attention from investors. The investment has increased and the applications have been growing since then (Huddleston & Brown, 2018).

4.2.3 Brief Review on Bayesian networks (BN)

BNs are graph-based tools modeling experts' knowledge and inferences; BN combines then data and knowledge, knowledge state and knowledge updating, correlation and causality. BNs' ability to explicitly manage uncertainty makes them suitable to a great amount of applications in a wide range of real-world problems including risk assessment (Fenton & Neil, 2013), bankruptcy prediction (Sun & Shenoy, 2007), product acceptability (Arbelaez Garces, Rakotondranaivo, & Bonjour, 2016), medical diagnosis (Constantinou et al., 2016), construction design process diagnosis (Matthews & Philip, 2012), etc.

We will elaborate the presentation of BNs below. Nevertheless, we can note that BNs fit to problems in which (1) causes must be correlated with a consequence, e.g. maturity criteria, as input variables, and a specific projects' operational performance, as output, (2) the amount of data is not huge and they change in times (their level of uncertainty is high), (3) one must combine data and experts' knowledge We can sum up the strengths and weaknesses of BNs in table 4.4.

Strengths	Weaknesses
➢ The amount of data to compute the model is moderate. ➢ It is possible to use expert judgment to build or refine the network ➢ They can represent different scenarios ➢ They have dynamic learning with time, once established the network, they can increase their accuracy by feeding more data ➢ *They can do a retro propagation analysis to inquiry the value of the causes of a non-performance.* ➢ *They can represent criteria values as independent nodes in a network*	➢ The model may be more subjective than the previous ones due to the experts' judgment ➢ *The prediction of the performance is uncertain because it is written in terms of conditional probabilities in the output node(s)*

Table 4.4 BNs' Strengths and weaknesses.

Once ANN, RL and BNs have been presented, we can then define data-focused requirements of a satisfactory AI and ML technique to elaborate the causality between project management process maturity and projects' operational performances.

4.3 Selection of the adequate technique

We have presented three AI and ML techniques – ANNs, RL, BNs – that could be used to solve our research problem. In this section, we compare them qualitatively in order to select the most valuable. The criteria we will use refer to data, and not knowledge.

4.3.1. Data assessment framework

Table 4.5 presents our set of requirements or criteria proposed by (OECD Glossary of Statistical Terms, 2008) and (Naïm, Wuillemin, Leray, Becker, & Pourret, 2008).

Category		Dimension
Input data	Access Criteria	Accessibility, Uncertainty and Incompleteness
	Contextual Criteria	Relevancy, Completeness, Appropriate amount of data Value added
Output data	Visualization	Interpretability, Ease of understanding, Concise Representation
	Intrinsic Criteria	Accuracy, Objectivity, Relevancy, Validity, Uniqueness

Table 4.5 Criteria to evaluate how models threat data

Let detail these criteria category by category.

Input data – Access criteria

Accessibility denotes the extent to which data are available, or easily and quickly retrievable. "*Accessibility refers to the ease with which statistical information can be accessed by users. This includes the ease with which the existence of information can be ascertained, as well as the suitability of the form or medium through which the information can be accessed. The cost of the information may also be as aspect of accessibility for some users. Data should be presented in a clear and understandable form, released in a suitable and convenient manner, and made available and accessible on an impartial basis.*" (OECD, 2008).

Uncertainty and incompleteness: The data acquired are not certain nor complete. The selected technique should maintain a probability distribution over the set of possible states, based on a set of observations and observation probabilities (Naïm et al., 2008).

Input data - Contextual criteria

Relevancy denotes the extent to which data are applicable and helpful for the task at hand. *"The relevance of statistical information reflects the degree to which it meets the needs of users. Assessing relevancy is a subjective matter dependent upon the varying needs of users."* (OECD, 2008).

Completeness denotes the extent to which data are not missing and is of sufficient extensiveness and depth for the task at hand. "*The proportion of stored data against the potential of "100% complete" for business rules. It is a measure of the absence of blank values or the presence of non-blank values."* (OECD, 2008).

Appropriate amount of data: The extent to which the volume of data is appropriate for the task at hand (OECD, 2008).

Output data - Visualization

Interpretability The *interpretability* of statistical information refers to the availability of supplementary information and metadata necessary to interpret and use data appropriately. This information normally covers the underlying concepts, variables and classifications used, the scope, the methodology of data collection and processing, and indications of the accuracy of the statistical information (OECD, 2008).

Ease of understanding: The extent to which data are easy to understand. It denotes the capacity of the technique to exhibit the causal relationships (OECD, 2008).

Output data - Intrinsic Criteria

Accuracy denotes the extent to which data are correct and free-of-error. In an accurate model, data describes correctly a «real world» object or event. *"Accuracy refers to the degree to which the data correctly describe the phenomenon they were designed to measure"* (OECD, 2008).

Objectivity: The extent to which data are unbiased, unprejudiced and impartial (OECD, 2008).

Validity: Data are valid if it conforms to the syntax (format, type, range) of its definition (OECD, 2008).

Uniqueness: Nothing should be recorded more than once based upon how that thing is identified. "*Analysis of the number of things as assessed in the 'real world' compared to the number of records of things in the data set."* (OECD, 2008).

Time Consistency: Data structure cannot change in time; it implies the perennial of the semantics of the data and the calculation mode (OECD, 2008).

Value added: The extent to which data are beneficial and provides advantages from its use, for example prediction and diagnostic (OECD, 2008).

Sensitivity analysis (evaluation impacts and changes): The technique should show how the output is effected by several inputs (Naïm et al., 2008).

4.3.2. Data assessment related to our inquiry

Table 4.6 shows a comparison between ANN, RL and BNs through the list of criteria presented above. Each AI and LM technique has a **+** sign if the characteristic is fulfilled and a **++** sign if the technique is the better in the characteristic. Similarly **-** sign if the characteristic is not fulfilled, and **- -** sign if the technique has an important weakness in the characteristic.

Criteria	**ANN**	**RL**	**BNs**
Accessibility	- -	- -	+ +
Uncertainty and incompleteness	- -	+	+ +
Relevancy	-	+	+ +
Completeness	- -	- -	+
Appropriate amount of data	- -	- -	+
Interpretability	-	-	+ +
Ease of understanding	-	- -	+ +
Accuracy	+ +	-	+
Objectivity	+ +	+	-
Validity	+ +	+	+
Uniqueness	+ +	-	+
Consistency (time)	+	+	+
Value added	+	+ +	+ +
Sensitivity analysis	- -	-	+ +

Table 4.6 Qualitative assessment of ANN, RL and BNs.

Access Criteria: Data accessibility is limited within our inquiry. One of the biggest challenges is to obtain a structured database of PM maturity audits and projects' operational performances evaluation. Hence, the methods that require an important amount of data inputs (ANN, RL) are not appropriate. BNs seem the most appropriate in terms of accessibility. They stand out for their ability to work with mixed data (from databases and experts), to process the uncertainty of data and to be easily readable.

Contextual Criteria: Given the context of project management maturity evaluation, the type and amount of data is limited. The completeness of the result is ensured by BNs better than with another technique. The volume of data needed to create a relevant BN is aligned with the reality of the research problem.

Representational Criteria: BNs' graph representation is explicit, intuitive and understandable by a PM expert. This facilitates both the validation of the model and its use. Decision makers are much more confident with a model whose working is understandable rather than with a black box model such as an ANN.

Intrinsic Criteria: ANNs have shown their capacity in terms of accuracy, objectivity, uniqueness and consistency. This proficiency is met only if they receive the adequate amount of data. BNs fail in 'objectivity': they can be biased. However, BNs can propagate data evolution from input to output, and back propagate information in the other direction, this characteristic makes them useful for this research problem.

Project management maturity audit data are usually scarce and incomplete. Making good decision from incomplete data is a challenge for projects managers, top managers and consultants in PM. While ANNs give answers based on available data, BNs include non-sample or prior human expertise, which is relevant in our research. Usually, an interview with an expert asking for the impact of several parameters is the best manner to recollect all that information that makes the Bayes network richer than the other techniques. Combining this expertise with sample data makes this technique powerful. Second, they present a graphical representation structure of the model, which is better in this case than a black box model, like ANNs. It is easier to explain obtained results and to communicate with experts: this gives an advantage when working with people, which are not experts in the modeling technique but in the business domain, i.e. healthcare, or in this case, project management. Another BNs' advantage is their capability to be built by expert knowledge and by raw data, even if prior knowledge is incomplete. It is possible to start with expert's knowledge, and refine with data, then have a feedback with expert's knowledge, etc.

4.4. Theoretical Review of Bayesian Networks

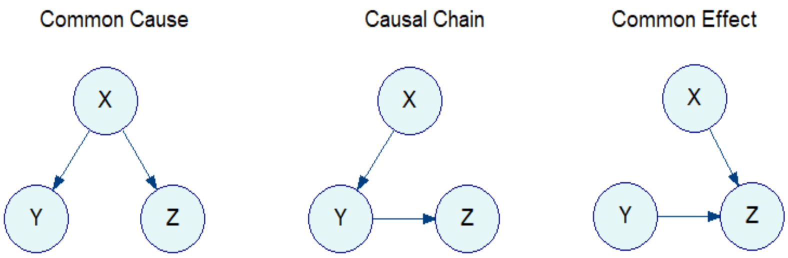
Bayesian Networks (BN) are part of probabilistic models representing a set of variables and their dependencies by a graph, i.e. a pair $G = (V, E)$, where V is a finite set of distinct nodes and $E \subseteq V \times V$ is a set of arcs. An ordered pair $(u, v) \in E$ denotes a directed arc from node u to node v, and u is said to be a parent of v and v a child of u (Pearl, 1988).

BN are usually direct acyclic graphs (DAG) representing probabilistic causal relationships in which nodes represent variables and arcs express the dependencies between variables. More precisely, nodes are the states of random variables and arcs pointing from a parent node to a child node is the causal condition dependency between two nodes. The causal relationship is represented by the probability of the node's state provided different probabilities of the parent node's state.

BN use conditional probabilities to describe events. Any belief about uncertainty of an event or hypothesis H is assumed provisional. This is called prior probability or ‘P(H)’. This prior probability is updated by the new experience ‘e’ providing a revised belief about the uncertainty of ‘H’. The new probability is called posterior probability given the evidence or ‘P(H|e)’. Bayes’ theorem (Eq.4.1) describes the relationship of posterior probability and the prior probability. ‘P(e|H)’ is the probability of the evidence been true given that the hypothesis is true, and ‘P(e)’ represents how probable is the new evidence under all possible hypotheses.

$$P(H|e) = \frac{P(e|H) * P(H)}{P(e)} \qquad \text{(Eq.4.1)}$$

The conditional probability table (CPT) demonstrates the probabilistic relationships between nodes. Figure 4.5 displays this relation on three basic graphs (Hagmayer, Sloman, Lagnado, & Waldmann, 2010). In this example, each node has two states: True (T) and False (F). This figure also displays the different CPT for each configuration of nodes.



Common Cause:

Y CPT	X = T	X = F
P (Y = T)	$\theta_{YT}(1)$	$\theta_{YT}(2)$
P (Y = F)	$\theta_{YF}(1)$	$\theta_{YF}(2)$

Z CPT	X = T	X = F
P (Z = T)	$\theta_{ZT}(1)$	$\theta_{ZT}(2)$
P (Z = F)	$\theta_{ZF}(1)$	$\theta_{ZF}(2)$

Causal Chain:

Y CPT	X = T	X = F
P (Y = T)	$\theta_{YT}(1)$	$\theta_{YT}(2)$
P (Y = F)	$\theta_{YF}(1)$	$\theta_{YF}(2)$

Z CPT	Y = T	Y = F
P (Z = T)	$\theta_{YT}(1)$	$\theta_{YT}(2)$
P (Z = F)	$\theta_{YF}(1)$	$\theta_{YF}(2)$

Common Effect:

Z CPT	X = T Y = T	X = T Y = F	X = F Y = T	X = F Y = F
P (Z = T)	$\theta_{ZT}(1)$	$\theta_{ZT}(2)$	$\theta_{ZT}(3)$	$\theta_{ZT}(4)$
P (Z = F)	$\theta_{ZF}(1)$	$\theta_{ZF}(2)$	$\theta_{ZF}(3)$	$\theta_{ZF}(4)$

Figure 4.5. The three basic DAG models

For BN, the conditional probability distributions can be represented as a set of parameters:

$$\boldsymbol{\theta} = \{\boldsymbol{\theta}_1, \boldsymbol{\theta}_2, \dots, \boldsymbol{\theta}_n\} = \left\{[\theta_{ik}(j)]_{k=1}^{r_i}\right\}_{j=1}^{q_i} \qquad \text{(Eq.4.2)}$$

where i = 1,…, n defines each node; k = 1,…, r_i defines each r_i variable value (the state of the nodes); and j= 1,…, q_i, defines the set of q_i variable configurations of parent variable nodes (e.g. each graph configuration in figure 4.5) (Lauría & Duchessi, 2006). Therefore, for each of the q_i valid configurations of parent nodes, there is a multinomial distribution with vector $\boldsymbol{\theta}_i(j) = [\theta_{i1}(j), \theta_{i2}(j), \dots, \theta_{ir_i}(j)]$.

For instance, in the *Common Effect* graph in figure 4.6, the parameter $\theta_{ZT}(2) \equiv P(Z=T \mid X=T, Y=F)$, represents the conditional probability of Z to be True given that X is True and Y is False.

The parameterization of a BN configuration requires the complete estimation of the vector θ. Subsequently, two types of analysis are possible: (1) backwards inference, which allows given an observation to find the most probable cause among the hypothesis (diagnosis), and (2) top down inference, which allows to estimate the probability of an observation given the assumptions (prediction) (Pearl, 1988).

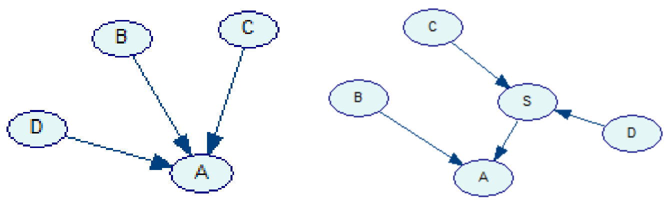
4.4.1 Interest of Synthetic Nodes

In BN, for a set of parent nodes of a node Xi denoted by *pa*(Xi), the joint probability distribution of the node values can be written as the product of the local probability distribution of each node and its parents:

$$P(X_1, X_2, \dots, X_n) = \prod_{i=1}^{n} P(X_i | pa(X_i)) \qquad \text{(Eq.4.3)}$$

The number of variables required to compute the probability distribution of the target node increases then with the number of parent nodes and their number of states, which is time-consuming. Synthetic nodes are supposed to reduce the amount of data required for computing the CPT of the target node. As (Constantinou et al., 2016) mention, *"A synthetic node is one which is simply defined by the value of its parents nodes using some expert driven combinational rule*". Consequently, synthetic nodes are useful for reducing causal complexity and the deleterious effects of combinatorial explosion in the CPT. Moreover, these nodes improve BNs' structure, the visualization of cause-effect relationships. By the use of synthetic nodes, the size and the complexity of a CPT are "*reduced vastly, increasing the computation speed and accuracy of the model*" (Fenton & Neil, 2013).

As an example, figure 4.6 (4.6a and 4.6b) displays a proposal using synthetic nodes starting with the diagram proposed in (Neil et al., 2000). In this example, the network has four variables A, B, C and D, each one has four states, the number of probability values to calculate the CPT of P(A|D,B,C) is 4^4 = 256. Instead, this calculation could be simplified into two tables, P(A|B,S) and P(S|C,D) by the introduction of the synthetic node S. Now the model needs to calculate two CPTs for S and A, using 4^3 + 4^3 = 64 values rather than 256.



4.6a. Without synthetic node, the model needs 256 values.	**4.6b**. With synthetic node S, the model needs 64 values.

Figure 4.6 Example of use of Synthetic node S described in (Neil et al., 2000)

"From a practitioner's point of view the process of compiling and executing, a BN, using the latest software tools, is relatively painless given the accuracy and speed of the current algorithms. However, the problems of building a complete BN for a particular problem remain, i.e. ***how to build the graph structure and how to define the node probability tables for each node of the graph****."* (Neil et al., 2000) Thus, in the next section we are proposing insights to solve these problems.

4.5. Building causal models based on BN

In this section, we discuss the structural criteria to take into account when building causal models based on BN. We will focus first on the structure of the model. For this, we will use the term "*hyperparameter*" as it is used in deep learning models, i.e. *"parameters that should be set before running the learning algorithms"* (Mnih et al., 2013). These hyperparameters fix the conditions to the learning parameters that are trained; they are experts-dependent. For example, in ANNs, hyperparameters are the learning rate (α), the number of iterations in gradient descent, the number of hidden layers, the number of hidden units, the activation function, etc. We need then to define specific hyperparameters for BN.

4.5.1. The hyperparameter setting problem

Usually, in any ML problem, the goal is to find the right parameters that minimize a given cost function. Conversely, when building BNs, these parameters depend both on data availability and experts' knowledge. Hence, the problem is more extensive than a parameter optimization; it is a hyperparameters setting problem. Selecting the right configuration of hyperparameters is a challenge when building BNs because these parameters are based on the semantics of the model. They should be useful regarding the data that will be used to train the model. The hyperparameters that we explore within this thesis are:

- The number of input nodes,
- The number of states of each input node,
- The number of states of the target node(s),
- The number of synthetic nodes (intermediate nodes),
- The structure of data before learning,
- The learning algorithm.

4.5.2. Eligibility Criteria selection

Selecting the good hyperparameters is challenging because there is no 'a-priori' right answer. It is a trial - error compromise. Usually, in BN building process, modelers try some parameters, then test the obtained BN, try other values for the hyperparameters, then test again the network, etc. For example, creating a network when all input nodes have two states, then create another network where they all have five states, etc. Therefore, for a candidate configuration of hyperparameters, how can we state that a network is efficient enough? Within this research, we propose some criteria that could evaluate BNs' validity. These criteria would help us judge whether a BN is efficient and useful.

1 - Ensure the semantic consistency: Experts should easily interpret BN semantics. The model should give backgrounds and results that are interpretable and useful for the experts' community. Ensuring the semantic consistency would increase *interpretability*, the *ease of understanding*, and the *time consistency*.

2 - Adjust the completeness of the network: BNs should use the appropriate quantity of nodes (and nodes' states) representing the concepts. This second criterion depends on the available amount of data and its *completeness*. It depends on the *accessibility of data*, its *uncertainty and incompleteness.*

3 - Guarantee the relevance of the result: The target node (and its states) should be useful for the decision-maker but its values should have enough *accuracy* and *precision*, as shown in figure 4.7.

> *"The accuracy of a measurement system is the degree of closeness of measurements of a quantity to that quantity's true value. The precision of a measurement system, related to reproducibility and repeatability, is the degree to which repeated measurements under unchanged conditions show the same results."* (JCGM, 2012)

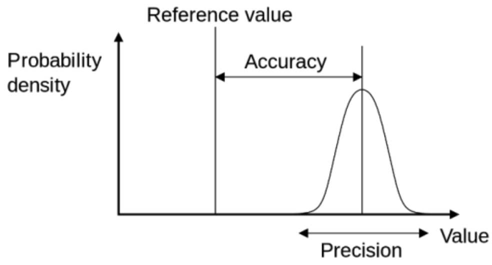


Figure 4.7 Accuracy and Precision

The relevance of results ensures several intrinsic criteria, such as the *validity*, the *uniqueness*, and the *objectivity.*

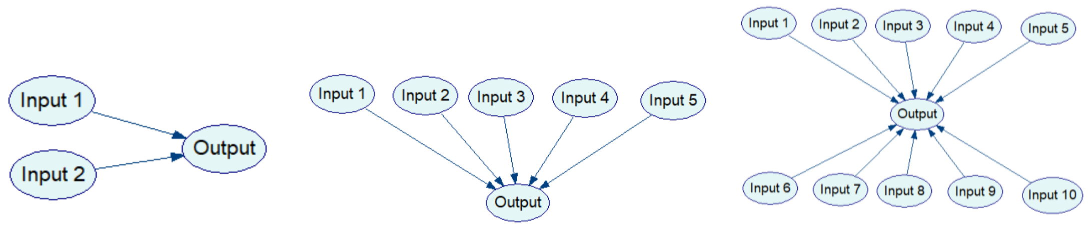
4 - Limit the combinatorial explosion. The number of relationships between parents and child nodes should be satisfactory. If the model uses a high number of nodes or states in each node, the network would be too complicated to be learned by the algorithms. When a CPT is too large for a given amount of available data, the capacity of prediction of the network would be low. When the size of the CPT is controlled, the *relevance* of the network is high, and the accuracy of the result increases. If the CPT is built by an algorithm based on a database, it can perform *sensitivity analysis*, therefore there is even more *value added* for the decision-maker.

5 - Guarantee a good quality of learning. BNs should have a complete learning, that is, CPTs must be calculated completely. When there is an explosion of configurations (too many states, or nodes), or not enough information, CPT calculation will be incomplete, therefore the quality of learning will be low (Naïm et al., 2008). There are several metrics to estimate the quality of learning, for example BIC (Burnham & Anderson, 2004) or AIC (Akaike, 1974). A good quality of learning implies the algorithms will perform well in a new data set, and the network would effectively help the decision-making process.

4.5.3. The influence of the hyperparameters on the eligibility criteria

When building BNs, there is a strong dependence between the choices of hyperparameters and eligibility criteria. The different network structures would change the results in the criteria:

The number of input nodes is the number of parents' nodes in the network. Figure 4.8 displays three networks with different configurations of input nodes. Experts should define which variables are corresponding to the input, and how many of them are necessary. From the semantic point of view, the model may represent the problem better with more input variables, but from the mathematical point of view, more input nodes may affect the *accuracy* and *precision* in the result, and the model would need a bigger *amount* of training *data*.



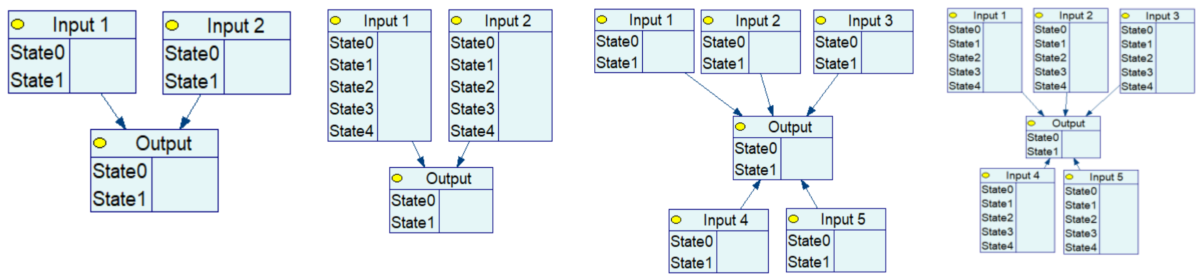
2 Input nodes — *+ accessibility, amount of data; - relevancy*

5 Input nodes — *+ accessibility, amount of data, completeness*

10 Input nodes — *+ Uniqueness, Interpretability;* *- amount of data, sensitivity analysis*

Figure 4.8 Examples of BN configurations (changes in the number of input nodes)

Number of states in input nodes: Each input node can have several states. Starting from two states, usually meaning (Yes/No) to many nodes (see Figure 4.9). As the number of states increases, the size of child nodes' CPT increases (see equation 2). BNs in literature use two inputs in each node. More states could be important from the semantic point of view (increasing the *interpretability* of the model); however, they would increase the difficulty in training the model, and the *sensitivity analysis.*



2 Input States — *+ easy of understating;* *- objectivity, value added*

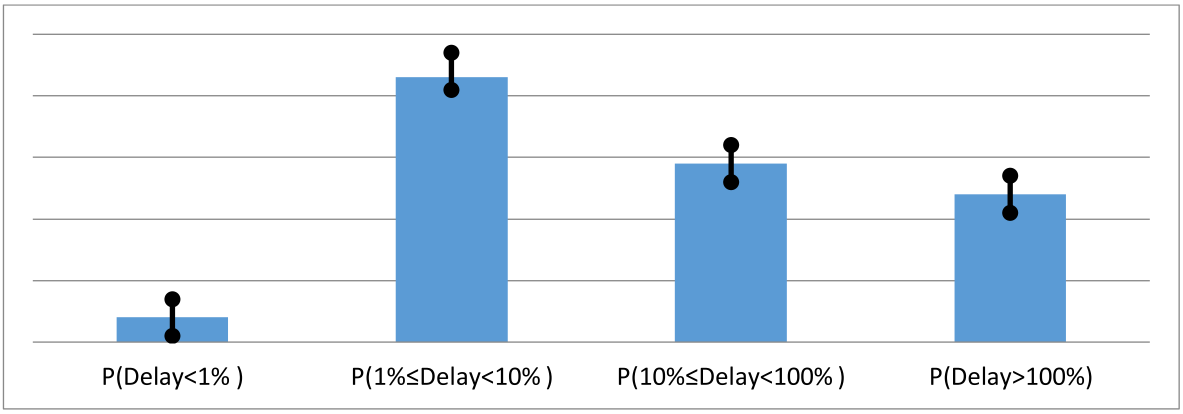
5 Input States — *+ interpretability;* *- amount of data*

2 Input States — *+ ease of understanding, interpretability, objectivity*

5 Input States — *- completeness, amount of data*

Figure 4.9 Examples of BN (changes in the number of input nodes and input states)

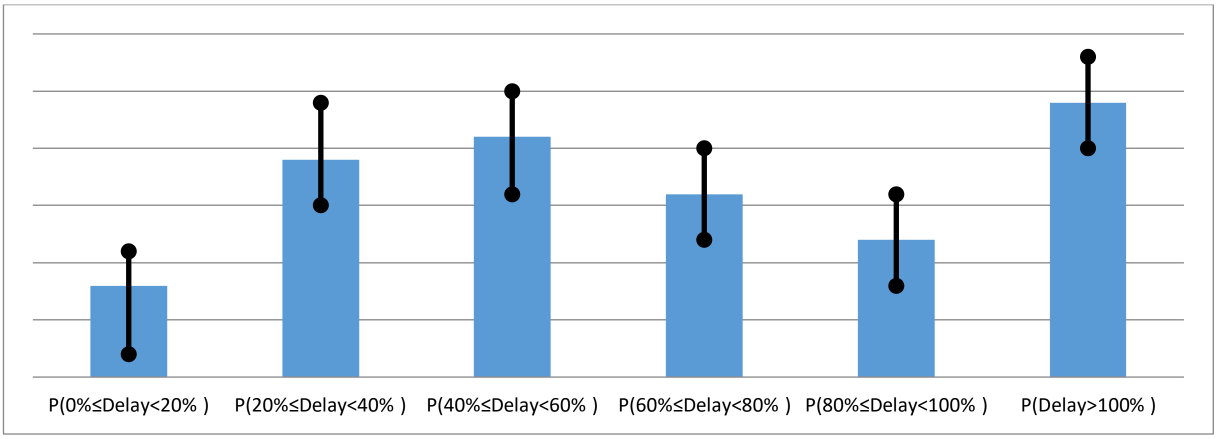
Number of States of the Output or Target Node: Supposing that the input nodes are going to be connected to one target node. The model should make a trade-off between the granularity of the answers, which is the number of states of the target node, and the precision of the value for each answer. As an example, figure 4.10 shows four states of a target node called 'project delay'.



+ *Accessibility, amount of data, completeness, precision, uncertainty;* - *interpretability, easy of understanding*

Figure 4.10. Precision (black line) for the four states in a target node.

In this case, we have four possibilities. The first one shows the probability of having a delay equivalent to less of 1% of the expected time for an event. The second one displays the probability of delay between 1% and 10% of the expected time, and so on for the other states (in a logarithmic scale). This distribution of states in the target nodes presents grouped information to the decision-maker, i.e. the range in the state P(10%<Delay<100%) may be too large. To tackle this problem, figure 4.11 proposes a more granular division, that is, more states in the target node.



+ *Interpretability, relevancy;* - *accessibility, completeness, accuracy, objectivity, uniqueness, precision*

Figure 4.11. Precision (black line) for the six states in a target node

The second case (figure 4.11) displays a target node with six states. Here the state segmentation is divided into every 20% interval of the expected possible delay. The presence of several states may appear better for the decision-maker because s/he would have more detailed output for each of the different input configurations; nevertheless, as the number of states increases, the precision and accuracy of the value for each state decrease, as presented by the black line in figure 4.11.

Number of synthetic nodes: As shown in the previous section, when the target node has several states, and several parents' nodes, the problem becomes more difficult to solve. The introduction of the synthetic nodes is proposed to limit the explosion of configurations (Constantinou et al., 2016; Fenton & Neil, 2013; Sun & Shenoy, 2007). However, the number of synthetic nodes to use will depend on the structure of the problem and its semantics.

Data structuration: Data must be clean and structured before training the algorithms. There should not be any error in the database. Once the data are ready, the columns in the database represent the parents' nodes and the last column represents the target node. Each row represents an instance (measure) i.e. every row is a new case to train the algorithm. Given a database, the expert who is building the network should ensure the correspondence between the number of columns and the number of rows, and the quality of the information containing in them to ensure the quality of learning.

Machine Learning Algorithm: Finally, a learning algorithm should be chosen. BN can use several classification algorithms, they can be divided into two classes: (1) those that are used to determine the graph structure and the parameters of the conditional distributions (learning algorithms). Also (2) those that calculate the propagation of the information once the network is done (inference algorithms) (Acid, De Campos, & Castellano, 2005; Druzdzel, 1999; Friedman & Goldszmidt, 1996; Ghosh, 2008; Naïm et al., 2008; Pearl, 1988). Table 4.7 shows some algorithms used in Bayesian learning.

Learning algorithms for Bayesian Networks			
To learn Parameters from:		**To learn the Structure from:**	
Complete Data	Incomplete Data	Complete Data	Incomplete Data
- MLE: Maximum likelihood estimation **- MAP:** Maximum a posteriori estimation **- EAP:** Expectation A Posteriori	**- EM:** expectation maximization (Dempster, Laird, & Rubin, 1977) **- GS:** Gibbs sampling	- **MWST** Maximum Weight Score Three (1968) - **K2** (Friedman & Goldszmidt, 1996) - **GS** Greedy Search (1995) - **CS:** Causality Search - **GES**: Greedy Equivalent Search (2002)	- Structural-**EM** (1998) - Heuristic **EMCMC** (1999) - **MWST-EM** (2005)
Inference algorithms for Bayesian Networks			
Exact		**Approximate**	
- Bucket Elimination - Message passing (Pearl, 1988) - Junction tree algorithm (Richardson & Jensen, 2006)		- Monte Carlo sampling (1998) - Cluster Variation Method (2002)	

Table 4.7 Algorithms used in Bayesian Networks, adapted from (Bouaziz, 2014)

In this section, we have made an evaluation on the importance of the structure of the network. Next, we will focus on the importance of its semantics.

4.6 Using Bayesian Networks for Project Management Evaluation

This section presents the work of five papers where project management metrics are related to project performance metrics. We built Bayesian Networks using the data found on those papers, and we evaluated the resulting network under the criteria described previously. This work was done because we want to understand how to model project management systems using BN, what the most common limitations are, and which insights we can get from previous work, with the aim to develop a new model.

This is not a criticism about the contents of these works, but a criticism about how **these researches are limited when trying to elaborate a BN based on their information.** In this section, we explore the importance of the semantics of the model based on solid scientific literature and we use the eligibility criteria to identify the rules of building truthful Bayesian networks.

4.6.1. First limitation: absence of synthetic nodes and conceptual structure

The first paper we consider is entitled **"***Exploring the value of project management: linking project management performance and project success***"** (Mir & Pinnington, 2014)**.** To achieve this goal, Mir and Pinnington identified key projects' success drivers depending on different areas (Table 4.8). These drivers correspond to input data of the BN. Moreover, the authors had a database from a sampling including 154 responses that were received over a period of 4 weeks.

PM Leadership Focuses on: • development and promulgation of awareness of the role of projects as a vehicle for managing all types of change • ensuring that PM system supports the development of open, two-way partnerships with customers and suppliers and a shared, common project language culture.	**PM Partnerships and Resources** Emphasize: • The role and importance of win–win partnerships between all stakeholders • Effectiveness of such partnerships on project management
PM Staff Emphasizes: • the planning and management relating to PM staff to increase its PM capability by maximizing the potential of project-related human resources • the extent to which the management of PM staff incorporates methods for rewarding performance relating to PM.	**PM Key Performance Indicators** (KPIs): Focuses on: •KPIs to indicate results achieved in relation to meeting the requirements of project stakeholders • The methods used within the PM system to improve performance against the KPIs.
PM Policy and Strategy: Focuses on how the development of PM, across an organization, is introduced in a planned and systematic fashion ensuring the linkage between strategic, organization level and the tactical, project level.	**Project Lifecycle Management Processes**: Incorporates processes which are required to manage the whole project life cycle

Table 4.8 Definition extracted from the paper (Mir & Pinnington, 2014).

We can model the study of Mir and Pinnington by choosing a BN with a star or hub feature (Fig.12.a). In the proposed causal model, there are no synthetic nodes. The limitation of using this BN comes from the underlying assumption of treating criteria as interdependent factors going from the causes' nodes to the 'project success' node. The main restriction of using this network emerged from the number of combinations needed to calculate the CPT of 'Project

Success’ node. This number may be too large to make the model accurate enough. For example, if each node has two states (True/False) the vector θ would need 4,096 values to complete the CPT for the project success node. If each node has five states, it will need 244 million values. This BN will lose its utility because the number of combinations needed to complete the CPT of ‘Project Success’ node may be too large to be accurate enough.

These reasons explain why we suggest using synthetic nodes; they reduce target node’s CPT size and improve the quality of the visualization of causality. Figure 4.12b corresponds to our proposal; it displays a BN based on synthetic nodes, which can replace the network displayed in figure 4.12a. If each node in the network in Figure 4.12-b has two states, with the introduction of the synthetic nodes, the ‘Project success’ node’s CPT would have 4 values to be calculated, ‘PM social configuration’ node, 8 values, ‘PM context configuration’ node, 4 values, and ‘PM Factors’ node, 8 values, that means a total of 24 values, instead of 4,096.

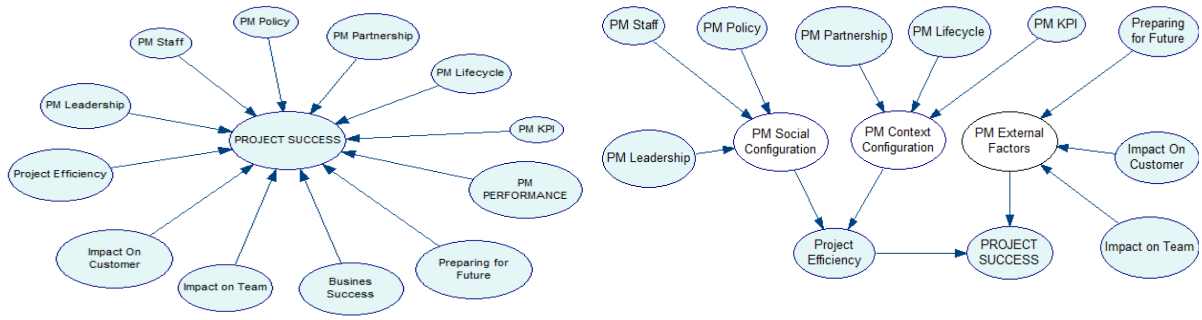


Fig. 4.12-a. Mir & Pinnington’s BN **Figure 4.12-b.** Proposed BN with synthetic nodes.

Figure 4.12 Mir & Pinningtons BN

Afterwards, we will complete a brief criticism of Mir and Pinnington’s BN based on this research following the criteria defined previously:

1 - Ensure the semantic consistency: Experts can misinterpret several variables since there are not specific measurable inputs for each node. For example, how is it possible to know the level of PM policy of an evaluated organization? Alternatively, how is it possible to measure the level of the effectiveness of PM partnerships?

2 - Adjust the completeness of the network: Mir and Pinnington’s BN does not focus on a specific area of project management, but it brings together concepts. It is not possible to ensure that the network has included the most important variables, or that it may reveal the most important relationships between them. The authors highlighted this point when talking about the limitations of their work: *“(…) Prior work also suggests that Project Success perceptions are influenced by various* ***other factors*** *relating to the project environment, for example, the project risk, or the choice of contract type”* (Mir & Pinnington, 2014).

3 – Guarantee results’ relevance: The trade-off between accuracy and precision on the target node is highly affected by the variance described in the research: *“It is acknowledged that other factors influence Project Success besides PM Performance.*

Indeed 45% of variance (as shown by the best fit model from multiple regression analysis) is explained by the PM Performance construct whereas 55% variance remains unexplained.” (Mir & Pinnington, 2014).

4 - Limit the combinatorial explosion: Since the target node depends on several inputs, the amount of data required to feed the network is too large. However, original Mir and Pinnington’s BN represents a good example of how introducing synthetic nodes can reduce drastically the amount of information needed to train the computer in which the model is encoded.

5 - Guarantee the quality of learning: Mir and Pinnington’s BN was built from a database from a sampling including 154 responses that were received over a period of 4 weeks. However, this information cannot be organized in a database with a structure allowing the learning of all CPT’s values. For this network, it is not possible to measure the quality of learning, doing a train/test ratio or using other test metrics.

In conclusion, this example shows the relationship between the semantic structure and the amount of data needed. This study is displayed as an example of how introducing the synthetic nodes can reduce CPT’s calculations, these nodes are necessary but they are not sufficient for building a network that fulfills the eligibility criteria.

4.6.2. Second limitation: incorrect number of states.

Our next study concerns a paper entitled “*Quantifying the impact of requirements definition and management process maturity on project outcome in large business application development”* (Ellis & Berry, 2013). The authors defined a correlation between requirements maturity and different metrics for projects’ operational performance. Table 4.9 displays the key practices driving Requirements Definition Maturity (RDM)

Describing project **goals** and objectives in concise, clear, and unambiguous terms	Uncovering **project interdependencies** or issues that need investigation
Facilitating cross-functional **group sessions** where requirements were discovered	Clearly describing project **risks** and assumptions
Conducting **efficient meetings**, and making effective use of stakeholder time	Presenting the results of analysis in clear, well-organized, and readable **documentation**
Accurately **documenting** the business process behind the application	Assessing **change requests**: determining the impact on scope and cost, and the impact of system changes on business processes
Describing the **information flow**, and key data needed by users at any given time in the business process	Achieving **consensus** on requirements among **stakeholders**
Assuring that **the scope of the project neither significantly changed** nor had major in-scope functions moved to follow on phases of the project	Getting **requirements documented** in a short, concentrated period of time

Table 4.9 List of Ellis and Berry’s concepts explaining RDM.

Our first task was to recover the information in order to create a BN reproducing Ellis and Berry’s results. The proposed network has thirteen inputs, one intermediate node

(Requirements Maturity) and five outputs. The network we built from this research is divided into two parts. The first one uncovers several factors that affect Requirements Maturity (figure 4.13). The description of each concept is displayed in table 4.9

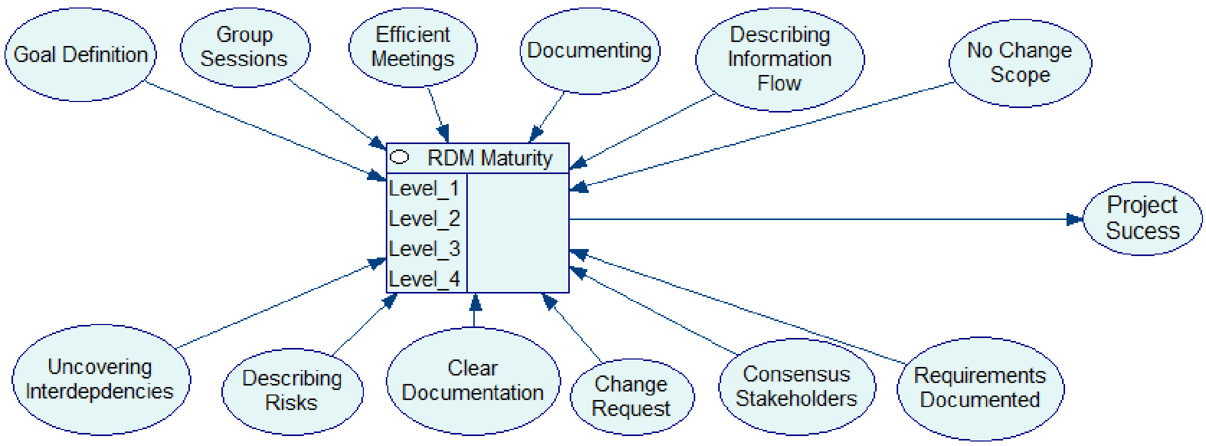


Figure 4.13 BN designed from (Ellis & Berry 2013)'s correlation factors with project success.

The second part of Ellis and Berry's paper shows how Requirements maturity could affect different metrics of project performance (Figure 4.14).

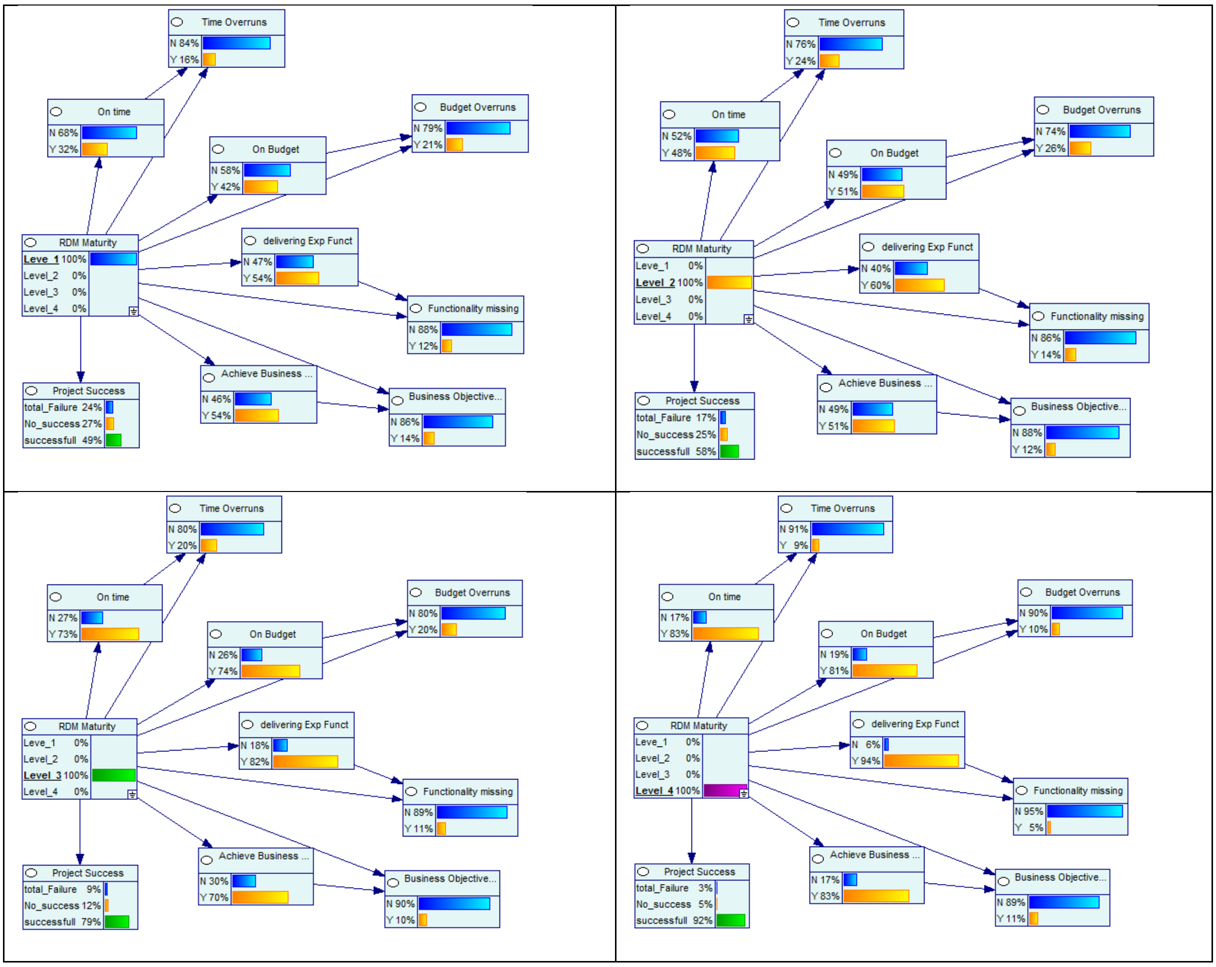


Figure 4.14 RDM Maturity and success metrics

Some key lessons can be identified from Ellis and Berry's BN.

1 - Ensure the semantic consistency: Their BN presents criteria selected by the experts in requirements engineering. These criteria are not exhaustive, but they can be relevant to the objective.

2 - Completeness of the network: Ellis and Berry have selected the main concepts accepted by the experts'' community in PM. The scope of their paper is limited to Requirements Maturity. Each concept clearly corresponds to each node.

3 - Guarantee the relevance of the result: The target nodes have two states, Yes or No, where each one depends on the combination of all the states in the RDM Maturity node. That is, all metrics for performance only depend on requirement maturity. Each output node has two clear states (Yes/No), but their dependency in the four states of RDM limits their accuracy. In addition, the dependence of RDM maturity in twelve input nodes limits the precision of the results.

4 - Limit the combinatorial explosion. Since all the input nodes are related to a single intermediate node 'RDM Maturity', and it has four states, the combination of its CPT is high (32 768 values). There is not enough data to create a CPT of the 'RDM Maturity' node that could give a reliable output.

5 - Guarantee a good quality of learning. As the CPT of 'RDM Maturity' node has an combinatorial explosion, it is highly probable that the quality of learning on its CPT is low. There is not enough data even to train the network or to test it. Therefore, the network cannot guarantee the quality of learning.

In conclusion, this network has a complete semantic structure; however, setting only one intermediate node with four states increases the combinations in the CPTs. Instead, it should be better to create several synthetic nodes.

4.6.3. Third limitation: semantics undefined strictly

The next paper is entitled **"***The role of project portfolio management in fostering both deliberate and emergent strategy***"** (Kopmann, Kock, Killen, & Gemünden, 2017)**.** The key variables and the model proposed by the authors were tested on a dual-informant cross-industry survey of 182 small and medium enterprises and large companies.

Environmental turbulence	Strategic control
ET1: The technology in our industry is changing rapidly **ET2:** There are frequent technological breakthroughs in our industry. **ET3:** Technological changes provide great opportunities in our industry. **ET4:** In our industry, it is difficult to predict how customers' needs and requirements will evolve. **ET5:** In our kind of business, customers' product preferences change quite a bit over time.	**SC1:** We frequently review the feasibility of portfolio strategy based on information acquired in projects. **SC2:** We frequently review the validity of the premises defined within strategic planning. **SC3:** We frequently review whether the strategy of the project portfolio is further justified in the light of changed conditions.

ET6: In our industry, it is difficult to forecast competitive actions.	**SC4**: Based on the information gained in the projects we deliberately challenge the portfolio strategy.
Deliberate strategy implementation	**Emerging strategy recognition**
DSI1: We put down the general guidelines for the portfolio via our strategic planning. **DSI2:** Portfolio planning and strategic planning are closely linked with each other in our company. **DSI3:** The goals of our project portfolio are derived from our company's goals	**ESR1:** Through our project portfolio analyses we obtain valuable impulses for our strategy. **ESR2:** Through our project portfolio analyses we discover major new investment needs. **ESR3:** Through our project portfolio analyses we discover new business opportunities.

Table 4.10 Concepts used as sub criteria in (Kopmann et al., 2017).

Figure 4.15 displays the network that we built with data included in (Kopmann et al., 2017) paper. We have a causal model based on a tree feature.

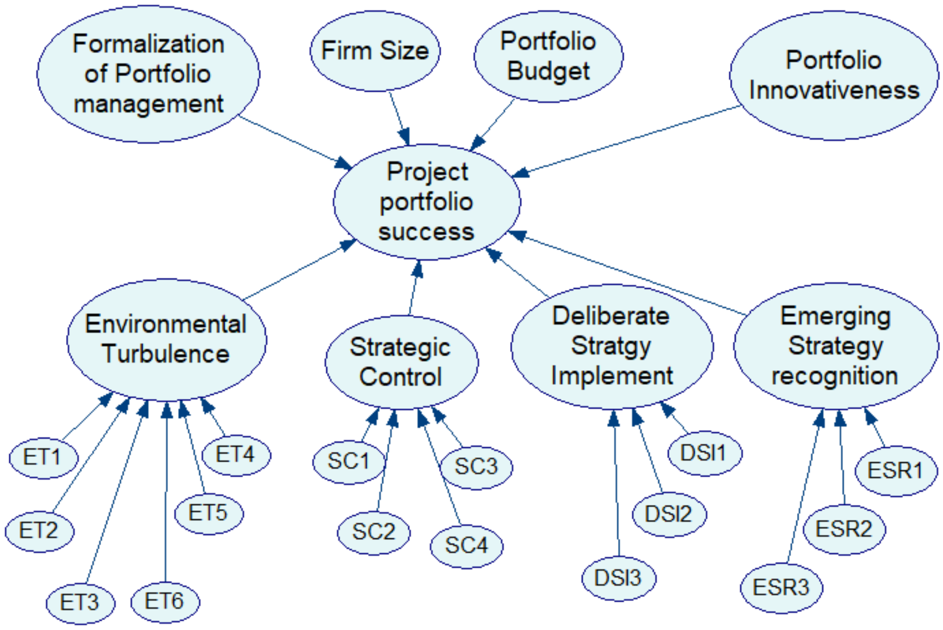


Figure 4.15 BN we built from the research of (Kopmann et al., 2017).

We can use the set of criteria mentioned in the two previous case to assess Kopmann et al. (2017) work.

1 - Ensure the semantic consistency: this. network presents elements included in the macro environment that could affect the portfolio success. The definition of criteria depends on some sub criteria, as shown in table 4.9. Elements were accepted in PM community. However, there could be several other elements affecting portfolio success regarding to its environment, strategy definition, etc.

2 - Adjust the completeness of the network: It is not possible to define whether this network is taking account all the necessary variables. The concepts are validated by the PM experts community (Kopmann et al., 2017).

3 - Guarantee the relevance of the result: There is no measure of the result's quality given the high number of variables. In addition, the amount of data related to each variable is not large enough to create relationships between them.

4 - Limit the combinatorial explosion: There are eight nodes targeting one single node, and the amount of data is not large enough to create an accurate CPT for the target node. In addition, each of the intermediate nodes proposed in the paper have several input nodes, these CPTs are not complete because of a lack of data.

5 - Guarantee a good quality of learning: The learning in the target node does not have enough accuracy, because there is not a structured database that helps to build its CPT.

In conclusion, Kopmann et al. (2017) network showed that BNs' semantics should be defined. Instead of building a causal model with a large scope and a limited number of variables, it could be better to create a BN with a reduced scope (e.g. not portfolio management but project management) with an exhaustive and necessary number of variables.

4.6.4. Fourth limitation: having too many target nodes

The next study we will criticize is called "*Impact of integration management on construction project management performance*" (Demirkesen & Ozorhon, 2017). This paper includes inputs described as best practices regarding project management integration, it uses an "*Integration Management*" node that could be used as a synthetic node. This node is measured in several performance metrics: Time, Safety, Quality, Cost, and Client Satisfaction. We built BN from Demirkesen and Ozorhon's work (Figure 4.16).

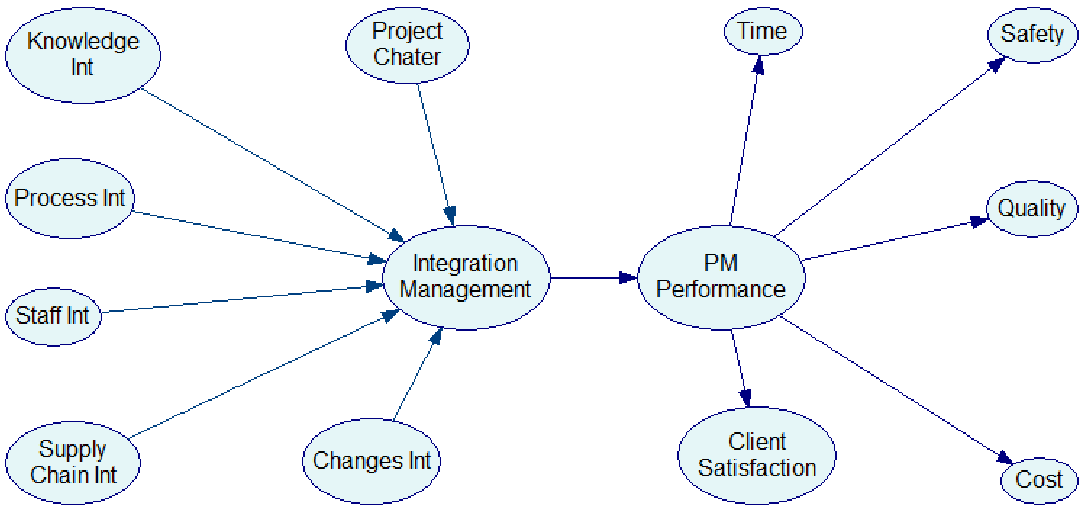


Figure 4.16 Demirkesen and Ozohorn's causal model conceived as a BN.

The limitation of this causal network appears when evaluating the extreme cases. For example, Figure 4.17 displays the expected performance when the integration management is fully accomplished. This network displays how even a 100% evidence in the "Yes" state would conduct to a 64% probability of performance, which is an improvement of 32% probability. Moreover, when dividing this probability in each one of the defined performance metrics (Time, cost, quality, safety, client satisfaction) the gain in probability becomes less important.

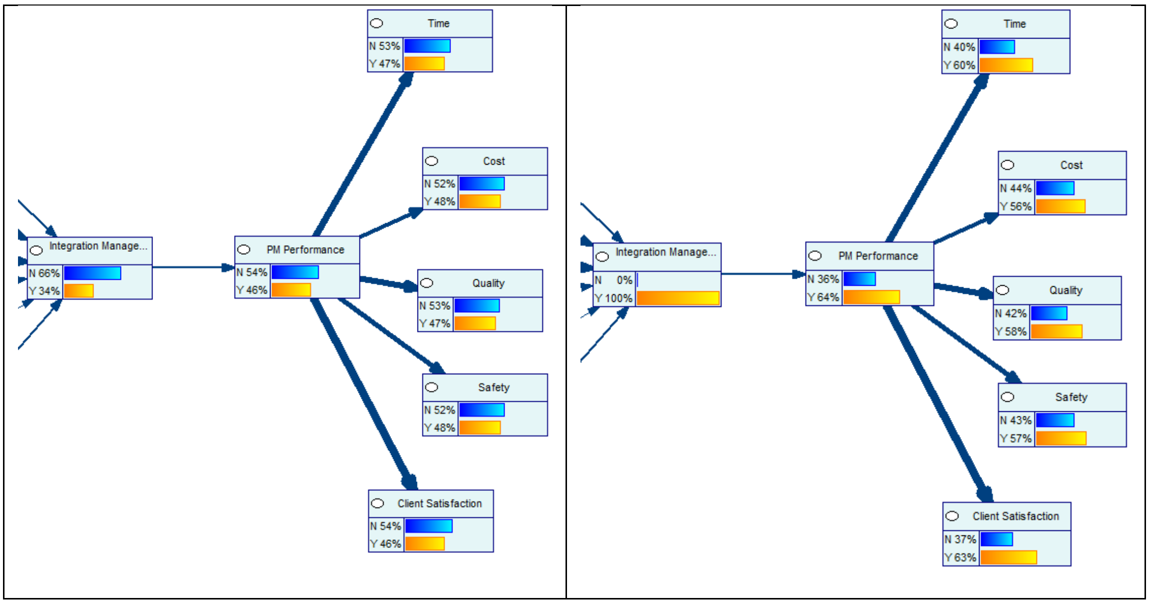


Figure 4.17 Sensibility analysis for (Demirkesen & Ozorhon, 2017).

More generally, Demirkesen and Ozorhon's model lacks of several key points.

1 - Ensure the semantic consistency: The causal model is focused on integration management and the nodes are related to this domain. The main contribution of the research explains how integration management is related to projects' operational performances. The semantic consistency of Demirkesen and Ozorhon's model is then good.

2 - Adjust the completeness of the network: The nodes of the causal model are defined with variables that are not possible to directly measure from the described project. There is no evidence that the concepts associated in this network are exhaustive, or include all the necessary evaluation items regarding integration management.

3 - Guarantee the relevance of the result: PM performance target node is derived into five nodes. Consequently, the accuracy of the answer was reduced. Introducing more concepts for measuring performance decreases the relevance of the results in terms of accuracy and precision.

4 - Limit the combinatorial explosion: The combinations on the Integration management node are high, but still possible to calculate. CPTs in the target node are low because each one exclusively depends on one factor (PM performance).

5 - Guarantee a good quality of learning: Since all the nodes have two states, and data available in this paper are enough, the quality of ML could be good. However, it is impossible to measure how good the learning is because there are not enough measures to do new tests.

In conclusion, the information available on Demirkesen and Ozorhon's paper allowed us to recreate a better BN. However, given the amount of data, it is advisable to work with one target only (instead of five) assuring the relevance of the result.

4.6.5. Fifth limitation: causal paths multiplicity and ML impossibility

The last studied paper, entitled **"***Towards modeling project complexity driven risk paths in construction projects"* (Qazi et al., 2016)**,** develops a BN modeling a previous study (Eybpoosh, Dikmen, & Talat Birgonul, 2011). The network proposed in (Qazi et al., 2016) has several intermediate nodes and four target nodes that converge in the 'utility' function. BNs are used to evaluate project cost overrun. Data were extracted from a survey to project managers in several companies. This model uses two states for each of its 26 nodes: True/False. It has eight input nodes and it has four output nodes:

The model proposed in (Qazi et al., 2016)**,** displayed in figure 4.18, explores the interdependencies between project complexity features, risk and project objectives.

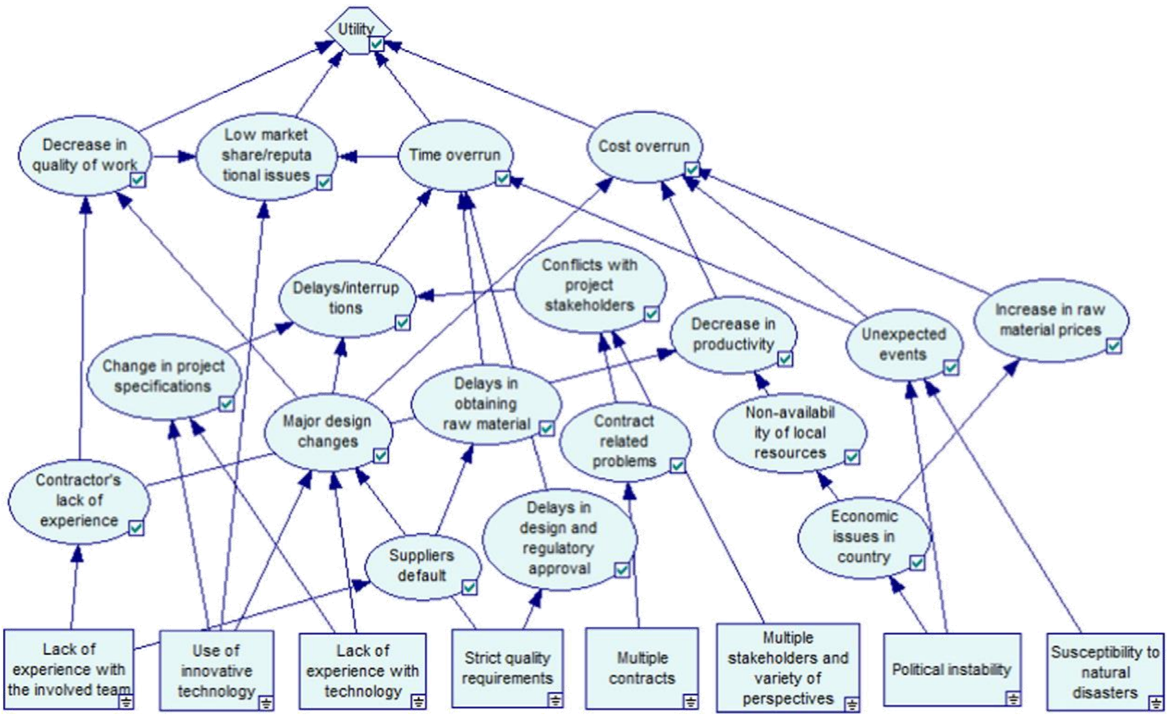


Figure 4.18 BN proposed in (Qazi et al. 2016)

How can we assess the proposed BN?

1 - Ensure the semantic consistency: The authors have selected the main concepts accepted by PM experts' community. However, there is no evidence that this model includes an exhaustive list of variables interfering a project development.

2 - Adjust the completeness of the network: The scope of the network proposed in (Qazi et al. 2016) is too large. Since there are four target nodes, it is not obvious whether the network is taking into account all the variables affecting those nodes. The study provides no justification about why some nodes are pointing to some target and not others.

3 - Guarantee the relevance of the result: There are four target nodes, and some of them are interdependent. These nodes have two states, so the precision and accuracy should be maximal. However, it is not possible to measure these characteristics in each target node.

4 - Limit the combinatorial explosion: Each node of the proposed BN has two states. There is no combinatorial explosion, even in the nodes with three parents. The paper presents all the CPTs explicitly, so it is possible to fully rebuild the entire network.

5 - Guarantee a good quality of learning. There is not enough data to train the network or to test it. Therefore, there is no database to measure by algorithms the accuracy and precision of each target.

There is a limitation in the data *accessibility* concerning the proposed BN. It cannot be totally reproduced, nor trained with a new data set. It does not show any perfection scale (maturity level) linked with PM best practices implementation (no measure of observable variables). It is not possible to evaluate the relevance of the result in each target node, nor the quality of learning of the full BN.

4.5.6. Synthesis

To conclude section 4.5, we propose the table 4.11 comparing five causal models based on the criteria mentioned in section 4.4. The table below shows a comparative rating based on the analyses carried out previously. Each paper has a + sign if the eligibility criteria is fulfilled. Similarly, a - sign if the criteria is not fulfilled, and - - sign if the technique has an important weakness in the criteria.

Criteria	(Mir & Pinnington, 2014)	(Ellis & Berry, 2013)	(Kopmann et al., 2017)	(Demirkesen & Ozorhon, 2017)	(Qazi et al., 2016)
Ensure the semantic consistency	-	+	- -	+	-
Adjust the completeness of the network	-	+	-	-	-
Guarantee the relevance of the result:	-	-	-	- -	-
Limit the combinatorial explosion	- -	- -	- -	+	+
Guarantee a good quality of learning.	-	-	-	-	-

Table 4.11 Qualitative estimation for the eligibility criteria evaluating the BN built from literature.

1. The first (ensure semantic consistency) is met by most of the networks built since in all cases, the information is extracted from scientific articles that have been worked on by researchers. In the next chapter, we should include the concepts used by the experts and justify them with the relevant scientific literature to meet this criterion.

2. The proposed causal models do not guarantee the completeness of the network. However, (Ellis & Berry, 2013)'s study is much closer to the construction of a model whose input characteristics effectively define the maturity of requirements, and its output characteristics: the efficiency parameters of the project.

3. None of the studied networks guarantees the relevance of the result. It is not possible to define a measure of precision or accuracy for the result. This is the most difficult point when building BNs. There is not enough data to test these networks, and it is not possible to apply performance measures on learning algorithms. However, authors (Demirkesen & Ozorhon, 2017) teach us that less target nodes could improve the relevance of the network's results.

4. The combinatorial explosion is an important problem presented when building the BNs, or more generally: networks. It could happen when several input nodes point to one target node (Mir & Pinnington, 2014), when there are too many states in the intermediates nodes (Kopmann et al., 2017), or when the model includes too many concepts and sub-concepts (Ellis & Berry, 2013). However, we found that using synthetic nodes and including two states in each node reduces the explosion of combinations. We must keep in mind this heuristic in our models.

5. We learned that in order to guarantee the quality of learning we should include a database and apply metrics once the network is defined. Even if the CPTs are presented in (Qazi et al., 2016), we cannot calculate any learning metric based on these CPTs.

4.7 Discussion: defining BN Building rules

The analysis led in this fourth chapter allows us to extract working rules to build our models explaining projects' operational performances by project management maturity. We can sum up these rules as:

- Rule 1: limit the semantics of the model. We have shown how literature in PM presents correlations of entities of different natures. Nevertheless, for a well-defined BN, it is advisable to start by modeling entities of the same nature. In our case, we will use concepts of project management maturity, excluding concepts concerning the core competences of the company or the environment of the project.

- Rule 2: limit the number of input nodes. Many input nodes linked to a node would create too many combinations to be solved. This would produce a combinatorial explosion in their child's nodes. More than five input nodes reduce the impact of the sensitivity analysis because the retro propagation algorithms would have to cover too many causes, and the importance of each one would be diluted.

- Rule 3: limit the number of states in the input nodes to two. Using several states in the input nodes induces a combinatorial explosion in the child's nodes. This reduces the accuracy and relevance of the result. Also having a node with two states as Yes/No increases the ease of understanding and objectivity of the network.

- **Rule 4: use synthetic nodes**. These nodes should represent the semantics of the network; consequently, their place in the structure should be discussed with experts. It is advisable to use synthetic nodes to reduce explosion of CPT. As consequence, the amount of data needed to train the algorithms will be reduced, the completeness of the BN is higher, interpretability increases, as well as accuracy.

- Rule 5: use only one target node with the appropriate number of states. We have shown how using several target nodes limits the sensitivity analysis, and the objectivity of the network. We propose to have only one target node with an appropriate number of states. This proposition solve the tradeoff between accessibility, completeness, precision, uncertainty, and interpretability and easy of understanding.

From these rules we extract some insights, for example, a tree is an ideal representation for a causal model, from a logical point of view and from ML quality point of view. This representation follows the construction criteria, and it is aligned with the semantics.

4.8 Conclusion

This fourth chapter has presented different Artificial Intelligence (AI) and Machine Learning (ML) techniques - Artificial Neural Networks (ANNs), Reinforcement Learning (RL) and Bayesian Networks (BN). We have evaluated them according to several criteria and we have justified the use of BN.

We have used BN because it reveals both the variables and the path of relationships between them. These characteristics let researchers and practitioners to have explicit representations. The BN has advantages over the other methods studied, including the use of experts' prior knowledge. It also reduces the complications associated with imperfect data gathering and uncertainty. BN uses an inductive mode of reasoning that permits to use both sample data and expert-judgment information in a logical and consistent manner to make inferences.

Given the nature of the research problem, we have chosen to use BN because we do not have huge amounts of data, but knowledge of experts are available and may help us create such networks. From this decision, we have explored the mathematical fundamentals of BN, and defined which parameters should be selected to create models from them. We also have defined the criteria under which networks are evaluated in order to verify their usefulness and avoid bias. Therefore, we have explored in-depth how to build models with this technique and we have defined 'eligibility Criteria' (section 4.5.2) to evaluate the quality of BN. We have shown that literature proposed structured information that can be translated into Bayesian networks (section 4.5). However, none of them fulfills our modeling requirements completely. In the next chapter we will propose a methodology to build Bayesian network structures that fulfill the eligibility criteria described in this chapter.

CHAPTER 5

5 Projects' cost overruns prediction methodology based on Bayesian Networks

About this Chapter—The project management aims at increasing projects' probability of success, which is expressed in terms of key operational performances achievement (clients' value, lead time, cost, etc.). Experts have thus developed several project management maturity models (PMMMs) to assess and improve projects' outcome and performances. However, the current literature lacks models correlating the measured maturity and the expected probability of success of projects. The aim of this fifth chapter is to explain how academics and practitioners, *e.g.* project managers, project management consultants, can enhance their decision-making and deliver more cost-effective services through the mixed analysis of qualitative expertise and data.

5.1 Introduction

As presented in chapter 2, PMMMs were conceived with high expectations. Academics and practitioners assume that a higher level of the project management maturity automatically leads to better projects' operational performances (Cleland & Ireland, 2002; Grant & Pennypacker, 2006). Literature shows some empirical evidences of this causal hypothesis, *e.g.* high levels of maturity reducing significantly cost overruns (Yazici, 2009). However, the weight of these evidences is not so heavy because some papers emphasize, on the contrary, the lack of clear evidences between a low level in project management maturity and projects' cost overruns (Brookes, Butler, Dey, & Clark, 2014). Studies did not proposed a causal model explaining the stated correlations between project management maturity and cost overruns (Mullaly, 2014). We can conclude then that literature has not shown by what means PMMMs' implementation reduces the probability of projects' cost overruns (Brookes et al., 2014; Y.H. Kwak & Ibbs, 2000; Mullaly, 2014). Up until now, it is not possible to build a causal model explaining the relationships (causality and related correlation) between project management maturity and projects' risk of overcosts because of two main reasons:

(1) the long lists of criteria in PMMMs lead to assessments which are often only partially achieved (incomplete input data),

(2) PMMMs have too many variables and that makes a quantitative causal analysis impossible (Dvir, Raz, & Shenhar, 2003; Ko & Cheng, 2007; Lahrmann et al., 2011; Wang et al., 2012).

In this fifth chapter, we will try to cope with this tricky issue by using the conceptual framework presented in the second chapter, i.e. our proposed Invariant-Based PMMM Model (I2BM) normalizing the concepts related to project management maturity evaluation. Additionally, we chose to use Bayesian Networks (BN), which are relevant tools for risk analysis diagnosis and prognosis (prediction) based both on experts' knowledge and data (chapter 4). BNs are based on observational inferences of conditional probability relations. Therefore, the methodology proposed in this fifth chapter has as inputs project management best practices considered as information atoms, and a probability range of projects' cost overrun as output. Our methodology will be applied to past data collected from projects in the oil and gas sectors. The data set focused on the most common causes of project cost overruns for a period of four years.

Thus, the goals of this chapter are as follows:

- proposing a methodology explaining relationships (causality and correlations) between project management maturity and projects' cost overruns,
- using the proposed methodology to build a BN predicting the ranges of cost overruns for a group of industrial projects,
- evaluating the proposed BN under eligibility criteria presented in chapter 4,
- presenting how it is possible to create BN-based recommendations scenarios.

This chapter is organized as follows: in Section 5.2 we present our methodology to build a BN explaining he causality between project management maturity and projects' cost overruns. In section 5.3 we present a case study where we apply our methodology. In section 5.4 we demonstrate how BN can be used in order to create recommendation scenarios. In section 5.5 we make a discussion about this research proposal. Finally, in section 5.6 we conclude about this work.

5.2 A Bayesian Approach

In the present case, a causal model should blend different sources, *e.g*. experts' knowledge in project management best practices and databases memorizing information about past projects' performances. Project management auditors check projects' performances and whether the client organization has (or has not) implemented a core of best practices. Experts have then causal patterns allowing diagnosis and prediction. Moreover, clients do not have an extensive structured database measuring the project management maturity of several projects across the same field. That means that only a low quantity of well-documented cases exists. We have then a situation in which we have expertise and incomplete data. Nevertheless, despite this raw material, we can use BNs to prototype causal models with learning capacity.

However, we cannot request experts to correlate a huge amount of input variables (maturity evaluation) to several criteria of projects' performance, cost overruns in our cause, because of human calculation limitations. Fortunately, we can ask the experts to elaborate the most likable structure of a causal network from a semantic point of view. Usually, consultants are requested to solve specific problems when their clients have trouble in their project management. Experts' approach is then focused on identifying dysfunctional points and implementing preventive actions before trying to cope with harmful consequences. Experts know how to find failure causes (here we call them drift factors) and what is the causal relationship between project management maturity and the probability of occurring one of these causes. Consequently, our research direction or heuristic is to ask them what the relationship between project management maturity levels and project management drift factors is, rather than to ask directly the relationship between project management maturity and projects' operational performances.

A relevant way to display consultants' risk quantification is the Gravity / Occurrence matrix defined in NF EN 50126 standard (Table 5.1). This matrix inspired our work in this way: the experts can provide the probability of occurrence of a drift factor, and the algorithm applied in the database calculates the probability of gravity of this explicative variable, that is, its impact on projects' operational performances. We oriented our methodology this way in order to reduce BNs' combinatorial explosion and facilitate the quality of the learning algorithm (See chapter 4 section 4.5.2.)

	Insignificant	**Marginal**	**Critical**	**Catastrophic**
Impossible	Negligible	Negligible	Negligible	Negligible
Unlikely	Negligible	Negligible	Acceptable	Acceptable
Unusual	Negligible	Acceptable	undesirable	undesirable
Occasional	Acceptable	undesirable	undesirable	undesirable
Probable	Acceptable	undesirable	unacceptable	unacceptable
Frequent	undesirable	unacceptable	unacceptable	unacceptable

Table 5.1 Gravity / Occurrence Matrix

As presented above, linking project management maturity with projects' operational performance is a very challenging problem. However, our first strategy to solve it is to use synthetic nodes. Our proposed methodology is displayed in figure 5.1., which made of two parts (vertical axis):

(1) the semantic modeling part identifies the concepts defining project management maturity evaluation domain,
(2) the Bayesian modeling part is related to the steps required to build a causal structure.

This figure also shows two sources of information feeding the model (horizontal axis):

(1) experts' qualitative knowledge, which is used to identify the structure of the causal network: input nodes, intermediate nodes, target node, etc.,
(2) a quantitative information source, in our case a database, which provides data to train the algorithm for calculating the CPTs for the nodes proposed in the causal structure.

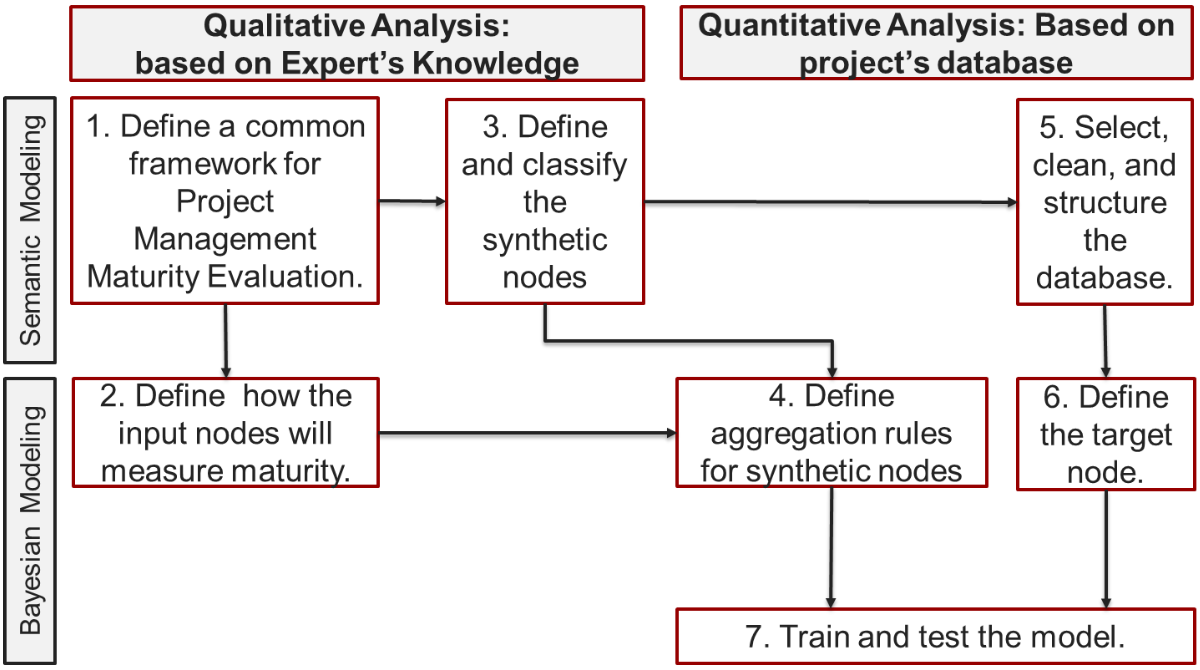


Figure 5.1. Method to build BN

We can explain now the steps of our methodology. These steps, inspired from the construction rules defined in chapter 4 (Section 4.6).

5.2.1. Step 1 - Define a semantic model for Project Management Maturity Evaluation

Following the construction rule #1 we have defined in Section 4.6, we should *"limit the semantics of the model to a specific field of project management".* Then, we limit the semantics of our causal model to project management maturity evaluation. We define an evaluation model that must achieve three requirements:

(1) It should have a reduced number of criteria compared to existing PMMMs in order to facilitate correlations and computation.

(2) The evaluation criteria should be based on the principles of project management maturity evaluation.

(3) These criteria must be understandable by experts in order to provide future recommendations for client organizations.

Therefore, we use our IB2M proposed in chapter 2, which a normalized model where best practices are the atoms. In this descriptive structure, the project process groups can be divided into three invariant time-related structures, called chronologies based on the phase of the project: Prepare, Monitor and Valorize. Additionally, activities and routines inside the chronologies have common invariant characteristics: they are doing by someone (resource invariant), they are doing in a specific time, or they may have a repetitive nature (frequency invariant) and they have several levels of detail and granularity (activity granularity invariant). We have also proposed that activities and routines can be grouped into four invariant domains grouping ten project management knowledge areas. Figure 5.2 shows the matrix of the corresponding nomenclature for our descriptive model.

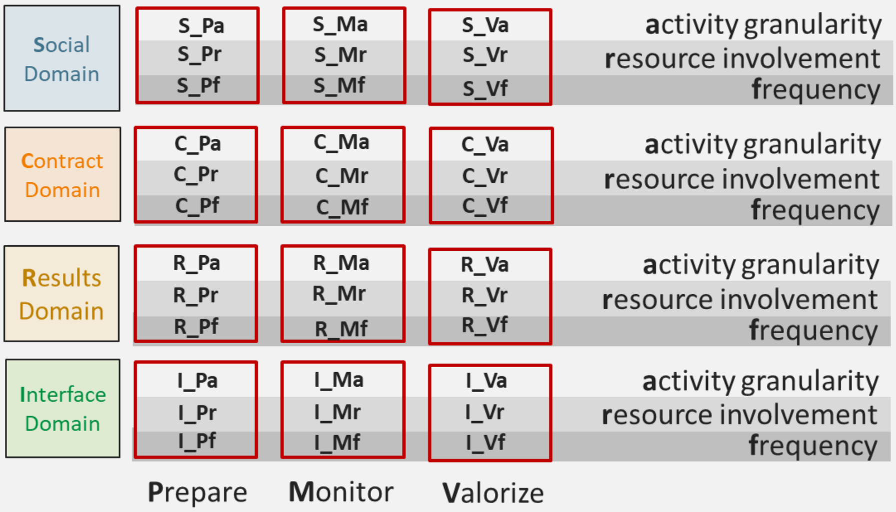


Figure 5.2 The Matrix of Invariant-based PMMM nomenclature.

The main characteristics of the invariant-based PMMM are grouped in three dimensions:

Activity Granularity (A): concerns the level of detail that may be used to describe the outputs of project management activities. It may depend on the chosen period of description (for instance, one hour, one day…) or on the aggregation of resources allocated to a project activity (for instance, at the member level or at the team level). **Resource involvement (R):** concerns the actors (the project manager, the team, the stakeholders) and tools necessary to complete the PM activities. Who is involved in the PM activities? Which tools does this actor need to perform his/her activity? **Frequency (F):** concerns the temporality of the PM activities: Is there a unique execution of the activity? Is it repetitive? This includes time plans, and deadlines.

The next layer concerns the phase of the project when the practice occurs. First, the **Prepare phase (P)** where the activities are performed before the start of the project execution and updated to prepare the work during the next phase(s) of the project. Next, the **Monitor phase (M)** where the activities are performed during the project execution and they follow the progress of the project. Finally, the **Valorize phase (V)** where the activities are performed at least at each milestone, and in the closing of the project. These activities will increase the value of the present project, or improve future projects.

The next layer concerns the project management domains. This work has defined four domains. Each domain corresponds to some of the knowledge areas presented in the PMBOK®. The **Social domain (S)** describes characteristics created by human interactions in the project. It corresponds to the PMBOK® knowledge areas of communication, human resource, and integration management. Then, the **Contract domain (C)** corresponds to the PMBOK® knowledge areas of scope and risk management. This domain includes all inputs relevant to the contract definition, the risk and the scope management. The **Results domain (R)** corresponds to the PMBOK® knowledge areas of cost, quality and schedule management. Projects would need safeguards and a contingency plan. Project managers should foresee overruns, and estimate contingency reserves to anticipate for schedule uncertainty. Finally, the **Interface domain (I)** corresponds to the PMBOK® knowledge areas of procurement management and stakeholder management. This domain includes reviewing the horizontal integration, data quality and knowledge management.

In order to facilitate causal analysis, we have to restructure our IB2M. Figure 5.3 displays then a multilayers or tree structure. From the top to the bottom, this structure contains a project layer, a project domain layer, a project chronology layer, and a project tasks layer. Each upper layer is related to the layers below with one-to-many relationships. Based on this structure, our IB2M can be conceived as a hierarchy (or taxonomy of project management best practices.

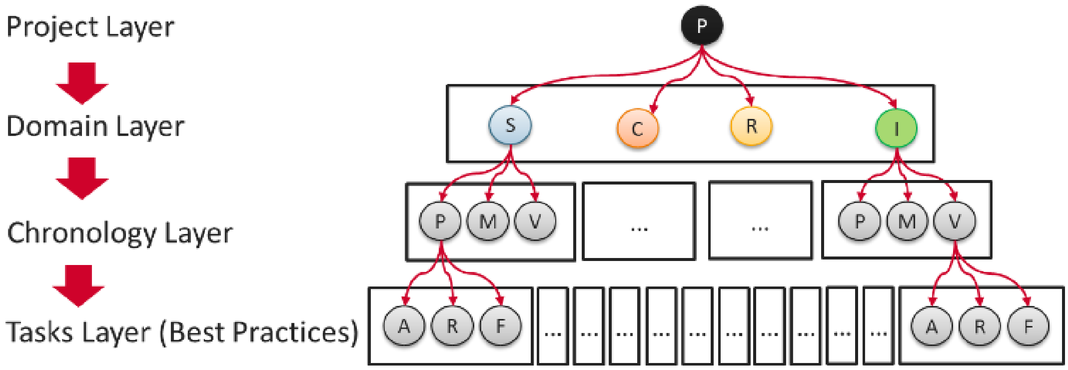


Figure 5.3. Multilayer invariant PMMM representation

5.2.2. Step 2 - Define how the input nodes will measure maturity.

BN resulting from questionnaires and interviews must incorporate mutually exclusive input nodes. They can be modeled in two ways:

- Case 1, as a set of input nodes (a node for each invariant) with 5 states (maturity level 1 to 5),
- Case 2, as a a set of five input nodes (maturity level 1 to 5) for each invariant with two states (Yes or No).

As we study maturity levels, we would tend to associate each state of the input node with each maturity level (case 1). However, this is not efficient regarding the *amount of data* in hand, and the *completeness* of the possible results. We have explained, with the construction rule #2 in Section 4.6, that we should "**limit the number of input nodes**". When learning the prior probabilities from historical data it is important to guarantee that the chosen number of states is appropriate regarding the database size. That means that a trade-off has to be found between the BN structure and the quality of the results. If the number of states is too high, then the CPT calculation increases the need for data. Under these circumstances, the number of states should be reduced, explaining why high-performing BN have two states in most variables (Constantinou et al., 2016).

In the proposed causal model, partially displayed in figure 5.4 (only for Social Monitor-Resources invariant), each independent node represents a maturity level and has two states: 'Yes' or 'No' (case 2). We are following the construction rule #3: "limit the number of states in the input nodes". Each state corresponds to the answer to a maturity assessment question, checking whether a practice is executed or not. For example, the Social_Monitor_Resources (S_Mr) invariant corresponds to the definition of a progress report. The level of which this invariant is carried out is shown by the quantity of nodes checked as 'yes', that is, if the report is not established or is ad hoc, level 1 will be checked 'yes' and the others will be checked as 'No'. If the report is established, is used to measure and to analyze data, level 1, 2 and 3 will be checked 'yes' and levels 4 and 5 as no.

Figure 5.4. Nodes of maturity levels for the Social Monitor - Resource invariant (S_Mr)

5.2.3. Step 3 - Define and classify the synthetic nodes.

Following the construction rule #4 (Section 4.6) we should "Use synthetic nodes". In this methodology, the synthetic nodes will explain problems that may occur during the project; here they are called 'drift factors', *i.e.* causes of possible future cost overruns between the expected cost and the actual cost stated at the end of the evaluated project.

Modeling drift factors (or drift factors) induces three modeling tasks:

1. *Identification of drift factors*: experts identify potential causes of drift in the specific project typology from the data set and then organize them in a set,
2. *Selection of drift factors*: they select significant drift factors from the set and eliminate the one with low significance,
3. *Matching of drift factors:* they identify the causal relationships between the drift factors and the PMMM invariants, and organize them as tuples.

The project management maturity levels are single nodes correlated with synthetic nodes (in this research called drift factors). Figure 5.5 shows how each drift factor has 5 parent nodes (to model the 5 maturity levels) for each domain (Social, Contract, Interface, Results).

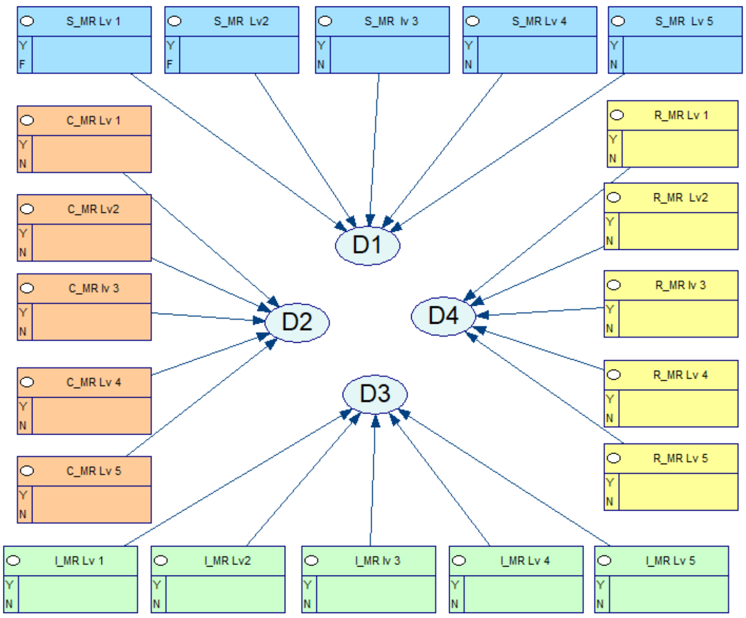


Figure 5.5. Aggregation of maturity levels nodes (intermediary elaboration of the BN)

In practice, the implementation of project management maturity assessments requires domain-specific knowledge. The identification and selection of the significant drift causes should be carried out with project management experts. After this process, the selected drift causes can be organized as tuples (matching drift causes and project management maturity criteria).

After this third step of our methodology, we have then a causal structure matching four drift factors and criteria referring to IB2M classes.

5.2.4. Step 4 - Define aggregation rules for synthetic nodes

To sum up, each drift factor node is the child node of five maturity level nodes. We interviewed experts and made their knowledge explicit to define how each maturity level is causaly related with each drift factor. In order to translate the expert knowledge into the CPT of BN, we propose equation (Eq. 5.1):

Let $\boldsymbol{D_i}$ denote the *i*-th drift factor, let ***k*** denote a PMM invariant (e.g. S_Mr, C_Mr, R-Mr, I_Mr, etc.), and let $\boldsymbol{t_{(i,k)}}$ denote a tuple of relationships between invariant - drift factors. We propose to model their relationships, as follows:

$$t_{(i,k)} = [w_{ik}(D_i, Lv1_k), w_{ik}(D_i, Lv2_k), \dots , w_{ik}(D_i, Lv5_k)] \quad \text{(Eq. 5.1)}$$

Where $\boldsymbol{t} \in (t_1, \dots t_i, \dots t_n)$, ***i*** is an identifier for drift factors, ***n*** is the number of retained drift factors. $\boldsymbol{w_{ik}}$ is a function to map each project management maturity level ($Lv1_k, \dots Lv5_k$) for the PMM invariant ***k*** to the probability of occurrence of the drift factor *i.*

5.2.5. Step 5 - Select, clean, and structure the database.

The database to train the model should contain projects' operational performances impacts of the most common problems found in the projects, *e.g*. how much are the expenses overruns induced by each drift factor. Nevertheless, this fifth phase is the trickiest step of our methodology. Most of the times, it is necessary to create a relevant database or to adapt an existing one which complies with the logical basements of our causal mode

5.2.6. Step 6 - Define the target node

Following the construction rule number 5 (Section 4.6) we propose, in our causal model, only one target node representing the probability of cost overruns (as a probability of risk occurrence). The target node should be explicit enough to be useful; it should have enough accuracy and precision. Defining the number of states of the target node is a choice that could increase the required calculations.

Figure 5.6 shows new layers in the model. The first new layer displays how each maturity criteria can be related to one or more drift factor, but each drift factor is related to only one maturity criteria. The last layer corresponds to the target node, for instance, the project cost overruns.

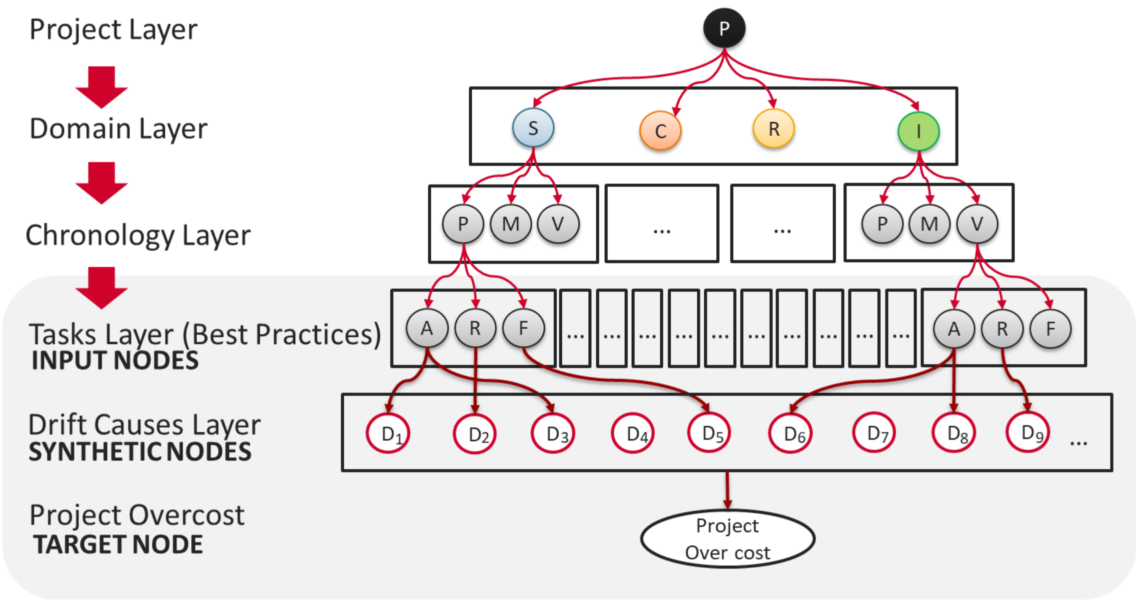


Figure 5.6. Full multilayers representation of the model.

5.2.7. Step 7 - Train and test the causal model.

It is necessary to define the joint probability distribution between the drift factors and the project operational performances' variables. This step implies the application of a BN-learning algorithm to projects' overcosts database, that is, to train the causal model. Then it should be tested with projects data not included in the training dataset. Finally, in order to verify the learning rate of the causal model, the accuracy of the test set should be checked.

5.3 Case Study: Evaluation of Drift Factors in Oil and Gas Offshore Projects

To evaluate the proposed methodology, an industrial data set captured from an oil and gas offshore projects has been used. In this case, 15 engineering projects that were lasting in a four-year period have been considered. Each one of them had a data repository containing the common causes of drifts. The data contained the detailed information regarding the causes of the drifts, such as the date, the amount of money loss, the main factors and some actions to correct them, or what should be done to avoid a repetition. In our work, we have discussed with the expert and this information was associated with IB2M proposed in chapter 2. The main purpose of presenting this case study is then not to propose a BN listing drift factors and their interdependencies applicable to any project closed to the cases (gas and oil projects). Each project and its relevant circumstances would drive the structure of the network (maybe with different drift factors) and different weights ($\boldsymbol{w_{ik}}$). We aim at demonstrating how practitioners can implement our proposed methodology and causal model.

Therefore, in this section, we will follow the methodology to build BN based on both expert knowledge and data from past project management maturity evaluation. After the development of the initial model, iterative analyses were conducted and various modifications were made to elaborate a causal model that best suits the collected data and supports the assumptions about the existence of a causality between process maturity and projects' cost overruns.

5.3.1. Step 1: Define a common model for Project Management Maturity Evaluation.

In this case study, we used an invariant-based PMMM model (IB2M). We adapted this descriptive model to the available information (experts' knowledge and data).

> **Review on the BN best eligibility criteria #1: Ensure the semantic consistency**
>
> As we have checked in chapter 2, the building of this model is based on best practices used in the project management community; moreover, as we showed, the experts accepted and utilized this model to evaluate project management maturity.

5.3.2. Step 2. Define how the input nodes will measure maturity.

In order to build the BN, we used a IB2M in which maturity levels correspond to input nodes with two states 'Yes' or 'No', respectively checking whether a practice is implemented or not.

Number of input nodes: This work tested several hyperparameters configurations: **(1)** Select four input nodes corresponding to each of the project management domain defined in IB2M, this selection was made as a first simplified approach of the network. **(2)** Select twelve input nodes corresponding to each one of the drift factors identified by experts, so the algorithms can create the relations between drift factors and projects' overcost. **(3)** Select 60 input nodes, that is 5 input nodes (5 maturity levels) for each drift factor (12).

Number of states in input nodes: This work tests **(1)** two states of the input nodes (Yes or No) indicating whether a practice was put in place or not, **(2)** five states for each input level; each state indicates the maturity level (one to five respectively).

5.3.3. Step 3. Define and classify the synthetic nodes.

Our inquiry concerns the analysis of significant drift factors that occurred in fifteen oil and gas offshore projects. Consultants who studied the reasons of common problems in Oil and Gas projects selected these causes. 720 events were then collected. Moreover, we interviewed six industrial experts. They were provided with a list of the main drift factors for the evaluated projects to check whether the causes were meaningful and consistent with the domain they belong. Since the evaluated projects belong to the same industry, they share specific drift factors. Our causal model has a limited number of drift factors empirically defined. Table 5.2 displays the most common drift factors in the studied projects. To confirm our research, this table also displays sources of PM literature where projects of the same field (Oil and Gas construction) experiment the same drift factors.

	Drift Factor	PM Literature source	Best practices (from chapter 2)
D_1	Not assigning the right Project Manager. S/He fails to bring all the team members together behind the project.	(Crawford, 2005; Jonas et al., 2013; Kopmann et al., 2017; Voss & Kock, 2013)	PM selection & Responsibility Matrix (RACI)
D_2	Lack of good communication inside the project team. The team members works in silos.	(Jonas et al., 2013; Kock, Heising, & Gemünden, 2016)	Communication plan
D_3	Requirements and contractual policy issues	(Ellis & Berry, 2013; Kock et al., 2016)	Requirement Analysis
D_4	No front risk Analysis & Contingency estimation	(Flyvbjerg, 2006, 2014)	Feasibility study & Contingency plans
D_5	Not being specific enough with scope	(Ansar, Flyvbjerg, Budzier, & Lunn, 2016)	Scope Statement
D_6	Not having a metric for detecting deviations	(Flyvbjerg, 2013)	Quality Plan
D_7	Reports doesn't reflect reality	(Dvir et al., 2003)	Control Charts (s-curve, Gantt, etc.)
D_8	Overoptimistic bias (time, cost)	(Flyvbjerg, 2006, 2014)	Baseline plan
D_9	Quality issues	(Flyvbjerg, 2013)	Quality Function Deployment
D_{10}	Not having a system that tracks changes from historical data	(Dvir et al., 2003) (Lipke, Zwikael, Henderson, & Anbari, 2009)	Database of historical data
D_{11}	Late delivery from suppliers/subcontractors	(Lipke et al., 2009)	(Late) Suppliers Evaluation
D_{12}	Lack of horizontal integration	(T. Cooke-Davies, 2002)	Horizontal Integration

Table 5.2 Drift Factors for selected Oil and Gas offshore projects.

In order to compare the characteristics of different projects, and to ensure consistency of the data, interviewed experts were requested to classify the drift factors in a proposed invariant matrix. The procedure is as follows: for two projects having similar problems or events for money losses, a common drift factor is assigned. Then, the selected drift factor is classified in one of the four domains (first layer). Afterwards, it is classified in a chronology (second layer). Finally, it is classified by the characteristics of the best practices (task layer). Figure 5.7 shows how we map the selected drift factors in the IB2M (Invariant-Based Maturity Model).. It should be noted that for this specific performance indicator, i.e. cost overrun, 11 maturity criteria out of 36 are concerned.

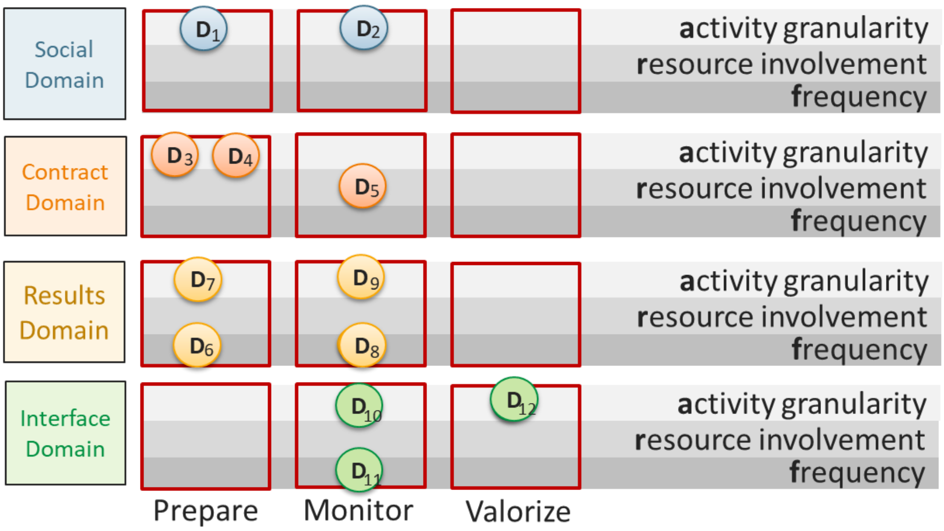


Figure 5.7. Drift Factors classification for oil and gas offshore projects

Number of Synthetic Nodes: The introduction of synthetic nodes as drift factors is a base of our modeling approach. We observed the difference in the quality of the output when **(1)** we did not use synthetic nodes **(2)** and when we used 12 synthetic nodes corresponding to the selected drift factors.

***Review on the BN best eligibility criteria #2: Adjust the completeness of the network**

In order to ensure that the proposed BN include all the most important drift factors that may occur in the projects, we have interviewed experts in Oil and Gas project recovery management. From each interview, we have extracted and collected the main drift factors. Finally, we have studied relevant scientific literature in project management, and we have linked the main sources to each drift factor as presented in Table 5.2.

5.3.4 Step 4: Define aggregation rules for synthetic nodes

To estimate the relationships between project management maturity levels and drift factors (w_{ik}), we define "aggregation weights". We assume that higher maturity levels imply lower drift occurrence. This assumption and the weights have been discussed with experts. They accepted this assumption and they determined the weights as shown in Table 5.3. This table displays how each maturity level contributes to the probability of not reaching a drift factor P(Drift= False) In this case, for the sake of simplicity, experts assumed that a given maturity level of all maturity criteria affects each drift factor equally.

Maturity Level	Cumulative probability of avoiding a drift if the maturity level is reached P(Drift) = False
Lv5	100%
Lv4	60%
Lv3	30%
Lv2	15%
Lv1	5%

Table 5.3 Maturity aggregation weights

The drift factor nodes have binary states: 'True (T)' or 'False (F)'. Once the experts chose the aggregation weights, we used equation (5.1) for the P (Drift = False) line of the CPT for each drift factor node.

Table 5.4 displays the result of this construction. Each maturity level has two states (Yes/No), the combination of them goes from all "No" to all "Yes". The line P(Drift = True) indicates the probability occurrence of the drift factor. Similarly, P(Drift = False) is its complement.

PR LV1	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
PR LV2	N	N	N	N	N	N	N	N	Y	Y	Y	Y	Y	Y	Y	Y	N	N	N	N	N	N	N	N	Y	Y	Y	Y	Y	Y	Y	Y
PR LV3	N	N	N	N	Y	Y	Y	Y	N	N	N	N	Y	Y	Y	Y	N	N	N	N	Y	Y	Y	Y	N	N	N	N	Y	Y	Y	Y
PR LV4	N	N	Y	Y	N	N	Y	Y	N	N	Y	Y	N	N	Y	Y	N	N	Y	Y	N	N	Y	Y	N	N	Y	Y	N	N	Y	Y
PR LV5	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y
P(Drift = T)	1	0.6	0.7	0.3	0.85	0.45	0.55	0.15	0.9	0.5	0.6	0.2	0.75	0.35	0.45	0.05	0.95	0.55	0.65	0.25	0.8	0.4	0.5	0.1	0.85	0.45	0.55	0.15	0.7	0.3	0.4	0
P(Drift = F)	0	0.4	0.3	0.7	0.15	0.55	0.45	0.85	0.1	0.5	0.4	0.8	0.25	0.65	0.55	0.95	0.05	0.45	0.35	0.75	0.2	0.6	0.5	0.9	0.15	0.55	0.45	0.85	0.3	0.7	0.6	1

Table 5.4 CPT for each drift factor node.

Drift factors selection is a process that may change according to the types of projects or to different contexts. In this case study, the evaluations of projects' operational performance (that is, cost overrun) concerned the same types of projects, in a similar period (within 4 consecutive years) and in the same region (similar political and economic characteristics).

5.3.5 Step 5: Select, clean, and structure the database.

The next step of our inquiry was to learn the effects of project management maturity levels on project overcost by extracting knowledge from the database. It is assumed that all drift factors converged to the target node (without any other intermediate node). The set of labeled projects is divided into training set (90% of the data set) and a test set (10% of the data set).

Data structuration: We adapted the database to obtain a table that adjusts to the BN and at the same time that uses sufficient lines to make the model reliable. We obtained the data as displayed in table 5.5. For each project, we had the amount of money that was lost due to specific problems. These data were unstructured and containing several errors; the first effort was to clean it.

		Date	**Description of the event**	**Total money loss**
Project 1	Problem 1			
	…			
	Problem n			
Project 2				
Project 3				
…				
Project 15				

Table 5.5 Raw data format

Then we had to convert problems into causes of recurring drifts in projects. This work was also done with the help of experts, who defined the recurring causes based on their understanding of the events' description in the database. Table 5.6 shows the structuration equivalent to our first data structuration: each cell displays the amount of money loss for each project (rows) due to each drift factor (columns).

		Drift Factor 1	Drift Factor 2	Drift Factor 3	...	Drift Factor 12	Total money loss
Project 1	Problem 1						
	Problem 2			Amount money loss due to Drift Factor 3 in Project 1			Total amount of money loss in Project 1 due to problem 2.
	Problem 3						
	...						
	Problem n						
Project 2							
Project 3							
...							
Project 15							

Table 5.6 Data including drift factors. Real losses by drift factor by project

Next, it is necessary to normalize the measures of the effects of the drift factors. Hence, we proposed to transform table 5.6 into another database where the measures are composed by the relative loss of money relative to each project regarding its **expenses**, that is, the **percentage** of loss due to each drift factor for each project, as shown in table 5.7. To make this calculation we divided each cell of table 5.6 into the expenses of the project.

		Drift Factor 1	Drift Factor 2	Drift Factor 3	...	Drift Factor 12	Total money loss / Project budget
Project 1	Problem 1						
	Problem 2			% of money loss due to Drift Factor 3 in Project 1			Total money loss / Project budget in Project 1 due to problem 2.
	Problem 3						
	...						
	Problem n						
Project 2							
Project 3							
...							
Project 15							

Table 5.7 Data including drift factors. Percentage losses by drift factor by project

Nevertheless, table 5.7 has not enough data to train a Bayesian algorithm. Hence, we applied another data configuration strategy consisting in separating the events by their dates and in segments of months and year. The database was reorganized as shown in table 5.8. In this table each cell summarizes the percentage of money lost by all the events of the given month (line) relating to the drift factors (column). This new table has 720 lines corresponding to 15 projects evaluated in 48 months.

			D1	Drift Factor 2	...	D12	Total money loss / Project budget
Project 1	**Year 1**	**Month 1**					
		Month 2		Occurrence (Y/N) of money lost due to Drift Factor 2 in Month 2, Year 1, Project 1			money loss / Project budget in Project 1 Year 1 Month 2
		...					
		Month 12					
	...						
	Year 4						
....							
Project 15							

Table 5.8 Final structured data format.

Once the database is ready, we defined the classes corresponding the four states of the target node. These classes are a discretization of the last column of the database.

5.3.6 Step 6: Define the target node.

In this sixth step of our methodology, we gave answers to these questions: How many states must have the target node? How can we ensure the accuracy of the target node's states? Is the quantity of states useful and understandable for the use of experts? Thus, we selected the number of states of the target node: the target node can have: **(1)** Two states showing the probability of occurrence of an overcost to be true, or to be false. Alternatively, **(2)** four states, giving better compromise of the criteria discussed in chapter 4 (section 4.5.3. see figures 4.10 and 4.11).

Number of states in the target node vs Precision.

We defined the number of states of the target node. To solve this problem, we use the algorithm of Gaussian mixture model (GMM) to determine the median and variation value of each state in the target node. The result is displayed in Table 5.9. This table shows that the best precision (lowest variation) is produced when the target node has either 2 or 4 states.

State of the Target Node	Mean	Variation
P(Overcost) = False	0,423	0,05123
P(Overcost) = True	0,565	0,07161
P(Overcost < 1%)	0,324	0,1543
P(1% ≤ Overcost < 10%)	0,409	0,1634
P(10% ≤ Overcost < 100%)	0,453	0,2124
P(Overcost ≥ 100%)	0,142	0,1377
P(Overcost < 1%)	0,2140	0,3231
P(1% ≤ Overcost < 20%)	0,2765	0,2421
P(10% ≤ Overcost < 40%)	0,3043	0,2756
P(1% ≤ Overcost < 60%)	0,3465	0,2675
P(10% ≤ Overcost < 80%)	0,3125	0,2958
P(Overcost ≥ 80%)	0,3316	0,3542

Table 5.9 Mean and Variation for three target nodes' configuration.

Number of states in the target node vs accuracy

Then, we evaluated the accuracy when clustering the database under several classes. We used two analytic criteria: Akaike's information criterion (AIC) (Akaike, 1974) and the Bayesian information criterion (BIC) (Schwarz, 1978) presented in section 4.5.2. These two criteria are very close and have a strong statistical basis (Vrieze, 2012). Figure 5.8 displays the result of the evaluated criteria for several numbers of states (two to nine). The best choice under these parameters is the one that minimizes both BIC and AIC values. These criteria point out that given the data in hand, four states in the target node maximizes calculations accuracy.

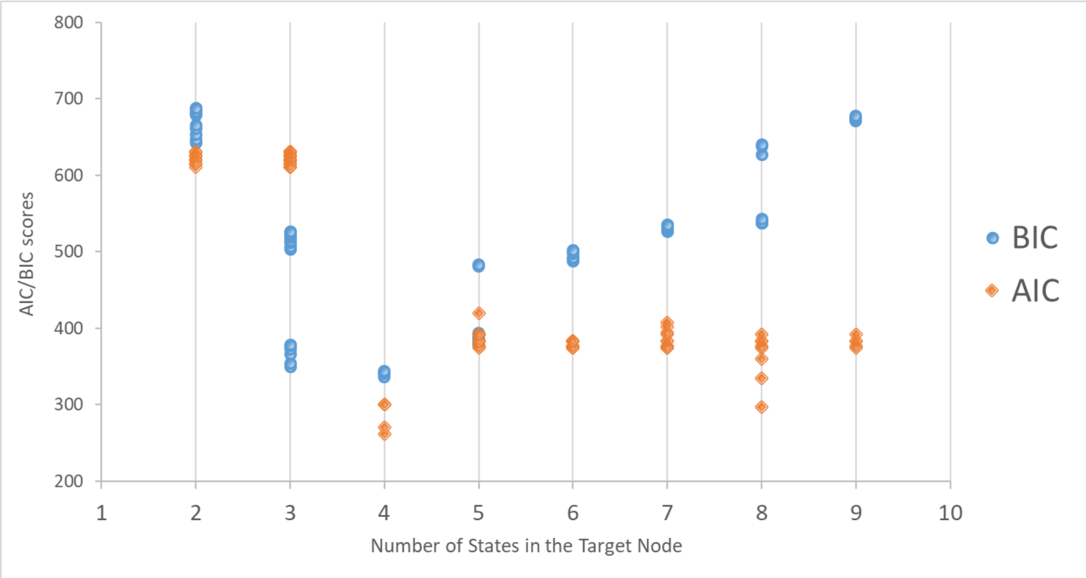


Figure 5.8. Different classes of the target node and their associated BIC and AIC values.

According to AIC and BIC criteria, the target node should have four states to represent four ranges of cost overruns in order to reach a good compromise between accuracy and precision.

- **P_1_ or P(Overcost) < 1% .** It is the probability of incurring in cost overrun equivalent to less than 1% of the total expenses.
- **P_1_10 or 1% ≤ P(Overcost) < 10% :** It is the probability of incurring in cost overrun between 1% and 10% of the total expenses.
- **P_1_100 or 10% ≤ P(Overcost) < 100% :** It is the probability of incurring in cost overrun between 10% and 100% of the total expenses.
- **P_100_ or P(Overcost) ≥ 100% :** It is the probability of incurring in cost overrun equivalent to more than 100% of the total expenses.

Given our database, we have chosen a base 10-logarithmic scale for two reasons. First, this selection generates ranges that can be useful for the experts. The target node presents four states, the first two *P(Overcost) < 1%* and *1% ≤ P(Overcost) < 10%* are considered by the experts as having a Negligible and Acceptable risk. The third level *10% ≤ P(Overcost) < 100%* is the "unknown area" (undesirable) where complexity of the project can produce a range of drift that is hard to predict exactly. And the four level *P(Overcost) ≥ 100%* defines a level of risk occurring when the project has so many weak points, that a significant drift impact (unacceptable) can be foreseeable. Second reason, it creates four classes with enough examples in each class to train algorithm efficiently (rule 5 chapter 4, section 4.7) as shown in Figure 5.9.

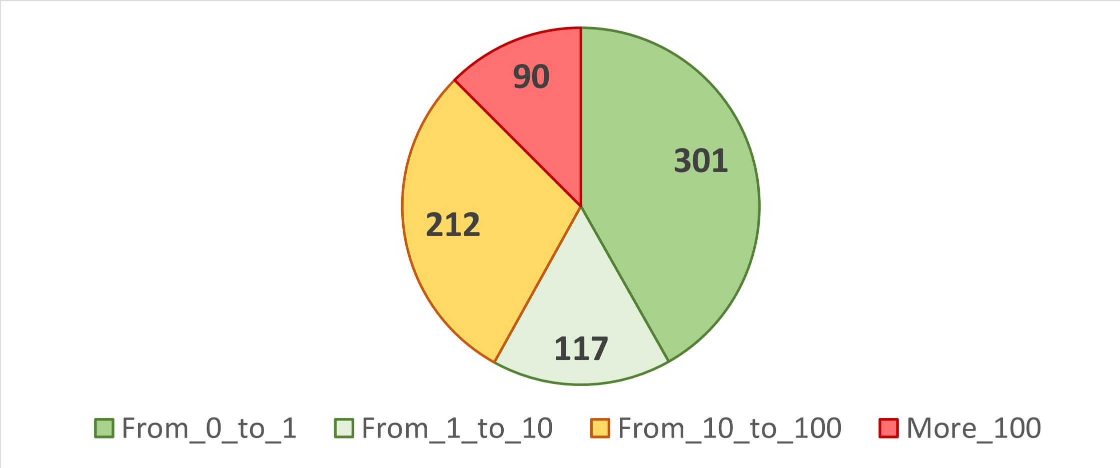


Figure 5.9 Distribution for four classes in the target node.

***Review on the BN best eligibility criteria #3: Guarantee the relevance of the result:**

The algorithm showed that the optimum value for the test was four states. (Figure 5.8). It showed fewer states could have a more precise value (less variation) but bad accuracy. Finally, a four-state selection provided the lower AIC/BIC values.

5.3.7 Step 7: Train and test the causal model.

We conducted several simulations until we got a good feature to train the algorithm. In each test, we modified the hyperparameters (number of input/output nodes, structure of the database, number of states of the synthetic nodes, number of states of the output node). We tried several simulations until we got a standardized and useful hyperparameters combination to train the algorithm. The values of the hyperparameters are summarized in table 5.10. We chose the structure of the database as shown in table 5.8. This database makes the algorithm learn the relationships between the drift factors and the percentage of cost overruns. It enables to build the CPT for the target node. Each column corresponds to a hyperparameter; each line displays the values that these hyperparameters can take. Different BNs can be built from the combination of the mentioned hyperparameters. In table 5.10, the green and underlined values indicate the hyperparameters combination we adopted in our model.

Number of Input nodes	Number of States in input nodes	Number of States of the Target Node	Number of Synthetic Nodes	Data Structuration
1) 4 Nodes (Project Domain) **2)**12 Nodes (Drift Factors) **3)** 60 Nodes (5 Maturity levels x 12 Drift Factors)	**1)** 2 States (Yes/No) **2)** 5 States (Maturity levels)	**1)** 2 States (True/False) **2)** 4 States (Logarithmic Levels)	**1)** 0 Nodes (No use) **2)** 12 Nodes (Drift Factors)	**1)** Real losses by drift factor by project **2)** Percentage loss by drift factor by project **3)** Percentage loss by drift factor by project each month

Table 5.10 Overview of the Hyperparameters, and their possible values.

***Review on the BN best eligibility criteria #4: Limit the explosion of combinations**

We realized that using five input nodes for each invariant could lead to an explosion of combinations in the CPTs (180 nodes pointing to one target node). We tested several hyperparameters to get an acceptable number of combinations. The use of synthetic nodes led to a reduction in the number of values in the CPT to be calculated (with synthetic nodes we got 12 nodes pointing to one target node). A learning algorithm calculated the relationships between the synthetic nodes and the target node CPT.

We applied the learning algorithm to the database. This algorithm generates $\theta = 16384$ values corresponding to the CPT of the target node (project overcost). The final model is created using GeNie software® (Druzdzel, 1999). Figure 5.10 displays it. The class of overcosts (target) node can be understood as follows:

- **P_1_:** The evaluated project has **0%** probability of incurring in an overcost equivalent to less than 1% of the expenses. That is P(Overcost) < 1% = 0.
- **P_1_10:** The evaluated project has **2%** probability of incurring in an overcost equivalent between 1% and 10% of the project's expenses. That is 1% ≤ P(Overcost) < 10% = 0.02.
- **P_1_100:** The evaluated project has **61%** probability of incurring in an overcost equivalent between 10% and 100% of the project's expenses. That is 10% ≤ P(Overcost) < 100% = 0.61
- **P_100_:** The evaluated project has **37%** probability of incurring in an overcost greater than 100% of the project's expenses. That is P(Overcost) ≥ 100% = 0.37

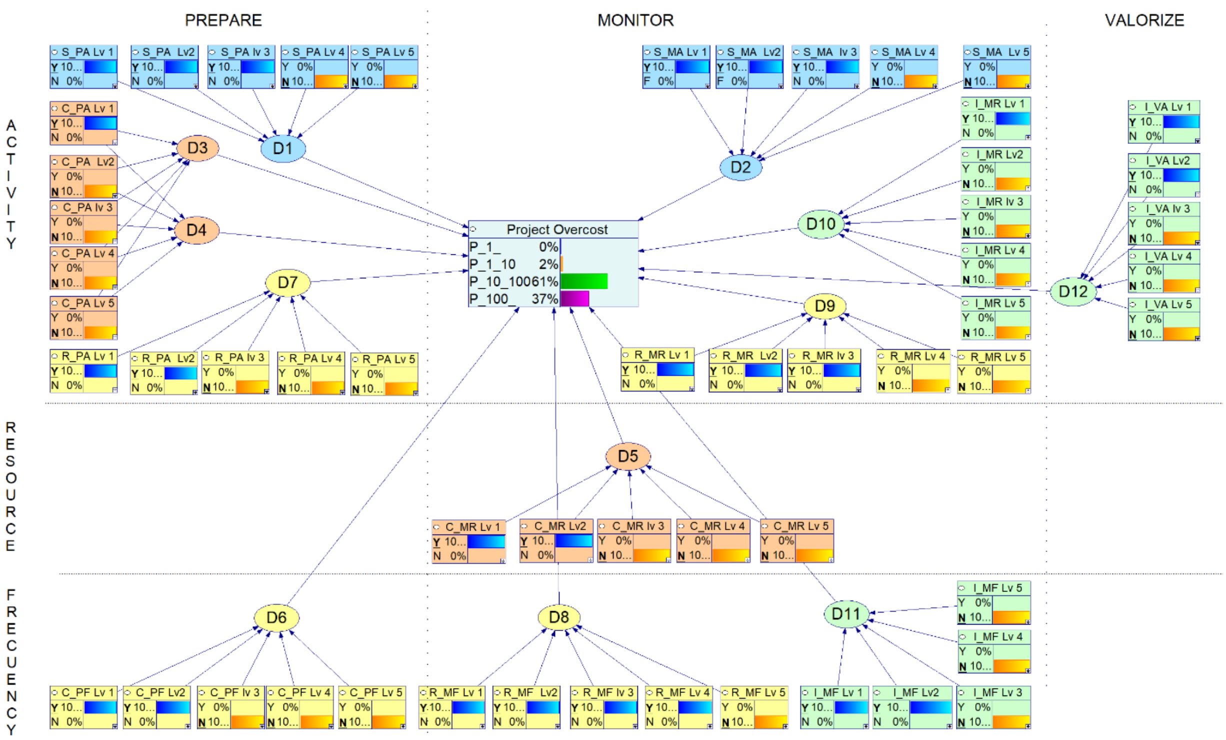


Figure 5.10. Project performance prediction BN model

Test of the model.

Then we tested the causal model with new data. We instantiated each maturity level with information corresponding to projects included in the project database, but not in the training data set. The corresponding overcosts for each state in the target node are registered. The accuracy is calculated for each state value. Figure 5.11 displays the results for this simulation. The relative error between the training data and the test data is inferior to 6%.

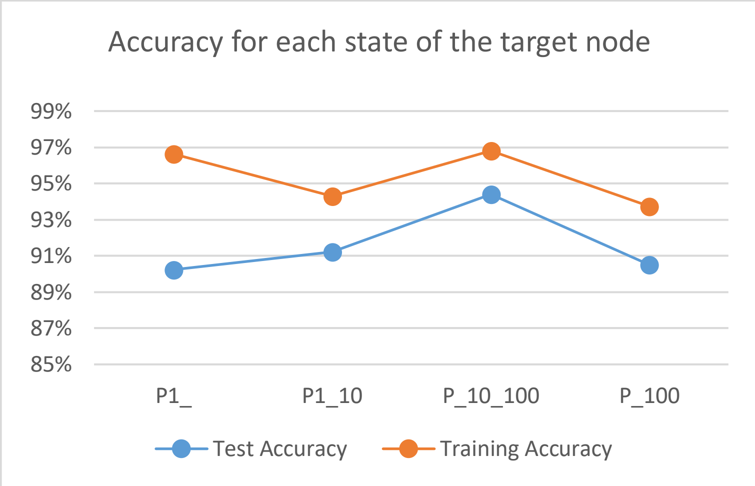


Figure 5.11. Maturity levels vs over cost probability.

Sensibility Analysis of the Methodology

We conducted computations with other parameters than those selected by experts in step 4. Remember that these parameters correspond to the probability of avoiding a drift if a maturity level is reached. Table 5.11 presents three value sets that we use to conduct the sensibility analysis. P_1 corresponds to the initial value set determined with expert knowledge. As we know that these values are approximate, we generate two other value sets with an inaccuracy of ±5%. P2 corresponds to a 5% decrease in the probability of a drift occurrence for each maturity level. In a similar way, P_3 corresponds to a 5% increase.

Maturity Level	P_1(Drift = False) Proposed	P_2(Drift = False) Proposed -5%	P_3(Drift= False) Proposed +5%
Lv5	100%	100%	100%
Lv4	60%	55%	65%
Lv3	30%	25%	35%
Lv2	15%	10%	20%
Lv1	5%	0%	10%

Table 5.11 Different probability distributions for the Drift factors

We conducted simulations with the same input parameters, varying the CPT of the drift nodes. The results are displayed in figure 5.12. This figure shows the probability distributions in the target node according to the three value sets (on table 5.11). As a result, we realized that the influence of this inaccuracy on the results is small (2%) when the changes are in the ± 5% range. This simulation shown how changes could affect the result, especially in the levels of lower overcost probability. This result depends on the probability of drift defined by experts on step 4. The result of the overall BN depends more on the links from drift factors to the target node.

Project Overcost probability distribution for P_1 *(proposed)*	Project Overcost probability distribution for P_2 *(Proposed - 5%)*	Project Overcost probability distribution for P_3 (Proposed + 5%)
P_1_ 9% P_1_10 9% P_10_100 35% P_100_ 48%	P_1_ 9% P_1_10 7% P_10_100 37% P_100_ 47%	P_1_ 8% P_1_10 9% P_10_100 34% P_100_ 49%

Figure 5.12 Results of the simulations

***Review on the BN best eligibility criteria #5: Quality of learning.**

To ensure the quality of learning we used one part of the dataset (10%) to test the behavior of the algorithm, as shown in Figure 5.11. The model shows accuracy over 90% in the test set for all states. The sensitivity analysis showed how changes made in the experts' estimation on the probability of drift occurrence could affect the result. A simulated error in the expert judgment of 5% could produce a change up to 2% in the states of the target node. Therefore, the quality of learning slightly depends on the definition of the probability of risk.

5.4 Improvement Scenarios

Similar to the exposition presented in chapter 3, we can develop some scenario to show how an organization can gain project management maturity. Additionally, we can define how these scenarios could be effective in terms of probabilities of project overcosts, helping to create an adequate improvement strategy and path.

This exploratory section presents some scenario and the consequence of them. Figure 5.13 displays one possible scenario where several practices are moving to an upper level of maturity. Starting from the "*Project Management Maturity Evaluation Output*" (level 1 - 3) and ending in the "*Proposed Scenario*" (levels 3 to 4). In this *"What happens if..."* case, the BN provides an estimation of the probability of projects' overcosts. If the result is acceptable for the decision-maker, he/she can select the scenario; else, s/he can use another scenario to check whether the new probability distribution fits better to its requirements.

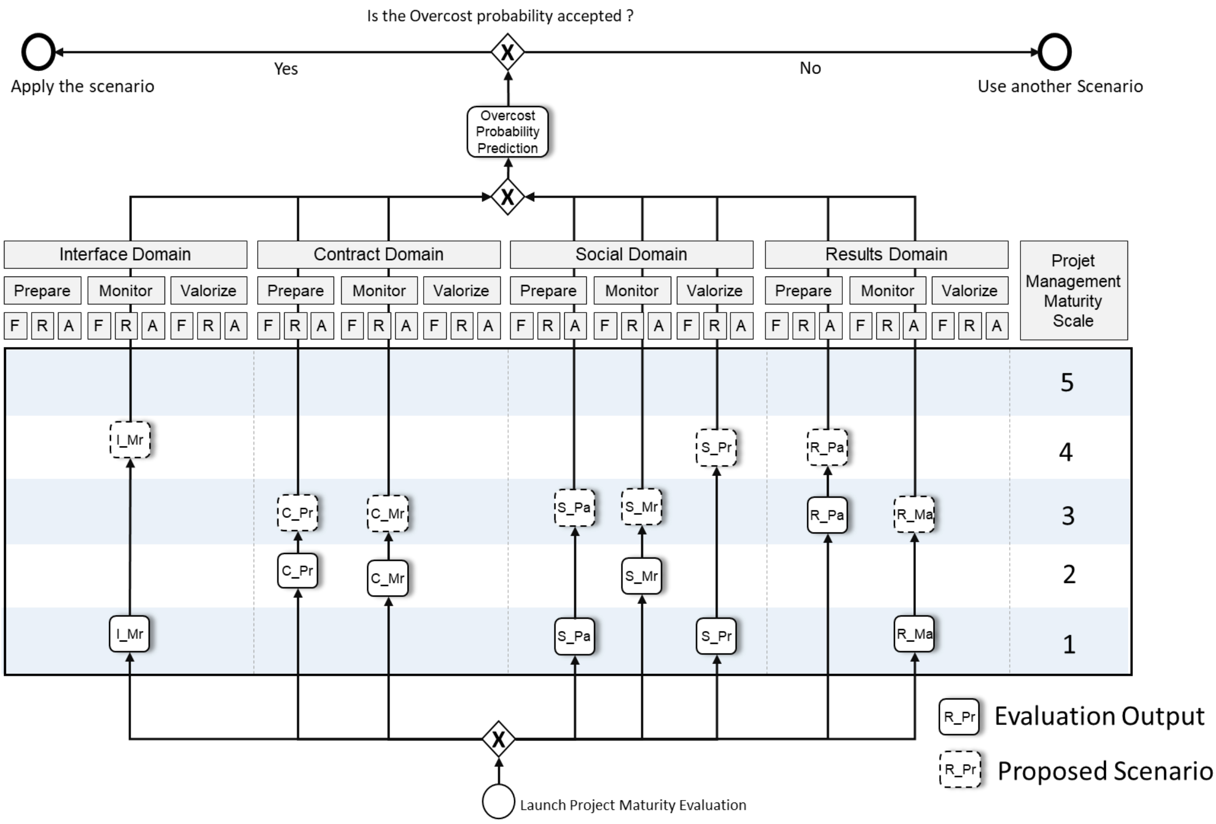


Figure 5.13 Scenarios for project management maturity improvement

Improvement Recommendations

Since there are many possible scenarios, we want to answer the question: how can the decision maker choose an appropriate scenario? As an example, we will use the result of the model in figure 5.10 because it shows an example of a maturity evaluation conducted in one of the projects of chapter 2. The recommendation should be expressed on those invariants where maturity is low, that is, the nodes having their evidence set as "No" in their input states. Nevertheless, we want to present a method for selecting the most influential nodes, with the intention of improving them as a priority.

First, we perform an analysis to detect which are the drift factors that have more influential in the causal network. This first analysis allows selecting which are the main causes of the problems for the specific evaluated project. Figure 5.14 displays the backpropagation analysis for the example. It shows that the nodes D1, D7, D8, D9 have a strong influence on the projects' overcosts. Therefore, the scenario of recommendations should be built using the maturity criteria associated to these nodes (S_Pa, R_Pa, I_Mr, R_Mf) because the decision maker can prioritize the work on the most influential nodes.

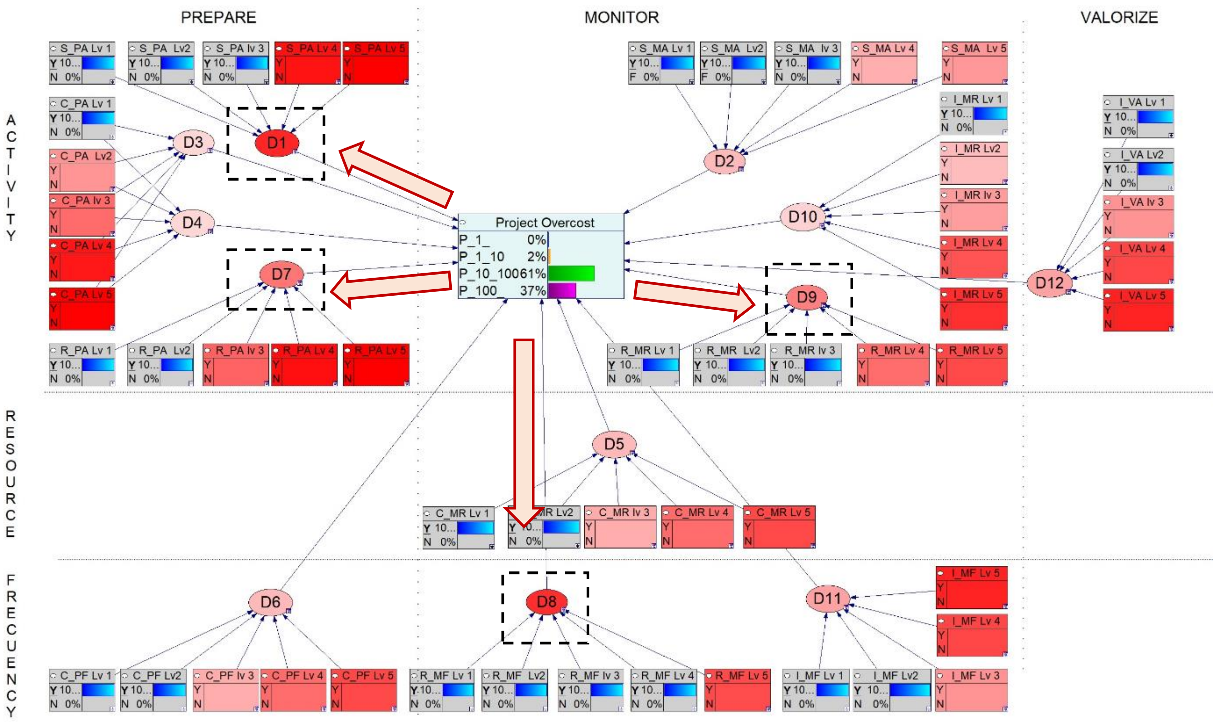


Figure 5.14. Backpropagation analysis for the given example.

Second, the decision maker simulates the assumption that new maturity levels for the selected maturity criteria are reached. Then running the new BN enables him/her to calculate how the new maturity levels would improve the probability distribution of projects' overcost. Figure 5.15 shows the results of this simulation. Changing the states of the nodes of the selected maturity criteria from "No" to "Yes" would produce a significant change in the project overcost node. The user can decide if this result is good enough, or if it needs to do another iteration on the process to get a better result.

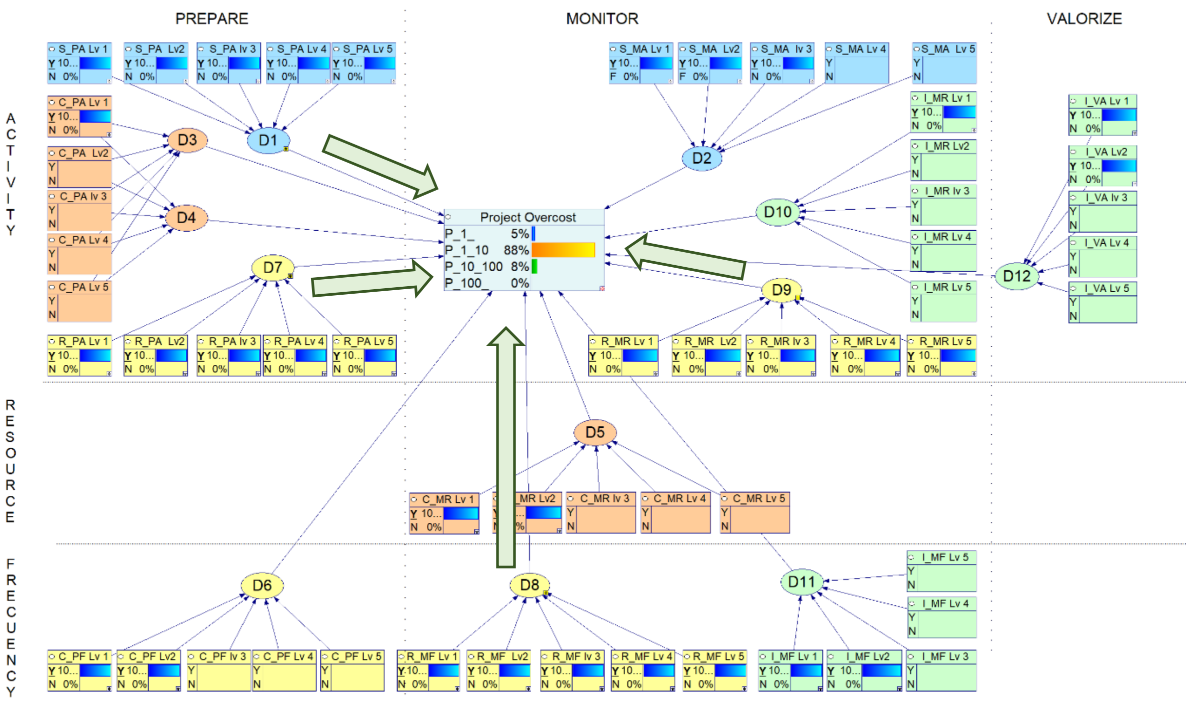


Figure 5.15. Performance prediction based on recommendations for the given example.

Figure 5.16 displays the summary of this scenario process. The first column shows the results of the probability of project overcost for each project before the simulation, that is, the baseline project management maturity evaluation. The second column proposes the main recommendations, these proposals are written as improvements in the maturity criteria, and each change supposes a series of actions to put into practice. The third column shows the result of the simulation after applying these recommendations.

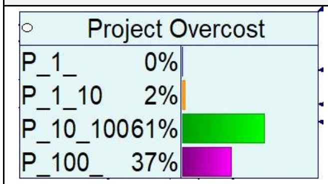
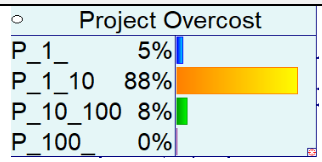
Result of the Project Management Maturity Audit	Recommendations	New result of the simulation after applying the recommendations
	Improve **S_Pa** from 3 to 5. Improve **R_Pa** from 2 to 5. Improve **R_Mr** from 3 to 5. Improve **R_Mf** from 4 to 5	

Figure 5.16 Simulation results for an improvement scenarios

Since recommendations are coherent with IB2M, they should be translated into best practices defined in chapter 2. Of course, these recommendations are not exhaustive and some of them can be out of the scope. Experts adapt them to the context of the projects and support them with other actions he/she judges necessary.

We can interpret the recommendation in Figure 5.16 as follows:

S_Pa from Level 3 to 5: Improving the social/planning activities such as the resource scheduling, from the use in one project to the use in the whole organization.

R_Pa from Level 2 to 5: Improving cost and time activities used in the planning of the project (*task scheduling, cost/benefit analysis, cost estimating, top/down estimating, etc.*) from the defined level (knowing they exist and sometimes using it) to the extent use in the whole organization.

R_Mr from Level 3 to 5: Improving cost and time monitoring tools used in the control of the project (*Control charts such as Gantt, S-curve, Cause-and-effect diagram*, etc.) from the use in a single project to the extent use in the whole organization.

R_Mf from Level 4 to 5: Improving the frequency of the use in the monitoring tools (present above) to the whole organization, for example, by improving the baseline plan.

Limits of the Causal Model

Project organizations call for project management experts when their projects fail. Experts' missions are usually focused on solving these ongoing problems, and in the best case, to avoid future drifts. Experts have built a database from the feedback of several missions, all of them sharing the same structure described before. As a result, the database contains only the causes of drift and consequences of them in terms of expenses or costs. Building a causal model with these data has several restrictions:

(1) First, if experts improve project management maturity to their maximum level, the probability of overcost will reduce to the range of 0-1% expenses overruns only. One excludes any possibility (that could occur in the real world) where several actions can cause a significant saving on time or money. In other words, "*a negative drift*" is not possible to achieve based on the current database. As a consequence, the proposed model is limited to avoid drift, or to reduce them to the minimum rank of probabilities i.e. $0\% \leq P(\text{Overcost}) < 1\%$.
(2) Second, this proposed causal model was built on data of a specific type of projects. The generalization of causality, scenario or improvement recommendations is limited by the database used to build it, and by the expert knowledge referring to the specific kinds of projects. It is meaningless to evaluate project management maturity from another economic sector (as test data) in order to predict future performance. The model is also bounded to the current type of training data.
(3) Third, the probability class $10\% \leq P(\text{Overcost}) < 100\%$ may appear too large. However, given the limited amount of data, our causal model cannot offer more granularity. As shown in chapter 4, when a model included more than four states of the target node, accuracy and precision severely decrease. Remember that this database corresponds to experts' missions that aimed to improve projects that coped with problems in their operational performance due to the occurrence of many drifts. That explains that the range $P(\text{Overcost}) > 100\%$ exists and then the frequency of each class is about the same.

5.5 Discussion

Literature lacks models explaining on empirical evidences the causality between project management maturity and projects' operational performances (Dvir et al., 2003; Ko & Cheng, 2007; Lahrmann et al., 2011; Wang et al., 2012). In this chapter, we have used BN to combine causal analysis and correlation to propose a more elaborated causal model. Nevertheless, we have focused on one operational performance, which is cost overruns. To achieve this goal, we simplified and restructured in a tree feature our IB2M proposed in chapter 2 because it has too many variables. We also used incomplete data, experts' knowledge and then BN as modeling and machine learning technique. We introduced the concept of synthetic nodes to reduce the complexity of the causal network and to allow better learning of CPTs with a small project database (720 events). We have combined values learned from historical project data with a causal structure provided by experts. The tool was tested and it demonstrated good accuracy (Figure 5.11).

However, we have shown that we cannot include an additional state meaning a "*negative drift*". In a project, it is possible that some actions may fortunately increase the project margin. The proposed model did not include any range of possibilities where project management practices may lead to gains in costs. In addition, our test scenario was limited to oil and gas offshore projects. Further research should be done in projects of different natures, with new drift factors and including other experts.

5.6. Conclusion

This research has developed a rigorous method for building effective BN for project management evaluation support. We have illustrated the application of the causal proposed model through an industrial case study related to heavyweight projects in oil or gas sectors. We have modeled the causal relationship between project management maturity levels and the probability of project overcost with a specific Bayesian Networks (BN). This network can be used to facilitate consultants' improvement recommendations. Aside from black box type models, our proposal allows the users to interact with the nodes, to understand the structure of the causal network, and to choose which best practices may be required to improve the project performance, according to the circumstance of the project.

We have presented how the proposed model meets the criteria of construction. Additionally, based on this model, we have shown how it is possible to establish scenarios of improvement in section 5.4. This work will help the experts to predict the risk of project overcost according to the level of maturity measured in the project. Our tools can assist the project management consultant to select the most appropriate project management improvement strategy (which best practices need to be implemented) and predict their probable impact on projects' operational performance.

We have shown that the underlying premise of our research is true: it was possible to build a system based on the evaluation of project management maturity criteria capable of predicting projects' operational performance. Further research should be led in projects of different natures, with new drift factors and including other experts.

CHAPTER 6

6 General Conclusion & Perspectives

About this chapter: This last chapter will sum up our contributions and present some perspectives about the development of the models and methods proposed in the previous chapters. Since projects increase in complexity over time and depend on their changing environment, we will suggest to continue our research by taking into account other variables that are necessary when dealing with complex projects. We will be to explain how our Invariant-Based Maturity Model (IB2M) and our Bayesian Networks (BN) building methodology can be used in an extensive way, *e.g*. evaluation of the complexity and the strategic importance of one or several project(s) under study.

6.1. Thesis Abstract

Our research work defined a methodology to create the architecture of a project performance prediction system based on the evaluation of project management maturity criteria. This system was based on the formalization of feedbacks from Sopra Steria consulting missions and project management literature.

Thus, our first task was to make our ideas clear about project management. As presented in the second chapter, project management maturity models (PMMM) are considered as models for assessing organization's project management competencies, then designing and implementing plans that may improve of these competencies, and thus, projects' operational performances. Literature in the field of Project Management (PM) displays several examples of companies applying PMMMs to improve their business (Christoph Albrecht & Spang, 2014). If these models have value, however, they are not based on clear conceptual backgrounds. Thus, there is no real consensus about the vocabulary, the categories, and the best practices in process evaluation. Moreover, authors multiply instances, making then their maturity models less clear. These limitations led us to a proposal standardizing some project categories included in an abstract descriptive model called Invariant-Based Maturity Model (IB2M).

In chapter three, we have tested the robustness of IB2M by verifying its ability to model the universe of Traditional Project Management (TPM) and the domain of Agile Project Management (APM). Despite several differences, PMMMs share a common assumption: gains in maturity of planned processes (TPM) or agile management processes (APM) improve projects' operational performances, *e.g*. deadlines compliance and no cost overrun (Christoph Albrecht & Spang, 2014; Jugdev & Thomas, 2002). Finally, in dynamic terms, PMMMs can be used to implement and monitor agilification, *i.e.* an organizational process by which APM tends to be routinized.

The two other chapters elaborated a causal model proving if there is (or not) a strong causal relationship between project management maturity and cost overrun. The universe of project management combining experts' knowledge or beliefs and partial and dynamic data, we have used a Bayesian approach to cope with our modeling problem. We selected an appropriate modeling technique using experts' knowledge and data collected from past project management maturity evaluation and we established the parameters for ensuring the quality of the causal modeling. Our results showed that process maturity significantly drives the risk of cost overrun. This interesting result must be relativized; The data we used concerning project management maturity evaluations only concern a certain type of projects, *e.g.* heavyweight projects in oil and gas sector in our case. Moreover, other causes that can be contextual can explain past projects' successes or failures.

The main contributions of this PhD thesis will be summarized in the next section.

6.2. Our Contributions in a nutshell

Chapter 2: This chapter proposed three criteria for evaluating maturity models: number of questions, consistency of theoretical framework, and use by auditors. Since most of the existing models did not respond adequately to these criteria (Albrecht & Spang, 2016; Ramirez, 2009; Torres, 2014; Vergopia, 2008) the study proposed a methodology to define a new project management maturity model based on the notion of invariants, that is, those characteristics that are transverse to different types of project management. Our proposal, called IB2M, simplifies project management maturity conceptualization, evaluation and audit. Our modeling work was complemented by the inclusion in IB2M of the 70 best practices in project management found in the literature (Besner & Hobbs, 2008, 2012; Fernandes et al., 2013b; Fortune & White, 2006; Fortune et al., 2011; White & Fortune, 2001), and series of interviews with consulting experts in large projects management. In addition, this second chapter presented a case study where IB2M was applied to series of industrial construction projects. Both the interviews and the case study validated the proposed conceptual framework**.**

The contributions of this chapter were submitted as paper called "*A step towards an invariant-based maturity model for assessment of project management practices. Conceptual foundations and industrial assessment"* in the *International Journal of Information Systems and Project Management* in March 2019.

Chapter 3: as mentioned, existing PMMMs belong to the universe of Traditional Project Management (TPM). We applied IB2M to other project management methodologies, more precisely Agile Project Management (APM). In order to solve this question, we investigated TPM principles and compared them with APM backgrounds. We found that it is possible to adapt IB2M to evaluate both maturity in TPM and APM, despite the difference of the nature of the process to assess. We have also defined a process stated in the literature, but not conceptualized, which is agilification. In addition, we proposed three tools, derived from

IB2M, that monitor the smooth transition between TPM and APM. Once again, we applied our proposal to an industrial project.

The contribution of this second chapter was published in a paper called "*A Step for Improving The Transition Between Traditional Project Management to Agile Project Management Using a Project Management Maturity Model.*" In the Journal of Modern Project Management, in April 2019. (Sanchez et al. 2019a). We also published an paper called "*Adapting project management maturity models for the Industry 4.0*" for the PMI Netherlands chapter conference in DELF "*project management adapt or die*", in April 2019. (Sanchez et al. 2019b).

Chapter 4: This fourth chapter presented a state of the art of Artificial Intelligence (AI) and Machine Learning (ML) techniques mentioned in project management to build causal models between causes of project failure and projects' operational performances, *e.g.* lead time, cost, quality, etc. Bayesian Networks (BN) were chosen because of their ability to integrate experts' knowledge and beliefs into predictions and to reduce the amount of data needed to feed ML algorithms (Neil et al., 2000). We explained (made explicit) the relevant parameters to take into account when building BN and the ideal causal structure by synthetizing literature. In addition, we defined requirements to evaluate BNs' eligibility. We then analyzed the causal value of the BNs proposed in project management literature (Constantinou et al., 2016; Fenton & Neil, 2013; Sun & Shenoy, 2007). We found that none of them completely met the requirements defined above. Thus, we presented the lines of improvement that we put into practice in the fifth chapter.

The contributions of the fourth chapter were published in IEEE KARE conference "Use of Bayesian Network characteristics to link project management maturity and risk of project overcost", in September 2018. (Sanchez et al. 2018).

Chapter 5: We proposed in this fifth chapter a BN-based methodology for the construction of causal models mapping project management process maturity and one particular projects' operational performance, which is the risk of costs overrun. In this domain, consultants' knowledge, experience, expertise, etc., has a great value. Indeed, they are requested to solve specific problems when their clients have troubles with their large projects management practices. Consultants are then focused on dysfunction points, failures, and they implement curative or preventive actions before facing harmful consequences. Therefore, experts know how to find projects' failure causes (we called them drift factors), and what is the causal relation between project management maturity and the probability of occurrence of these drift factors. The way experts reason refers then to the Bayesian framework of reference. Consequently, we asked experts what are the causal relationships between best practices and project management drift factors, rather than to ask directly the relationships between best practices and projects' operational performances. We tested our causal modeling methodology for a group of offshore Oil and Gas (O&G) projects. The causal model derived met the eligibility requirements defined in the fourth chapter. In addition, the fifth chapter demonstrated how the causal model created can be used to choose which project management practices (defined from the best practices in chapter 2) should be improved in priority in order to reduce the probability of incurring in large cost overruns.

The contributions of this fifth chapter were submitted as a paper called "Learning to predict the risk of project over cost from project management maturity using Bayesian networks." In the *Artificial Intelligence for Engineering Design, Analysis and Manufacturing Journal*. This proposal is under review.

We can now present some perspectives derived from our research.

6.3. Research perspectives

In this section, we will present the perspectives for each chapter (for each research goal we addressed in this thesis) following the framework proposed in introduction, which is based two levels of analysis: abstract level *vs.* specific level. Thus, Table 6.1 mirrors table 1.1

Chapter	Goal	Abstract Level Perspectives	Specific Level Perspectives
2	Propose a general PMMM to evaluate project management maturity.	Create an invariant based project management maturity model from building blocks	Instantiate the model to projects from different activity sectors (more than energy)
3	Apply the proposed model in projects of the specific industrial environment	Improve the definition of agility for example by creating criteria to define when a project is agile.	Test the model on more projects from Industry 4.0. Look for the possible "drift factors" of agile projects.
4	Evaluate several AI techniques that could explain causal relationships within PM	Formalize explicit rules to create BN architectures. These rules can help to transform descriptive graphs into BN.	Evaluate the possibility to create a hybrid model from different AI techniques. Such as a Bayesian Deep Learning (Gal, 2016)
5	Evaluate specific projects where project management maturity can explain project performance	**Develop a more complete causal model that includes the automation of data gathered based on traces of the project**	**Include more components to our proposed BN, such as the strategic importance of the project, its complexity, and its impacts on the core competencies**

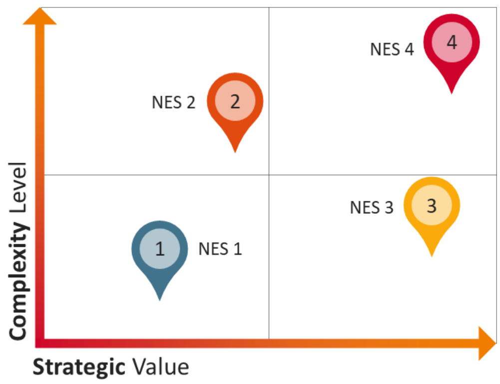
Table 6.1 Perspectives by chapter

Since the model presented in chapter five synthetizes all the knowledge developed in this work, we are developing more in detail the last two contributions.

6.2.1. Project organization as a system placed in its environment.

Theorists in project management recognize that different types, methodologies, versions, modalities, etc., of project management are required in different circumstances, according to organizational cultures, industry sector, organizations' size (Sanchez, Terlizzi, & de Moraes, 2017), etc. They also state that projects complexity increases, making difficult, and even impossible, to determine and plan which the effects of the problems occurring in projects are (Xia & Chan, 2012). Therefore, project complexity has become an issue, which needs to be considered at organizational levels (Aubry, Hobbs, & Thuillier, 2008; Brennan, 2011). For instance, authors propose that there is a need to adapt the concept of maturity to the complexity of the project. They suggest that projects that are more complex may need more maturity in project management in order to satisfy requirements. For this reason, this section aims to expand the scope of our causal model proposed in chapter 5 to take into account a new cause, which is the complexity the project to assess, its strategic importance, and the context where it is developed. All these characteristics could be synthetized and evaluated as a NES metric (coming for the French: ***N****iveau d' **E**xposition **S**tratégique*)

We define two axes displaying complexity level vs. strategic value of the project to evaluate. Then we define the "NES" of the project as a variable characterizing the complexity of the project to assess, and its relative importance it has for the organization. Hereafter, we define NES as a combination of two main variables: complexity of the project, and strategic importance of the project in its environment. In order to simplify the explanations, we define four NES quadrants and scale (figure 6.1)



	Complexity	Strategic Value
NES 1	Low	Low
NES 2	Low	High
NES 3	High	Low
NES 4	High	High

Figure 6.1. NES Quadrants and scale

Complexity Analysis

Sopra Steria consultants take into account several criteria to assess project complexity, a feature related to the fact that projects are "*composed of many interconnected parts and characterized by a very complicate or involved arrangement of parts units*" (Oxford Online dictionary). Complexity refers then to a thing with many interrelated entities, explaining why building a causal model is very difficult, or even impossible.

Complexity sciences (CSs) cope with this challenge in general terms. They describe complexity as emergent behaviors of a system that are created from a high number of nonlinear and temporary-dynamic relationships occurring between several components (Johnson, 2010;

Mitchell, 2009). CSs provide concepts, theories, *e.g.* Chaos, modeling techniques, software applications, etc., simulating and displaying self-organization phenomena.

In the field of project management, complexity is conceived in a narrower way. Authors proposed several complexity indicators, *e.g.* projects' scale, uncertainty, the quantity and variety of variables influencing the condition of the projects (T. Cooke-Davies, Cicmil, Crawford, & Richardson, 2008; He, Luo, Hu, & Albert P.C. Chan, 2015; L.-A. Vidal & Marle, 2008), etc. However, the aspects of complexity they presented do not take into account the dynamic feature of the projects. We have then a complexity without dynamics, which is not relevant for CSs' point of view. Nevertheless, some authors mention emerging projects occurring in organizational changes (McKenna & Baume, 2015) or the idea that a project is a complex phenomenon because in a given sectorial, cultural, organizational, etc., environment and set of constraints, its internal structure evolves (L.-A. Vidal & Marle, 2008). To sum up, the main criteria based in the study of complexity in project management literature are the next four factors.

Project size	the number of variables of the project, stakeholders, end users, etc.
Project diversity	the variety (of range of change) of those variables.
Emerging relationships	the relationships created between stakeholders
Complexity of the solution	from the technical point of view (engineering problem)

Table 6.2 Proposed Complexity criteria

Strategy Analysis

The strategic importance of the project for the organization is easier to define and to measure than complexity. The main criteria based in the study of strategic value in project management literature are the next four factors; the list of criteria and sub criteria can be found in annexes.

Financial Impact for the organization	The cost of the project, revenue, value creation.
Integration (Alignment) within the organization.	The relative importance of the project compared to other projects or portfolios.
External factors alignment.	The importance of the project regarding external factors.
Destabilization potential	The risk of changing the structure of the organization.

Table 6.3 Strategic criteria

This partition would permit to build an evaluation framework, including the complexity and environmental factors of projects.

Proposed Bayesian Network Model

A full version of the proposed model is sketched in figure 6.2, which has three modeling blocks: core capabilities, NES and project performance as defined in our research (maturity, projects' operational performances).

The first block (red square) was studied within this research. It is a BN sub-model displaying project management maturity evaluations. For example, in our model proposed in chapter 5, this evaluation was characterized by several input nodes, and each one has two states representing whether a best practice (defined in chapter 2) has been implemented or not. Additionally, synthetic nodes represent the drift causes and the target node represents the probability of occurring cost overruns.

The second block packages NES concepts presented above. There would be a NES node with four states, each one representing a quadrant of the figure 6.1. The 'Strategic implication' node and the 'complexity of project' node are parents of NES node. Each of those nodes has several parents depending on the criteria defined before; they could have more parents depending on the sub criteria defined in the tables of annexes.

Third, within our research proposal, we were assuming that core capabilities do not influence projects' operational performance. Hence, a wider evaluation must take into account this key element.

The final target node is the projects' operational performance, which could be evaluated as a delta performance related to the expected output of the project. That performance can be described for example in gain/loss of cost, quality, lead time, etc.

We tried to model the NES as a BN. However, we have found that the amount of available data was limited regarding all the criteria needed to be consider. The causal model proposed below supposes then an amount of data which is bigger to the one required in chapter 5. This issue is not so easy to manage.

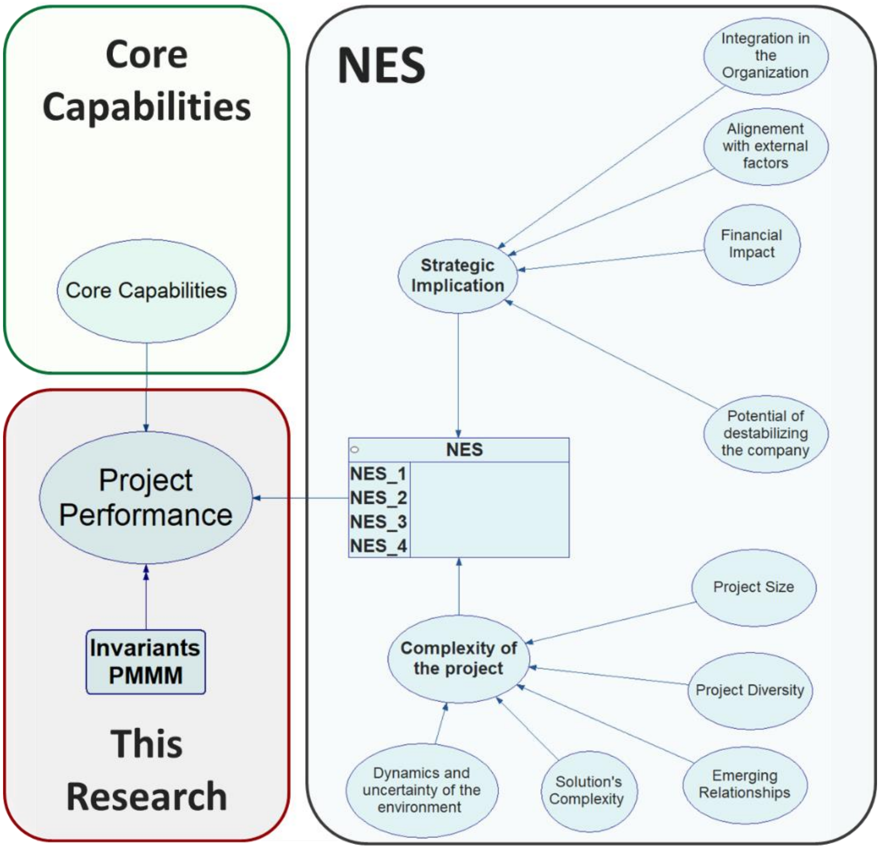


Figure 6.2 Perspective for an extended BN explaining projects' operational performances.

6.2.2 Evaluating project management maturity from traces

In our thesis, data, AI and ML were only used to build a causal model. However, we may expect that with the support of automated tools, auditors would not be required to check detailed data related to project management practices. Instead, algorithms should be able to gather and analyze project monitoring data, assess the mastering of each practice and compute maturity levels. Therefore, our proposed IB2M is no longer a 'pure' conceptual model, but a computerized model, as underlines Akoum (2014): *"it is possible to construct the operational process, implemented during the collaborative activities in a product development study, from the traces recorded by the used IT tools. The constructed operational process allows the business actors and experts to step back on their work and formalize the new deducted experience to enhance the expertise business processes."*. Those detailed traces can be evaluated in our IB2M (Chapter 2 and 3) in order to feed a database where the appropriate AI technique (chapter 4) would be applied, giving recommendations to auditors (chapter 5). These recommendations can be re-incorporated in the trace-based systems.

In this thesis, experts have confirmed the causal relationships between project management maturity and projects' operational performance. In order to confirm this hypothesis with more data, we are proposing a model capable of capturing data from project management traces (Figure 6.3).

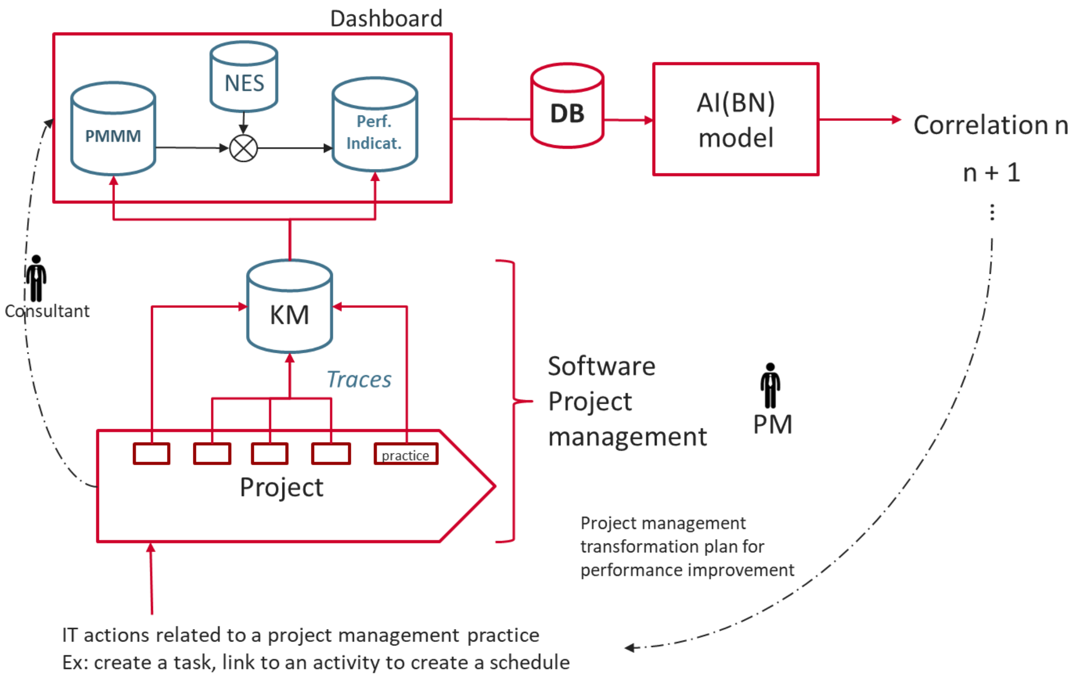


Figure 6.3 Full model, evaluating PMMM from traces

We also propose to use the system defined in Figure 6.3 to evaluate projects where experts can put into practice improvements, and then they can create new databases displaying the real consequences of those improvement actions (*shown in the figure as Correlation n, then step n+1*). To conclude, we are aware that our thesis is just a step for promising future researches making model-based project management a reality.

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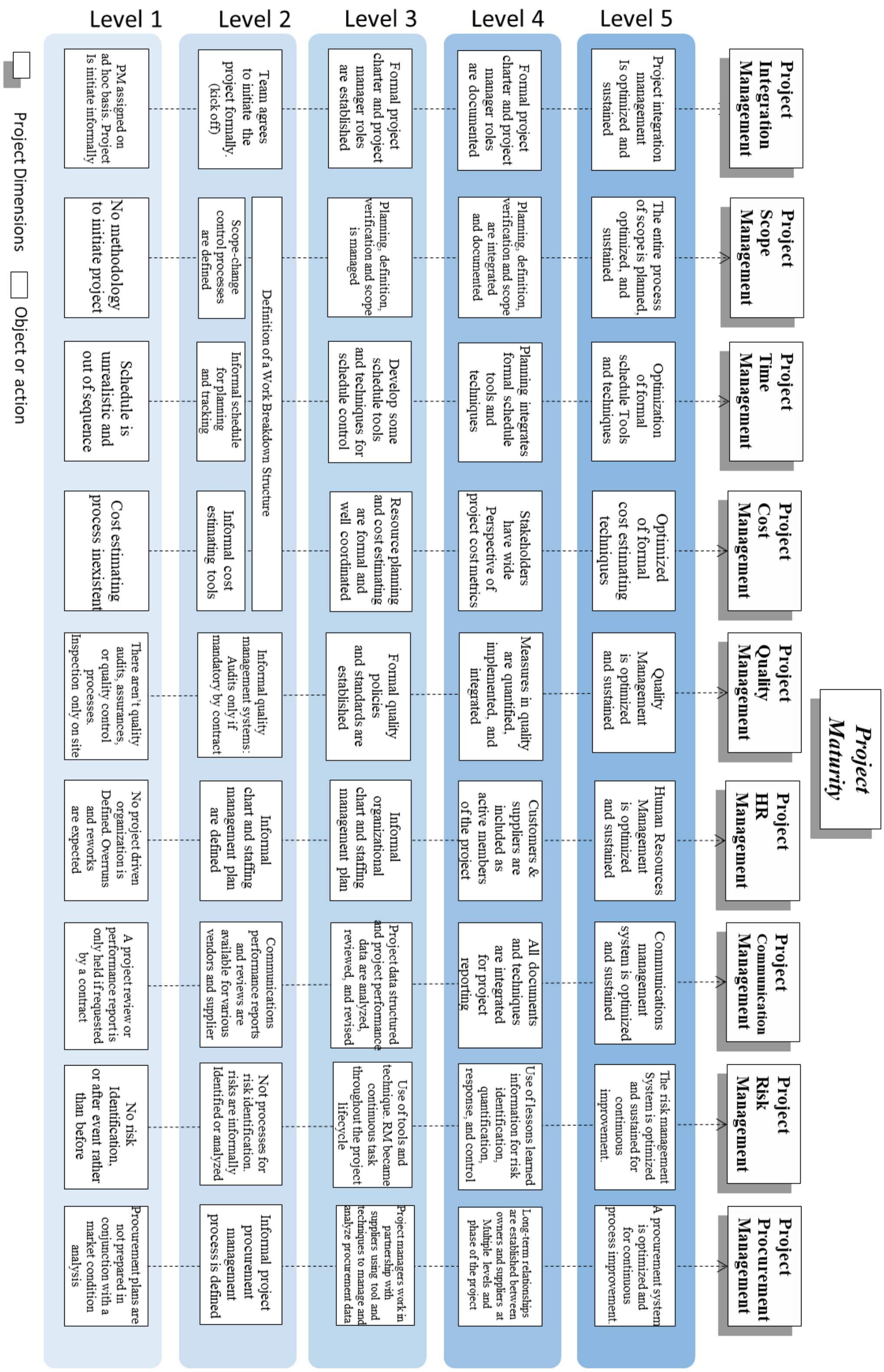
8 Annexes

ANNEX 1. (From CHAPTER 2) Example of a Project management maturity grid based on the Berkeley maturity model. (Author creation)



ANNEX 2 (From CHAPTER 3): Project Objects And Characteristics Comparation By Domain For Each Invariant

SOCIAL DOMAIN: *Integration (INT), Human Resources (HR), Communication (COM)*

SOCIAL DOMAIN		
	Classic	**Agile**
Preparation	**Roles**: Responsibility and Authority description for each author. Hierarchical-type charts, matrix-based charts. Use of the Organization Breakdown Structure (**OBS**)	Core **Roles**: Product Owner, Scrum Master, Team. Non-core roles: Chief Scrum Master, stakeholders (customers, users, and sponsors), vendors.
	Hierarchical and one directional communication	Communication are implicit in the system within share sites (Kanban & tableau de board)
Control and Follow	Follow and control documents. The work is more reactive than proactive. If something should change, it follows an exhaustion process: identify the change, discuss solution alternatives, call control change committee, follow workflow to change approval and make change baseline	Changes are smooth. Systems are adaptive and new request becomes changes added to the backlog. Then the team will upload the changes into the projects. The whole **system is adaptive and highly reactive**; the final objective is the customer satisfaction. A change request from the customer takes between 2 and 4 weeks to be taken account.
	Hierarchical control of teamwork.	The control follows customers' satisfaction and it should adapt to changes in request (or needs). In sprint, the team expect changes from the customer and accept changes in the workflow. The team uses new changes to add value in each iteration. The team is self-manage. The leader checks if the process is working in the daily scrum. **Serious games** are used to incentive collaboration
	Most of the Project Manager work is communication on what each actor must do.	The key roles communicate first what add more value. The team uses visual and horizontal communication in a share space community. The team is reactive to communication: They uses techniques such as **Daily scrum** where continuous communication can be used to make small improvements to the process.
Share and Valuation	Pmbok® request to create several deliverables.	Several iterations are done to assure the customer satisfaction: The customer changes their goal towards what he needs in each iteration, when the product full satisfy the customer the project is close.

CONTRACT DOMAIN: *Risk (RIS) & Scope (SCO)*

Contract Domain		
	Classic	**Agile**
Preparation	Create a **Project Charter** to define the Project purpose and justification, including: • Measurable project objectives and related success criteria, • High-level requirements, • Assumptions and constraints, • High-level project description and boundaries, • High-level risks, • Summary milestone schedule, • Project approval requirements	Do a **Business justification** based on the concept of Value-driven Delivery. One of the key characteristics of any project is the uncertainty of results or outcomes. Considering this uncertainty of achieving success, Scrum attempts to start delivering results as early in the project as possible.
	Before the project, the team should do a risk assessment. It is a heavy and slow process described in the **control chart**	The **Risk Daily Meeting** is used to decrease risk iteratively, in it let each actor detect what can be a possible risk source and share it as early as possible.
	Create and then break tasks in small pieces (**WBS**), make sequences, assign resources to each task, assign time per task next generate chronogram and flow diagram: "*synchronize the clock of all stakeholders*". In addition, estimate the expected final date, the PM should make **critical path analysis**, or another set of analytic techniques to fit to the expected date.	The chronogram is conceived by collaboration with customer. People should discuss which activities would add more value in order to prepare them first. The team and customer will define the scope only for each single first iteration. The team is expected to deliver value in each iteration, for that the project Owner classify the activities to do **first the high adding value activities**.
Control and Follow	The project initiator or sponsor provides the **SOW (Statement of Work)** based on business needs, product, or service requirements. This document is a narrative description of products, services to be delivered.	**Define a Project Vision Statement** that will serve as the inspiration and provide focus for the entire project. However, the organization should be adaptive: the customer can change request, and the project may change as well.
	The project follows **the business case,** including the market demand, the organization need, the customer request, the legal requirement, etc.	Team builds a **Story Mapping** to control the process of taks' execution.
	The projects uses several follow agreements, for example memorandums of understanding (MOUs), service level agreements (SLA), etc.	The business justification is validated throughout project execution, typically at predefined intervals or milestones, such as during portfolio, program, and Prioritized **Product Backlog Review Meetings.**
	Enterprise Environmental Factors : • Governmental standards, industry standards, or regulations • Organizational culture and structure, and • Marketplace conditions.	Agile adaptability allows the project's objectives and processes to change if its business justification changes.
	Organizational Process Assets • Organizational standard processes, policies, and process definitions, • Historical information and lessons learned knowledge base	**Pareto Risk Action:** The activity with most risk is done at first in order to get the risk continuous decreasing

RESULTS DOMAIN: *Cost (COS), Quality (QUA), Schedule (SCH).*

RESULTS DOMAIN		
	Classic	**Agile**
Preparation	Planning integration is complex and it is exhaustive	Apply system thinking to make all work together it should be simple and participative. Implicit planning actors take activities, define politics, the systems controls itself, daily/weekly scrum adapt planning (planning poker)
	Detail plan of quality assurance: How can a project get the expected quality? How does each process can be improved?	Implicit Quality. Team doesn't need to plan Quality. **Kanban** suggested improving process, using for example lean agile principles. If the new process is adding value in each iteration, the quality can be improve in next iteration.
	Additive logic: Find scope, activities, time, cost and value per activity, chose people per activity, add all people in all activities and get a full budget.	**Adaptive & Modular** logic: set the team to work and add cost of all member per iteration, charge customer per iteration and depending on number of iteration get the final project cost. Lead the team to add value in each iteration. Support the team and make the system **flows seamless** and continuously. Not controlling all but making the customer satisfy in each iteration.
Control and Follow	Control that actions are **following the planning.** Control that each team member is doing its role.	Stablish **cadences**: The purpose of a cadence is to establish a reliable and dependable capability, which demonstrates a predictable capacity. Cadence gives some confidence in the upcoming work when we are triggering rather than scheduling work.
	To assure quality the PM should assure that the process is being following the plan with 100% accuracy	The process itself assure quality and stakeholders satisfaction: The quality follows the improvement in each new release. Kanban can be used to improve quality, the team doesn't need a specific quality plan.
	Reactive: The quality process is defined before work is done.	**Zero waste** policy by light quality control but high quality assurance. Quality control is dissolved in the process for example using Kanban. Quality is driven by changing the behavior of work: the customer defines how he wants the product and the team will change its behavior to adapt the project to the new sub goals.
	Follow **cost breakdown structure**. Assure that cost are under control for each activity/actor to avoid projects over costing	Customer pays in each iteration according to the value added in each milestone, not just for accomplish tasks. Alternatively, when the projects arrives to the promise value after some iterations.
Share and Valuation	Finally better process shall become assets to improve organizations process	Deliverables are create in the end of each iteration. New request are updated, The project does not need and end deliverable. Nevertheless, improve each one in each iteration. Deliver what was promise in each sprint (2-4 weeks) If not possible discuss with the customer, focus on deliver faster the most value possible : Check on value generation more than work generation (deliverables) If the team is not delivering value, they should make another activity

INTERFACE DOMAIN: *Procurement (PRO) & External Stakeholders (STA)*

INTERFACE DOMAIN		
	Classic	**Agile**
Preparation	Make a market study and have a bid management strategy: select suppliers and produce tenders	Involve suppliers in **planning poker** sessions. Make people participate actively: having always communication in two direction adapt better proposal for the project
Control and Follow	Follow and evaluate suppliers' products flows	Collaborative work with suppliers. The organization work together to give value to ask best value in procurement Stakeholders are always in contact with the Product Owner. They validate each step in each iteration. **-** Execution of project is working parallel to the customer. Project deliverables should add value to the customer in each iteration for example: having working software in each sprint.
Share and Valuation	Close Statement of Work (**SOW**) : Check all is done according to the plan, write lessons learned and heavy document	

ANNEX 3 (From CHAPTER 6): NES Criteria

COMPLEXITY AXE:

Project Size sub criteria: Complexity based in project size

Criteria	References
Number of stakeholders	(Ackermann, Howick, Quigley, Walls, & Houghton, 2014; Bergmann, 2002; Jonas et al., 2013; L.-A. Vidal & Marle, 2008; Williams, 1999)
Quantity of information to analyze	(Geraldi & Adlbrecht, 2008)
Number of sources of information	(Geraldi & Adlbrecht, 2008)
Number of Information Systems	(L. A. Vidal, Marle, & Bocquet, 2011a)
Number of groups or structure to manage	(L. A. Vidal et al., 2011a)
Number of hierarchic levels involucres	(Baccarini, 1996; Brockmann & Girmscheid, 2007; Maylor et al., 2008; Remington & Pollack, 2007; L. A. Vidal et al., 2011a)
Number of external stakeholders	(Bergmann, 2002; A. H. I. Lee, Chen, & Chang, 2008; L.-A. Vidal & Marle, 2008)
Number of companies sharing resources	(Bergmann, 2002; L.-A. Vidal & Marle, 2008)
Number of inverters	(Bergmann, 2002; A. H. I. Lee et al., 2008; L.-A. Vidal & Marle, 2008)
Number and type of suppliers	(Bergmann, 2002; A. H. I. Lee et al., 2008; L.-A. Vidal & Marle, 2008)
Resource Availability	(Bergmann, 2002; A. H. I. Lee et al., 2008; L.-A. Vidal & Marle, 2008)
Number of Resources	(Bergmann, 2002; A. H. I. Lee et al., 2008; L.-A. Vidal & Marle, 2008)
Number of end users	(Bergmann, 2002; A. H. I. Lee et al., 2008; L.-A. Vidal & Marle, 2008)
Number of resources with the required skills	(Bergmann, 2002; A. H. I. Lee et al., 2008; L.-A. Vidal & Marle, 2008)

Project Diversity sub criteria: Complexity based in variety of variables of the project

Criteria	References
Dispersion of teams (multi-sites, multi-country, ...)	(Bergmann, 2002; Heylighen, 2013; Schrader, Riggs, & Smith, 1993; L. A. Vidal et al., 2011a)
End-user diversity	(L.-A. Vidal & Marle, 2008)
Multidisciplinary of knowledge and experience	(A. H. I. Lee et al., 2008; L.-A. Vidal & Marle, 2008)
Multi-culturalism of stakeholders (Experience and social background)	(Ackermann et al., 2014; Bergmann, 2002; Jiang, Klein, Hwang, Huang, & Hung, 2004; A. H. I. Lee et al., 2008; Maylor et al., 2008; Remington & Pollack, 2008; L.-A. Vidal & Marle, 2008)
International / multicultural environment	(Bergmann, 2002; Heylighen, 2013; L.-A. Vidal & Marle, 2008)
Dynamism and Level of stability of the stakeholders (clients, partners, suppliers) on the project (social, legal, environmental, ...)	(Bergmann, 2002; Heylighen, 2013; L.-A. Vidal & Marle, 2008)
Incertitude and changes	(Bergmann, 2002; Kim & Wilemon, 2002; Schrader et al., 1993; L.-A. Vidal & Marle, 2008)
Diversity of tasks	(Maylor et al., 2008; L.-A. Vidal & Marle, 2008)
Change of information	(Bergmann, 2002; Kim & Wilemon, 2002; Schrader et al., 1993; L.-A. Vidal & Marle, 2008)
Change of specifications - Orders	(Bergmann, 2002; Kim & Wilemon, 2002; Schrader et al., 1993; L.-A. Vidal & Marle, 2008)

Emerging Relationship between stakeholders sub criteria: Complexity based in the relationship between variables of the project

Criteria	References
Trust of the project team	(Bosch-Rekveldt, Jongkind, Mooi, Bakker, & Verbraeck, 2011; Brockmann & Girmscheid, 2007)
Sense of cooperation	(Brockmann & Girmscheid, 2007)
Relationship between PP	(Bergmann, 2002; Geraldi & Adlbrecht, 2008; Levine, 2005)
Quantity de relations (data exchange) between departments	(Bergmann, 2002; Geraldi & Adlbrecht, 2008; Levine, 2005)
Data exchange with External stakeholders	(Bergmann, 2002; Geraldi & Adlbrecht, 2008; Levine, 2005)
Dependence between task relationships	(Bosch-Rekveldt et al., 2011; Xia & Chan, 2012)
Dynamics of task activities	(Brockmann & Girmscheid, 2007)
Level of stakeholder involvement in the project	(Bergmann, 2002; Heylighen, 2013; L.-A. Vidal & Marle, 2008)
Inter-project Interdependence	(Kaplan & Norton, 2006; Platje, Seidel, & Wadman, 1994; Remington & Pollack, 2007; L.-A. Vidal & Marle, 2008; Zirger & Maidique, 1990)

Engineering solution complexity sub criteria : Complexity in PM based in complexity of the solution

Criteria	References
Description of the problem inaccurate	(Bergmann, 2002; Schrader et al., 1993; L. A. Vidal et al., 2011a)
Space of solution open, undefined.	(Bergmann, 2002; Schrader et al., 1993)
Level of definition & stability of need	(Bergmann, 2002; Schrader et al., 1993)
Project structuring and methods, associated control tools: WBS high complexity. EVM implementation (for example).	(Bergmann, 2002; Schrader et al., 1993)
Stability level of the operational concept	(Schrader et al., 1993)
Impact of scheduling drift on contract	(Schrader et al., 1993)
Larger of scope (number of components)	(Schrader et al., 1993)
Number of deliverables	(Schrader et al., 1993)
Number of Objectives	(Schrader et al., 1993)
Duration of the project	(Schrader et al., 1993)
Number of decisions to make	(Schrader et al., 1993)

Dynamics and uncertainty of the environment sub criteria : Complexity in PM based in characteristics of the environment

Criteria	References
Uncertainty the Environment	(Atkinson, Crawford, & Ward, 2006; Bergmann, 2002; A. H. I. Lee et al., 2008; Schrader et al., 1993; L. A. Vidal, Marle, & Bocquet, 2011b)
Dynamics of the Environment	(Bergmann, 2002; Heylighen, 2013; Jonas et al., 2013; L.-A. Vidal & Marle, 2008)
Strong internal and external constraints and pressures with a major influence on the final outcome of the project	(McDonald, 2007)

STRATEGIC AXE

Financial impact sub criteria : Strategy sub criteria based on the financial impact

Overall financial volume of the project	(Beringer, Jonas, & Kock, 2013; Chao & Kavadias, 2008; Cooper, Edgett, & Kleinschmidt, 2001; Northcraft & Wolf, 2011)
Value Creation	(Thomas, Delisle, Jugdev, & Buckle, 2002)
Added value of the project	(Thomas et al., 2002)
Market development	(Thomas et al., 2002)

Integration (Alignment) of project within the organization sub criteria: Strategy sub criteria based on the Integration of project within the organization.

Alignment with strategy : • Contribution to the company's strategy • Client sector is not part of the strategic sectors • Typology of the project is not part of the target projects	(Beringer et al., 2013; Cooper et al., 2001; Jonas et al., 2013; Kopmann et al., 2017; Meskendahl, 2010)

• Project not essential to the proper functioning of the company • Highly strategic project (medium/long term) for the company	
Alignment with portfolio	(Cooper et al., 2001; Kopmann et al., 2017; Payne, 1995; Platje et al., 1994)
Alignment with other projects: • cooperation quality between projects (sharing resources) • Resource Allocation Quality: power of project managers and availability of resources. • Shared Information Quality • Organizational structure	(Cooper et al., 2001; Jonas et al., 2013; Payne, 1995; Platje et al., 1994)

Alignment with external factor (clients, stakeholders) sub criteria: Strategy sub criteria based on the Alignment with external factor

Alignment with the environment	(Meskendahl, 2010; Miller, 1962; Payne, 1995; Platje et al., 1994; Tushman & Nadler, 1978; Venkatraman & Camillus, 1984)
Involvement and motivation of the project client	(Gray & Balmer, 1998; Kopmann et al., 2017; Matzler, Bailom, Hinterhuber, Renzl, & Pichler, 2004; Peterson, 2007)
Alignment with external needs (clients, stakeholders) • New customer leader in a new strategic sector of the company • Involvement of the client's General Management in the follow-up of the project • Project officially registered as a major contributor to the organization's strategy • Image exposure & corporate reputation	(Beringer et al., 2013; Chandler, 1962; Jonas et al., 2013; Kopmann et al., 2017; Miller, 1962; Tushman & Nadler, 1978)
Alignment with external values	(Balmer & Greyser, 2006; Peterson, 2007)

Potential for destabilizing the company: Strategy sub criteria based on the Potential for destabilizing the company

Destabilizing criteria	- Change / temporary adaptation of the organization to manage the project - Unusual project for the organization - Strong involvement of teams not exclusively dedicated to the project - Project to introduce significant changes in the organization's practices.
Resistance	Represents the ability of a system to absorb drastic changes in its environment on its own. It is therefore the ability of a system to respond on its own to certain disturbances (Schwind et al, 2016).
Resilience	represents the ability of an element to anticipate, resist while adapting and recover by returning as much as possible to the acceptable functional state it had before disruption or dysfunction (Madni, 2007); (Haimes, 2009).
Vulnerability	represents the ability of a target to resist and be resilient to the dangerousness of at least one source.

9 Synthèse de la thèse en français

Notre thèse s'inscrit dans le cadre d'une Convention Industrielle de Formation par la Recherche (CIFRE) entre Sopra Steria, et plus précisément sa filiale spécialisée en consultance, et l'Équipe de Recherche sur les Processus Innovatifs (laboratoire ERPI) de l'Université de Lorraine. Ce travail a commencé en décembre 2016.

La filiale de Sopra Steria mentionnée ci-dessus a une grande expérience en matière de gestion et d'audit de projets complexes. Elle dispose même d'une communauté, appelée "*EOI : Excellence des Opérations Industrielles*", réunissant des consultants souhaitant partager leurs connaissances et leurs pratiques. L'un des thèmes abordés par EOI concerne l'amélioration des missions d'audit de la maturité des **processus de management de projet (PMP)** des organisations clientes. Notre thèse entend proposer à cette communauté l'architecture d'un système de prévision de la performance d'un projet reposant sur des données.

Pour élaborer une telle architecture, il nous a fallu définir une méthodologie et proposer des modèles (1) décrivant de façon rigoureuse et abstraite ce qu'est la maturité d'un PMP et (2) explicitant la relation causale entre cette maturité et les performances opérationnelles des projets, notamment la réduction du risque de surcoûts. Nos propositions ont été élaborées à partir d'une revue de la littérature relative aux modèles de maturité des processus de management de projets pour ce qui concerne les modèles descriptifs, et aux **Réseaux Bayésiens (RB)**, pour ce qui concerne la relation causale entre maturité et performance opérationnelle. Elles ont été validées à partir de l'expertise de consultants interrogés de façon semi-directive et de données tirées de gros projets d'ingénierie dans les secteurs des biens d'équipements électriques, du pétrole ou du gaz. Notre méthodologie et nos modèles nous paraissent toutefois suffisamment généraux pour dépasser le strict cadre de Sopra Steria et de ces secteurs.

Questions de recherche et structure du mémoire

Les pratiques en matière de management de projets sont anciennes. Depuis quatre décennies, des professionnels cherchent à les améliorer et à les standardiser. L'une de leurs propositions s'appelle un **PMMM (*Project Management Maturity Model*)**. Il s'agit d'un modèle décrivant l'univers du management de projet et réunissant un ensemble de bonnes pratiques à mettre en œuvre par le chef de projet et à évaluer par l'auditeur. Le PMMM comprend une échelle de perfection dans la mise en œuvre de ces pratiques. Lorsque la maturité est faible, le chef de projet improvise ; lorsqu'elle est élevée, il anticipe les risques et les performances du projet et sait quel outil mettre en œuvre pour gagner en efficacité, réactivité, qualité, etc.

De nos jours, il existe de nombreux PMMM. Malheureusement, ils présentent des limites rédhibitoires. En particulier, ils listent de façon peu structurée les bonnes pratiques et posent trop de questions (Ramirez 2009 ; Torres 2014), par exemple 183 items (Kerzner 2017) ou même plus de 400 dans le *Project Management Institute Body of Knowledge* (PMI BoK, 2013), auxquelles l'auditeur doit répondre pour apprécier la PMP d'une organisation. De plus, ils ne reposent pas sur un vocabulaire standardisé (Lasrado 2018), etc. Ces lacunes indiquent que les PMMMP actuels ne reposent pas sur une base conceptuelle suffisamment robuste et précise. Par conséquent, il se pose une première question de recherche qu'on peut énoncer comme suit : c*omment proposer une méthode pour construire un PMMMP plus abstrait, plus rigoureux et plus concis que les modèles existants ?*

De plus, le contexte actuel de la digitalisation des activités professionnelles, donc des organisations privées ou publiques, et de l'industrie 4.0 pose de nouveaux défis au management de projet (Westerman, Bonnet et Mcafee 2014 ; McAfee et al. 2012). A titre d'exemple, les PMP évoqués précédemment promeuvent un Management de Projet Traditionnel (***TPM : Traditional Project Management***) (Wysocki, 2000) dans lequel le chef de projet doit se conformer à des processus préétablis extrêmement détaillés. Or, dans le secteur des technologies de l'information, un Management de Projet Agile (***APM : Agile Proejct Management***) s'est développé du fait des insuffisances du TPM en matière de satisfaction du client, de respect des délais ou d'engagement des acteurs projet. Le APM et ses méthodes agiles (Scrum, Extreme, etc.) (Doug 2004 ; Setpathy 2016) deviennent la nouvelle référence en management de projets, y compris auprès des industriels. Nous avons appelé 'agilification' le processus par lequel une organisation passe du TPM au APM. La prise en compte de ce dernier style de management de projet pose une deuxième question de recherche : *Comment pouvons-nous utiliser notre PMMM proposée pour évaluer la maturité de la gestion de projet agile ? De plus, comment aider les organisations à changer leurs pratiques de gestion de projet d'une méthode traditionnelle à une méthode agile ?*

Nos deux précédentes questions de recherche sont descriptives. Les questions suivantes concernent la relation causale entre le niveau de maturité du PMP d'une organisation et la performance opérationnelle des projets réalisés en son sein. Ainsi, notre troisième question de recherche est la suivante : c*omment choisir la bonne technique de modélisation causale adaptée aux spécificités de l'univers du management de projet ?* Attendu que parmi ces spécificités, il faut tenir compte d'un nombre de données plus faible que dans d'autres domaines (la reconnaissance d'image, par exemple), l'hétérogénéité des données, leur caractère mouvant, ou encore le nécessaire recours à l'expertise des chefs de projets ou des auditeurs empêchant de corréler une grande quantité de données d'entrée (rétroaction de projets antérieurs) à plusieurs critères (performance opérationnelle des projets). Les RB apparaissent comme un outil de modélisation pertinent dans un tel contexte.

En interrogeant les consultants de Sopra Steria, nous avons constaté, ce qui est favorable pour notre travail, que leur raisonnement causal consiste (1) à identifier des points dysfonctionnels en management de projet (que nous appelons ici facteurs de dérive) susceptibles d'induire des dérives de performances et (2) considérer une maturité insuffisante en PMP comme l'une des causes de dérive importantes. Par conséquent, nous avons demandé aux experts quels sont les liens de causalité entre les critères de maturité (liées à de bonnes pratiques) et les facteurs de dérive, plutôt que de demander directement les liens entre ces pratiques et la performance opérationnelle du projet. Par conséquent, la quatrième question de recherche s'exprime comme suit : *quelle méthodologie reposant à la fois sur les données et l'expertise peut-on créer pour prédire la performance opérationnelle des projets à partir de la maturité des PMP ?*

En résumé, la question générale de recherche de notre travail est donc :

Comment construire un modèle élaborant des relations de cause à effet entre la maturité de la gestion de projet et les performances opérationnelles des projets ?

Nos questions de recherche peuvent être réunies dans un tableau à quatre cases principales. Ce tableau croise deux critères : (1) l'enjeu de la modélisation (décrire *vs*. expliquer/relier) et (2) le niveau d'abstraction de la modélisation (général *vs*. spécifique). Notre thèse reposant sur une CIFRE, nous avons ajouté une dernière ligne rappelant ses enjeux opérationnels.

Niveau	**Décrire l'évaluation de la maturité du PMP**	**Expliquer la relation causale entre maturité du PMP et performance opérationnelle du projet**
générique	(question 1) Proposer un PMMM plus abstrait et concis que ceux qui existent	(question 3) Choisir une technique de modélisation causale, dans le champ de l'IA, adaptée à l'univers du management de projet
spécifique	(question 2) Appliquer le modèle proposé aux projets de l'environnement industriel spécifique (gestion de projet agile).	(question 4) Proposer une méthodologie et un RB pour expliciter le lien entre maturité des PMP et risque de surcoût dans les gros projets d'ingénierie de secteurs pétrolier et gazier
Objectif opérationnel : créer une architecture d'un système de prévision de la performance des projets fondée sur l'évaluation des critères de maturité en gestion de projet et satisfaisant les besoins des consultants de Sopra Steria		

Table 9.1 Répartition des questions et des objectifs de recherche

La structure de notre thèse, reprend la forme du tableau ci-dessus.

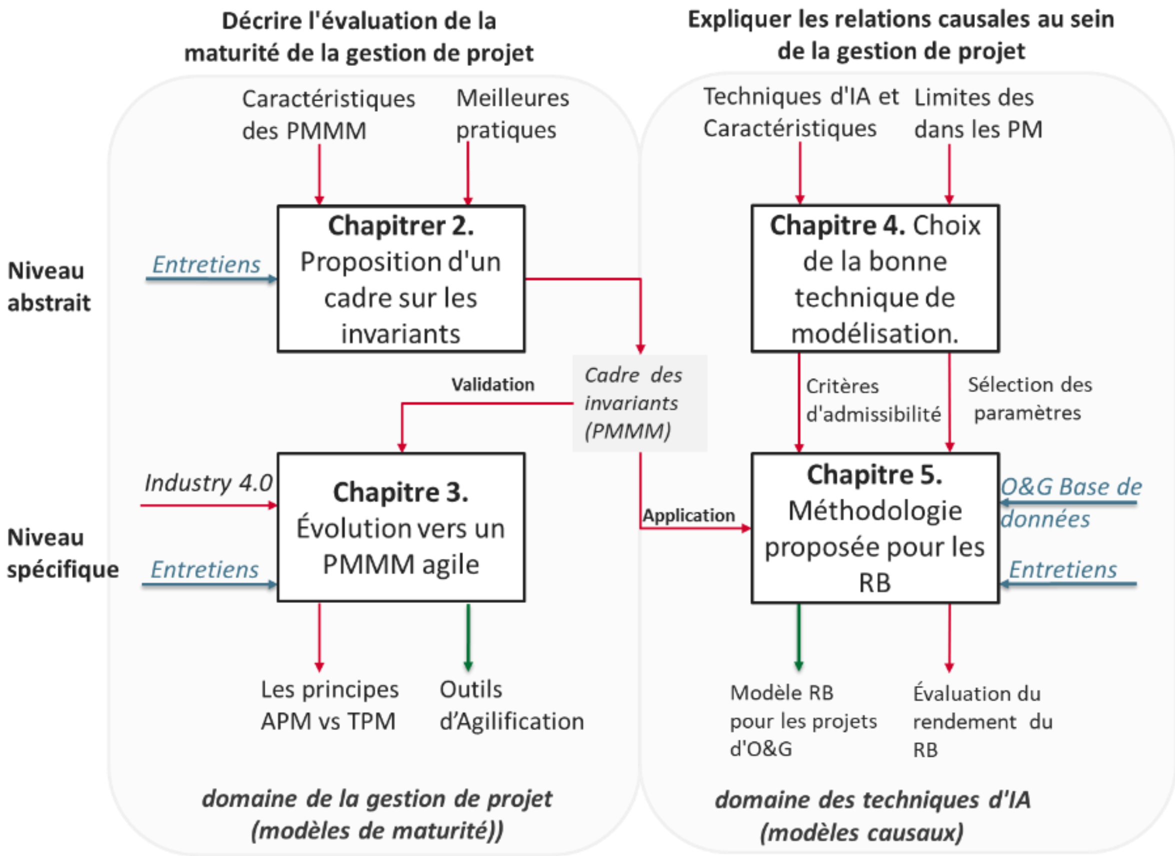


Figure 9.1 Structure des contributions de la thèse

Pour répondre à nos quatre questions de recherche et rédiger les chapitres associés, nous avons posé un certain nombre d'hypothèses recensées ci-dessous.

Hypothèses

Notre recherche est fondée sur deux hypothèses clés.

H1. La première hypothèse concerne notre conceptualisation de l'univers du management de projet. En tant qu'ingénieur, notre rôle est d'apporter à des acteurs de cet univers des modèles, des outils, des méthodes, etc. pour travailler plus efficacement. Ces modèles doivent être à la fois conceptuellement robustes (ligne du haut du tableau et de la figure précédents) et avoir une réelle valeur pratique (lignes du bas).

H2. La deuxième hypothèse concerne la limitation de nos connaissances. L'univers du management de projet n'est pas aussi structuré, aussi bien défini que celui des sciences physiques, biologiques, etc. De ce fait, les modèles produits pour décrire la maturité des PMP ou pour expliquer la causalité entre cette maturité et la performance opérationnelle des projets sont provisoires, susceptibles de révisions notables. Cette hypothèse explique pourquoi nous ne sommes pas restés au niveau abstrait, générique (ligne du haut du tableau et de la figure précédents), et avons tenu à mettre à l'épreuve nos modèles sur des cas spécifiques (ligne du bas), c'est-à-dire sur une population de projets présentant des traits communs (secteurs, taille, années de réalisation, etc.). Enfin, si la maturité des PMP explique une partie d'une performance opérationnelle donnée, à savoir l'absence de risque de surcoût, d'autres facteurs y contribuent dans des proportions sans doute non-négligeables, par exemple les capacités de l'entreprise en matière d'ingénierie, la qualité des partenaires ou des clients, etc.

Méthode suivie

Pour mener à bien notre travail de recherche, nous avons combiné en parallèle quatre approches :

1. une revue de la littérature en management de projet et en IA ;
2. la modélisation descriptive, à l'aide de modèles conceptuels, et causale, à l'aide de RB ;
3. la collecte de données de Sopra Steria relatives à des missions d'audit passées ;
4. des entrevues avec des consultants, puis une évaluation de leur part de nos propositions.

Contributions

Chaque chapitre de notre thèse traitant d'une question particulière, notre thèse a donc quatre contributions.

Contribution 1 : un PMMM fondé sur les invariants. Le deuxième chapitre présente un PMMM répondant à trois critères : concision, cohérence conceptuelle et facilité d'utilisation par les auditeurs. Le modèle que nous proposons comporte un élément clé appelé invariant, c'est-à-dire une caractéristique transversale aux différents types de méthodes de management de projet. Notre proposition simplifie les modèles actuels tout en permettant d'intégrer les 70 meilleures pratiques qui ont été identifiées dans la littérature (White et Fortune 2001 ; Fortune et al. 2011 ; Besner et Hobbs 2012 ; Fernandes, Ward et Araújo 2013b ; Fortune et White 2006 ; Besner et Hobbs 2008). Notre modèle conceptuel a été validé par les consultants de Sopra Steria. Ce modèle est également utilisé dans les chapitres 3 et 5 car il permet de réduire le nombre de causes à prendre en compte dans l'élaboration d'un modèle causal et rend possible l'élaboration d'une réponse à notre question de recherche globale.

Contribution 2 : un PMMM accompagnant l'agilification. Le chapitre 3 compare les principes du MPT et du MPA. Or, moyennant adaptation, il est possible d'adapter notre PMMM élaboré à partir du MPT au MPA. Enfin, notre modèle permet de suivre l'agilification ; une étude de cas concernant le processus d'ordonnancement de projet prouvant cette proposition.

Contribution 3 : des modèles causaux d'IA adaptés au management de projet. Partant de notre PMMM à base d'invariants, il nous a fallu expliciter la relation causale entre maturité de processus et performances opérationnelles des projets. Avant de développer un modèle spécifique, nous avons comparé des techniques d'IA candidates à la modélisation envisagée : les réseaux neuronaux artificiels (ANN) (McCulloch et Pitts 1943), l'apprentissage par renforcement (RL) (Sutton 1988) et les réseaux bayésiens (RB) (Pearl 1988). Les RB ont été choisis en raison de sa capacité d'intégrer les connaissances des experts aux prévisions, ce qui réduit la quantité de données nécessaires pour alimenter les algorithmes (Neil, Fenton et Nielsen, 2000). Enfin, nous avons étudié systématiquement les RB proposés dans la littérature en management de projet et montré qu'ils ne répondaient pas aux exigences relatives à la qualité de la modélisation causale (explosion combinatoire, par exemple) ou des données disponibles.

Contribution 4 : un RB pour expliciter la relation causale entre maturité de PMP et risque de surcoût. Les résultats conceptuels et méthodologiques des précédents chapitres ont été utilisés pour développer un RB montrant, dans projets dits *offshore Oil and Gas* (O&G), la force du lien entre maturité des PMP et risque de surcoût. Le RB proposé montre des résultats significatifs même si bien d'autres facteurs de dérive contribuent à expliquer les surcoûts.

Perspectives

Notre thèse se conclut sur deux perspectives majeures.

La première concerne l'intégration de nouvelles variables organisationnelles dans l'évaluation des performances opérationnelles des projets, à savoir le niveau de compétences des métiers impliqués dans les projets et le niveau de criticité desdits projets. La première idée vise à élargir notre modèle qui s'est focalisé sur les pratiques de gestion de projets pour s'intéresser aussi à l'impact du niveau de compétences des métiers sur les performances du projet. La seconde 'idée est que plus un projet est critique, plus la maturité de son management doit être élevé. L'évaluation de la maturité ne devrait donc pas être réalisée dans l'absolu mais être adaptée à la criticité de chaque projet. Il s'agirait, dès lors, de développer le RB proposé en chapitre 5 en intégrant ces nouvelles variables.

La seconde perspective, quant à elle, vise à déployer un système, reposant sur des algorithmes de *Machine Learning*, et traitant des données des projets passés pour automatiser certaines tâches d'évaluation de la maturité des PMP.

Résumé

Cette thèse CIFRE, réalisée au sein SOPRA STERIA, apporte une contribution sur l'élaboration d'un modèle causal entre la maturité de la gestion de projet et les performances du projet et propose une méthodologie pour construire une architecture d'un système de prévision des performances d'un projet. Pour élaborer une telle architecture, il nous a fallu définir des modèles décrivant de façon rigoureuse et abstraite ce qu'est la maturité de la gestion de projet et une méthode explicitant la relation causale entre cette maturité et les performances des projets, notamment la réduction du risque de surcoûts. Nos travaux se déclinent dans les contributions suivantes :

- Proposition d'un modèle de maturité pour l'évaluation de la maturité de la gestion de projet, plus abstrait et concis que ceux qui existent.
- Application du modèle proposé dans le contexte de l'Industrie 4.0 (gestion de projet agile). Nous avons utilisé ce modèle pour développer une méthodologie permettant de passer de la gestion de projet classique à la gestion de projet agile.
- Choix d'une technique de modélisation causale, dans le champ de l'Intelligence Artificielle, adaptée au domaine du management de projet.
- Proposition d'une méthode pour construire un modèle de réseaux bayésiens permettant d'expliciter le lien entre maturité de gestion de projet et risque de surcoût.

Nos propositions ont été validées à partir de l'expertise de consultants et de données issues de grands projets d'ingénierie. Des travaux futurs pourront porter sur l'adaptation du modèle à d'autres types de projets et sur la prise en compte des compétences métiers.

Mots clés : Gestion de projet, Modèle de maturité, Agilité, Réseaux bayésiens, Modélisation des connaissances.

Abstract

This thesis, performed in collaboration with the company SOPRA STERIA, proposes the architecture of a system for predicting the performance of a project. To develop such an architecture, we defined what project management maturity is in a rigorous and abstract way. Then we develop a methodology to create models that explain the causal relationship between project management maturity and the operational performance of projects, specifically the predicting cost overrun risks in engineering projects. Our work has the following contributions:

- Proposal of a maturity model for project management evaluation more abstract and concise than the existing ones
- Application of the proposed model to projects in the specific industrial environment (agile project management). We used that model to develop a methodology to move from classical project management to agile project management.
- Choice of a causal modeling technique, in the field of Artificial Intelligence, adapted to the world of project management.
- Proposal of a methodology to clarify the link between project management maturity and cost overrun risks in engineering projects.

Our proposals were validated on the expertise of consultants and data from large engineering projects. Nevertheless, our methodology and models are general enough to go beyond the strict framework of these sectors.

Keywords: Project management, Maturity model, Agility, Bayesian networks, Knowledge modeling.