Improving performance measurement of engineering projects: methods to develop indicators

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I always remember one sentence that I have read in an acknowledgement of a dissertation, meaning that doing a thesis is like a voyage, sometimes we don't know where to go, sometimes we have some crossroads before; but it is still a deserving one. I remember that at the first year of my thesis, among friends, we talked often of the feelings about doing a PhD, we reached one common conclusion, that is, if we can draw a graph in a X-Y scheme, X representing the periods, and Y meaning the feelings (such as excited, confused, dumb, dead), you will see that many new researchers like us will plot so often the points of "feeling dead" or "feeling confused". I am not meaning some negative implications for those still in the upward path to get their PhD degree, or those still in crossroad to decide if they will pursue a higher education. What I want to tell is that in spite of so many moments of "feeling confused", the short moment of getting excited for what we advanced in our research deserve all what we have experienced.

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Abstract

Performance measurement is essential to ensure the success of a project. To this goal, companies need to determine a system of performance measures, classically including cost and schedule measures, which provide the project manager with the project health status and help her or him to evaluate the project successes and failures. However, with the increasing complexity of projects and the absolute necessity to reach the project objectives, project managers cannot only rely on such information about cost and schedule to evaluate the project performance; they need to consider, for instance, other indicators such as the satisfaction of customer requirements, the technology maturity, etc. Moreover, they need to have a precise evaluation of these indicators values while the project is in progress, in order to monitor it at best so that it reaches its goals, and not only after the project ends, to only conclude on the project success or failure without any mean to react. Considering these two issues, the objectives of the thesis thus are to extend the number, scope and type of current project performance indicators with a proposal of complementary indicators, and to propose a method for designing project-specific indicators, in order to improve project performance measurement. To define supplementary indicators and elaborate such a method, we proceed by integrating good measurement practices from different engineering disciplines and illustrate our proposal on use cases.

The thesis first introduces the notion of performance and characterizes performance measurement systems (PMSs); such systems offer a wide panel of models for organizational performance measurement. Focusing on PMSs, we provide some insights for project performance measurement. More precisely, we identify several issues highlighted in literature, relative to the limitations of current project performance measurement such as the need to balance lagging indicators (to control) with leading indicators (to monitor), and the need to construct performance indicators that are relevant to project-specific information needs.

We then focus on project performance measurement and reviews literature in this domain. It highlights the issue of the unbalanced use of leading and lagging indicators. To bring a solution to the issue, we review literature of performance measurement in engineering disciplines, with a focus on systems engineering practices, especially a panel of 18 generic leading indicators that are currently engineered in guidance. A method has been proposed to adapt the set of systems engineering leading indicators to project management, thus resulting in developing the set of indicators to measure project performance. Moreover, focusing on standards and guides on measurement in systems and software engineering led us to identify other issues in project performance measurement, such as the difficulties to define indicators dynamically for a project, and how to collect and combine data in order to construct these indicators.

We finally consider the methodological difficulties about designing relevant performance indicators. More precisely, we identify 3 issues: different opinions among researchers about the sources from where the indicators will be derived; the problem in relation to the transformation from data to indicators; and the association of data collection, analysis and report with project management processes. To solve these issues, we analyze good practices from the Practical Software and Systems Measurement, the ISO/IEC 15939 norm and the Project Management Body of Knowledge that proved to be able to address the identified issues respectively. This work results in a method integrating these practices to address the 3 identified issues in project performance measurement. The method is illustrated on a real project context. Evaluation of the method has been conducted in workshop of project managers, which confirmed the interest for the proposal.

Résumé

La mesure de la performance est l'une des nombreuses activités de la gestion de projet, elle contribue à assurer le succès du projet. Pour atteindre ce but, les entreprises ont besoin de déterminer un système de mesures de la performance. Ces mesures fournissent au chef de projet l'état de santé du projet et l'aide à évaluer s'il a atteint ou va atteindre ses objectifs. Néanmoins, avec la complexité croissante des projets et la nécessité économique absolue d'atteindre les objectifs, les chefs de projets ne peuvent plus se contenter de superviser les coûts et le planning pour évaluer la performance du projet. Ils ont besoin de considérer par exemple d'autres indicateurs comme la satisfaction des exigences du client, la maturité de la technologie, etc. De plus, ils ont besoin d'avoir une évaluation précise des valeurs de ces indicateurs tout au long du projet et pas uniquement à la fin, pour monitorer au mieux le projet afin qu'il atteigne ses objectifs. Pour satisfaire ces nouveaux besoins, les objectifs de cette thèse sont d'étendre le nombre d'indicateurs génériques et de diversifier le type des indicateurs, ainsi que de proposer une méthode pour concevoir des indicateurs spécifiques à un projet. Pour cela, nous procédons par l'intégration de bonnes pratiques pour la mesure de performance issues de plusieurs domaines de l'ingénierie, et illustrons nos propositions sur des cas pratiques.

Ce rapport introduit la notion de performance et caractérise les systèmes de mesure de performance, en mettant notamment en évidence un emploi non cohérent de la terminologie selon les sources. Il identifie plusieurs limitations des systèmes de mesure de performance actuels et souligne notamment le besoin d'étendre le nombre et le type des indicateurs, et de construire des indicateurs de performance spécifiques et pertinents pour chaque projet. Une étude bibliographique sur la mesure de la performance dans les domaines de l'ingénierie, notamment en ingénierie système, montre que la mesure de performance est particulièrement bien développée dans cette dernière discipline, avec une offre de 18 indicateurs génériques avancés permettant une grande proactivité. La thèse propose de ce fait d'adapter ces indicateurs au management de projets, résultant en la définition d'un ensemble d'indicateurs étendu et diversifié pour la mesure de performance. Par ailleurs, l'étude des normes et guides en ingénierie système et logicielle (Practical Software and System Measurement, ISO/IEC 15939) nous amène à identifier d'autres besoins, comme la création dynamique d'indicateurs ad hoc qu'il est nécessaire de définir en cours de projet afin évaluer certains risques spécifiques, et soulève de nouvelles difficultés, comme la collecte et la manipulation des données pour la construction des indicateurs. Pour y répondre, ce rapport propose donc également une méthode guidant la construction dynamique d'indicateurs spécifiques. Celle-ci, illustrée dans le mémoire sur un cas concret de projet, a été validée par un panel d'experts.

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LIST OF ACRONYMS

IEC	International Electrotechnical Commission
INCOSE	International Council on Systems Engineering
ISO	International Organization for Standardization
KPI	Key Performance Indicator
PMI	Project Management Institute
PMSs	Performance Measurement Systems
PPM	Project Performance Measurement
PSM	Practical Software and System Measurement
SE	Systems Engineering
SEM	Systems Engineering Measurement

Chapter I Introduction

The objective of the thesis is to contribute to the improvement of performance measurement methods in engineering projects, by developing the currently limited set of generic performance indicators used to measure performance and by offering a method to help managers to build project-specific indicators.

This section presents the context of this study, our research motivations and objectives, and introduces the issues drawn on from literature of performance measurement, along with objectives. Then it explains the scientific process we followed through its different steps to give the reader a global vision on how we proceeded to achieve our research objectives. It also introduces the structure of the report in chapters and the logical links between them.

1. Context of the study, research motivations, issues and objectives

This section presents the context, motivation & issues, and objectives. To introduce the research context, we start from the definition and characteristics of a project, and progressively focus on project management, then project performance measurement, to come to the very concern of the study, performance indicators. An extensive review of literature relative to performance indicators enables us to state our motivations to lead this study, to outline the related issues and to define the research objective.

(1) Context of the study

A project is a process itself (ISO 2003) (Mesly 2017), a temporary endeavor undertaken to create a unique product, service, or result (PMI 2013), subject to its environment (Marques, Gourc and Lauras 2011). The objectives of a project can be variable, reflected by various interests from involved stakeholders (Kerzner 2011).

Project management is the application of knowledge, skills, tools, and techniques to project activities to meet the project requirements (PMI 2013). It can be seen that project management is a methodology that enables the success of a project, generally the success meaning the achievement of project objectives. This can be proved by its wide use in organizations or business and large number of studies in academic fields. The primary challenge of project management is to achieve all of the project goals and objectives while adhering to project constraints (Cao and Hoffman 2011). As a methodology, project management consists of 5 main functional parts: initiating, planning, executing, monitoring & controlling, and closing (PMI 2013). In these, monitoring & controlling by measurement is an essential one.

Indeed, as people say, “if you cannot measure, you cannot control; if you cannot control, you cannot manage.” Thus project performance measurement plays an important role in ensuring the achievement of project objectives. It is defined as “a process of assessing about the magnitude of variation from the original baselines” (PMI 2013). It is considered as the force that drives project management improvement (Almahmoud, Doloi and Panuwatwanich 2012). To successfully conduct this process, **a system of performance indicators is considered essential**. This is the very concern of this PhD dissertation.

(2) Motivations & issues

Projects become more and more complex. This complexity is characterized by: the time duration can be several years, project scopes can be changed over the project duration, technology can be changed as the ever-changing whole environment, multiple stakeholders are engaged, and project objectives and targets may be moving over the project (Kerzner 2011) (William 1999) (Marques, Gourc and Lauras 2011). However, William (1999) divided the project complexity into two dimensions: structural complexity and uncertainty. Project complexity is also considered as one of essential project characteristics that decide an appropriate selection of project management approach (Patanakul et al. 2016). As the complexity of projects is increasing, it appears to be an accepted fact that **classical project management techniques are unsuitable for dealing with such projects** (William 1999). The demand for new management techniques and models rose from industry; it has also been addressed in research (William 1999) (Kerzner 2011), as stated by Morris and Hough (1987): “Complex projects demand an exceptional level of management, and that the application of conventional systems developed for ordinary projects have been found to be inappropriate for complex projects”. Traditional project management methodologies can be used in the complex projects, but according to the context and the needs, their use may not be sufficient or well adapted. For example, traditional performance measures focusing on cost and schedule measures may be too narrow to adapt to complex project (Kerzner 2011) (Almahmoud, Doloi and Panuwatwanich 2012). It has been addressed in literature that traditional performance measurement in terms of cost and schedule performance measures are incapable of capturing and dealing with the increasing complexity of modern projects (Zhu and Mostafavi 2017). Cao and Hoffman (2011) argued that the sole use of cost and schedule performance measures is not sufficient, and the consideration of key project input variables helps the improvement of project performance measurement system. Moreover, the performance management approach that addresses only on performance indicators that indicate the past and current performance of projects can no longer be sustained in today's competitive complex environment. Project managers need to manage a project's performance in a proactive rather than reactive manner (Almahmoud, Doloi and Panuwatwanich 2012). Thus it is obvious that **there is a need to extend the scope and type of performance indicators**.

On the other hand, complex projects require flexibility-focused project management practices (Eriksson, Larsson and Pesämaa 2017). Many new project management methodologies have been proposed to manage complex projects. Among them, one very popular is agile project management. Agile project management is characterized by its flexibility for the ever-changing project environment. However, “the more flexibility the methodology contains, the greater the need for additional metrics and key performance indicators”, as stated by Kerzner (2011). Thus **there is a need to measure project performance in a flexible way**. Moreover, it has been addressed in literature that **performance indicators should be designed to match to organizational context** (Neely et al. 1997) (Wouters 2009).

(3) Objectives

With regards to the current context and outlined issues, the objectives of this thesis report are to develop a complementary set of indicators (leading indicators) to help managing project performance in a proactive way, and to propose a method to design project-specific performance indicators to address information needs of project stakeholders in a dynamic way. Based on the new set of indicators, or the method to design performance indicators, project performance measurement is expected to be able to drive the improvement of project management, and finally to ensure the success of a project.

2. Research methodology

The research methodology followed first consists in 1) studying the performance measurement systems, then 2) focusing on the development of a set of generic performance indicators including leading indicators, to better lead projects, and finally 3) designing project-specific indicators. Figure I–1 shows how we proceed along these 3 stages and explains what activities are led, and what are our different contributions at each stage.

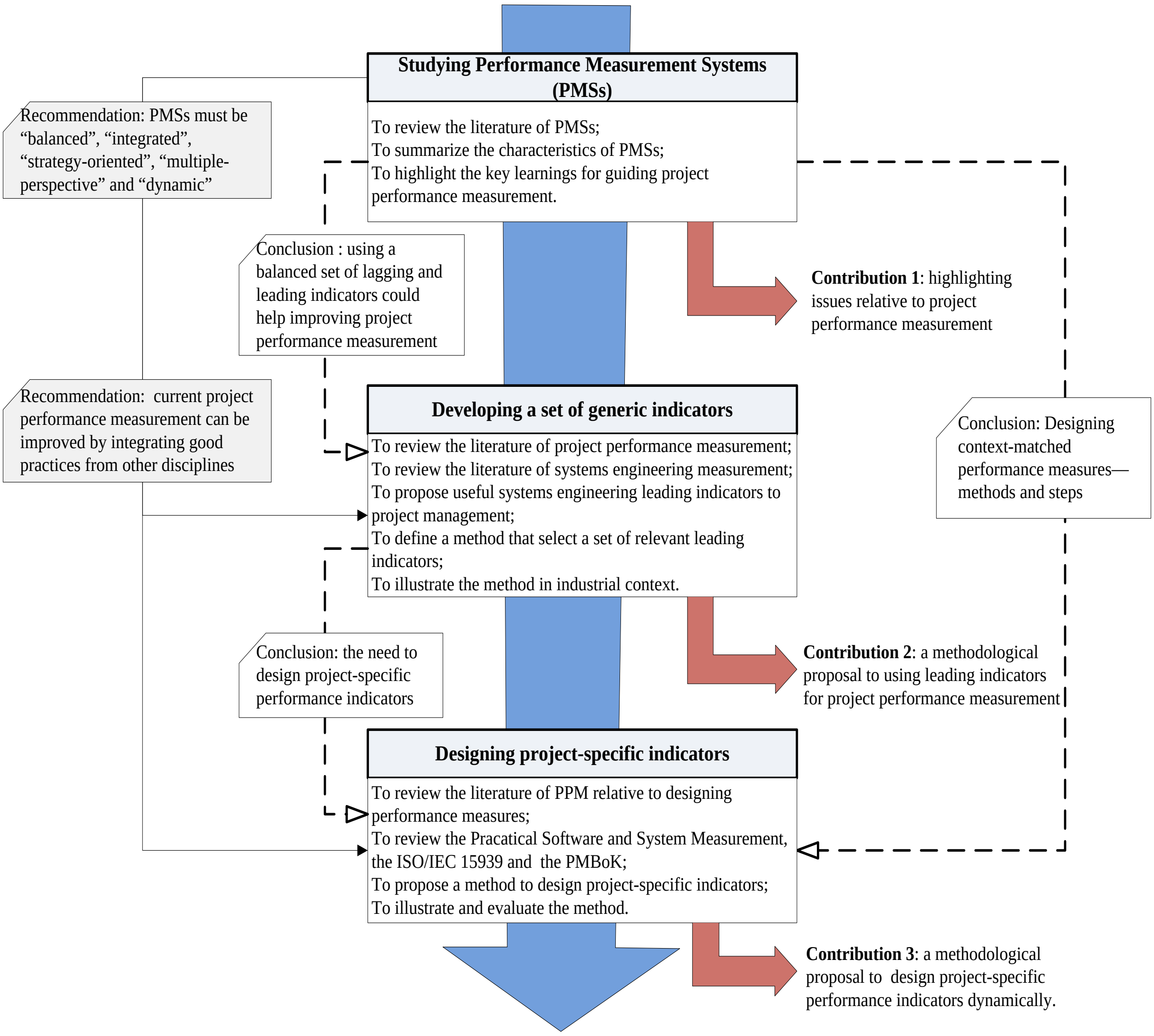

Figure I–1 The research methodology

The goal of the study is to improve the performance measurement of complex projects. This research emerged from a lack of knowledge about effective performance measurement for complex projects. **To full in this gap, we began from studying performance measurement systems (PMSs) (Stage 1)**. PMSs are a well-developed research area, and have got the focus of researchers since a century when management accounting was a dominant tool for organizational performance monitoring. Since 1980s, PMSs have been extended from sole focus on financial measures to a multiple-perspective performance management approach by considering also non-financial performance measures. With the development and evolution of the PMSs, a large number of classical models or frameworks have been documented, which have revolutionarily changed the way the organizational performance is measured. Some classical PMSs such as Balanced Scorecard have obtained great success in both academic and practices. Nowadays, new theories and methods of organizational performance measurement have been developed by bringing multiple-disciplinary knowledges into the existing knowledge system. In this stage, the characteristics of classical PMSs have been identified, and some characteristics of new models or frameworks have been also analyzed. According to these characteristics, we get two recommendations that enable us to think in a global way when we consider building new models or frameworks to improve project performance measurement. The two useful recommendations are, as depicted in the two grey boxes of Figure I–1: **PMSs must be "balanced", "integrated", "strategy-oriented", "multiple-perspective" and "dynamic"**; and **current project performance measurement can be improved by integrating good practices from other disciplines**.

Further, the systematic and deep literature review of PMSs provided some insights for how to improve performance measurement of engineering projects with regard to performance measures. Two conclusions are summarized from the issues highlighted in PMSs, relative to measures. They are respectively: **using a balanced of leading and lagging indicators;** and **designing context-matched performance measures—methods and steps**. Indeed, the importance of leading indicators in the PMSs has been addressed by various researchers, and has been proved to be able to improve organizational performance overall. Designing an appropriate set of performance measures has been also widely discussed in the PMSs, and many studies focus on some rules and guides to the selection of performance measures. These two conclusions lead us to explore the current situation of project performance measurement regarding the use of leading indicators and the design of project-specific measures, constituting our first contribution of the report:

Contribution 1: highlighting the issues of PMSs relative to project performance measures.

As mentioned precedently, one conclusion from studying the PMSs led us to investigate the current status of use of leading indicators in project performance measurement. According to the investigation, we obtain one of our research opportunities, deployed in **Stage 2**: **literature review on project performance measurement shows that there is an unbalanced use of leading and lagging indicators**. It shows that lagging indicators dominate the practice, evaluating past performance or providing current project status, rarely helping the improvement of project performance. In reverse, leading indicators predict project performance by tracking past performance data and adding some prediction mechanism, aid to avoid project risks and thus improve performance. However, this kind (leading) of indicators has not got enough development in project performance measurement. Indeed, a balanced set of leading and lagging indicators is essential for effective project performance measurement. **To fill in this gap, we seek in other disciplines to find insightful measurement practices to bring more leading indicators into the system of project performance indicators.** Literature review has been conducted from systems engineering, software engineering, civil engineering, safety engineering and business performance measurement. Leading indicators have received good development in all these disciplines. We have compared their definitions for leading and lagging indicators, and abstracted the common characteristics from them to define the concept of leading and lagging indicator in project management context. And then we have proposed a framework for bringing useful SE leading indicators into project performance measurement. Based on our methods, project performance measurement obtains a set of generic leading indicators, which focus on not only classical performance areas like time and cost, but also lay a lot of weights to product, technical performance and customer requirements. In conclusion, in this stage, we improve performance measurement by:

Contribution 2: a methodological proposal to using leading indicators for project performance measurement.

Then, our second research opportunity emerged from the conclusions of Stage 1 and Stage 2. Stage 2 proved that having a set of leading indicators could improve the effectiveness of PPM. Although useful, the set of indicators are generic and limited, and **the need to design the project-specific performance indicators** (one conclusion from Stage 2) that address information needs in a dynamic way has been raised. And this conclusion corresponds well to that of Stage 1, which has addressed: **designing context-matched performance measures—methods and steps.** However, to design performance measures is complex, and multiple aspects should be considered. Trying to find a good way to design appropriate project performance indicators brought us to **Stage 3**. According to "methods and steps" suggested in PMSs research, three issues have been distinguished in designing measures for project management, including: deciding the resources/origins of performance indicators, the transformation process from data to indicators, and the association of data collection, analysis and report with project management processes. **To solve these three issues, we seek in other disciplines to find good measurement practices and thus from these practices to select methods that address respectively the three issues**. Literature review has been conducted from the Practical Software and System Measurement (PSM) (McGarry et al. 2002), the ISO/IEC 15939 (ISO/IEC 2007), and the Project Management Body of Knowledge (PMBoK) (PMI 2013). The PSM is an information-driven measurement, which has used "information needs" to replace the dominant "project objectives" to derive performance indicators. The ISO/IEC 15939 allows to define an indicator which combines heterogeneous data and structures the elements (e.g. base measure, derived measure and indicator) for interpreting the results. The PMBoK for its part has well-designed processes that relate to data collection, analysis and report. We propose a method that integrates three parts from these practices to address the three previously identified issues in project performance measurement. This method is illustrated on a real project context to demonstrate its usability. Evaluation of the method has been conducted in a workshop of project managers to confirm the interest for the proposal. In conclusion, we obtain another contribution:

Contribution 3: a methodological proposal to designing project-specific performance indicators dynamically.

3. Organization of the report

This thesis report is divided into 5 chapters as illustrated in Figure I–2, which shows the connection between chapters. The publications during this research are related to chapter II, chapter III and Chapter IV.

Chapter I states the research context, motivations & issues and objectives of the research.

Chapter II introduces the notion of performance and characterizes performance measurement systems; such systems offer a wide panel of models for organizational performance measurement. We identify several issues highlighted in literature, relative to the limitations of current project performance measurement systems.

Chapter III focuses on project performance measurement and reviews literature in this domain. It addresses the issue of the unbalanced set of leading and lagging indicators in project performance measurement. It also reviews literature on performance measurement in engineering disciplines, with a special focus on systems engineering practices. A method is proposed to adapt systems engineering leading indicators to project management, thus resulting in developing the set of indicators to measure project performance.

Chapter IV considers the methodological difficulties about designing relevant performance indicators. We identify related issues, seek good practices from the Practical Software and Systems Measurement (PSM), the ISO/IEC 15939 norm and the Project Management Body of Knowledge (PMBoK) and result in a method that integrates them. The method is illustrated on a real project context, which demonstrates its usability. Evaluation of the method has been conducted in workshop of project managers.

Chapter V recalls the research objectives and highlights the results achieved for all the objectives. This chapter discusses the findings and addresses the contributions to knowledge and practices in project performance measurement. It also underlines the future work that should be done for strengthening methods and results in this research.

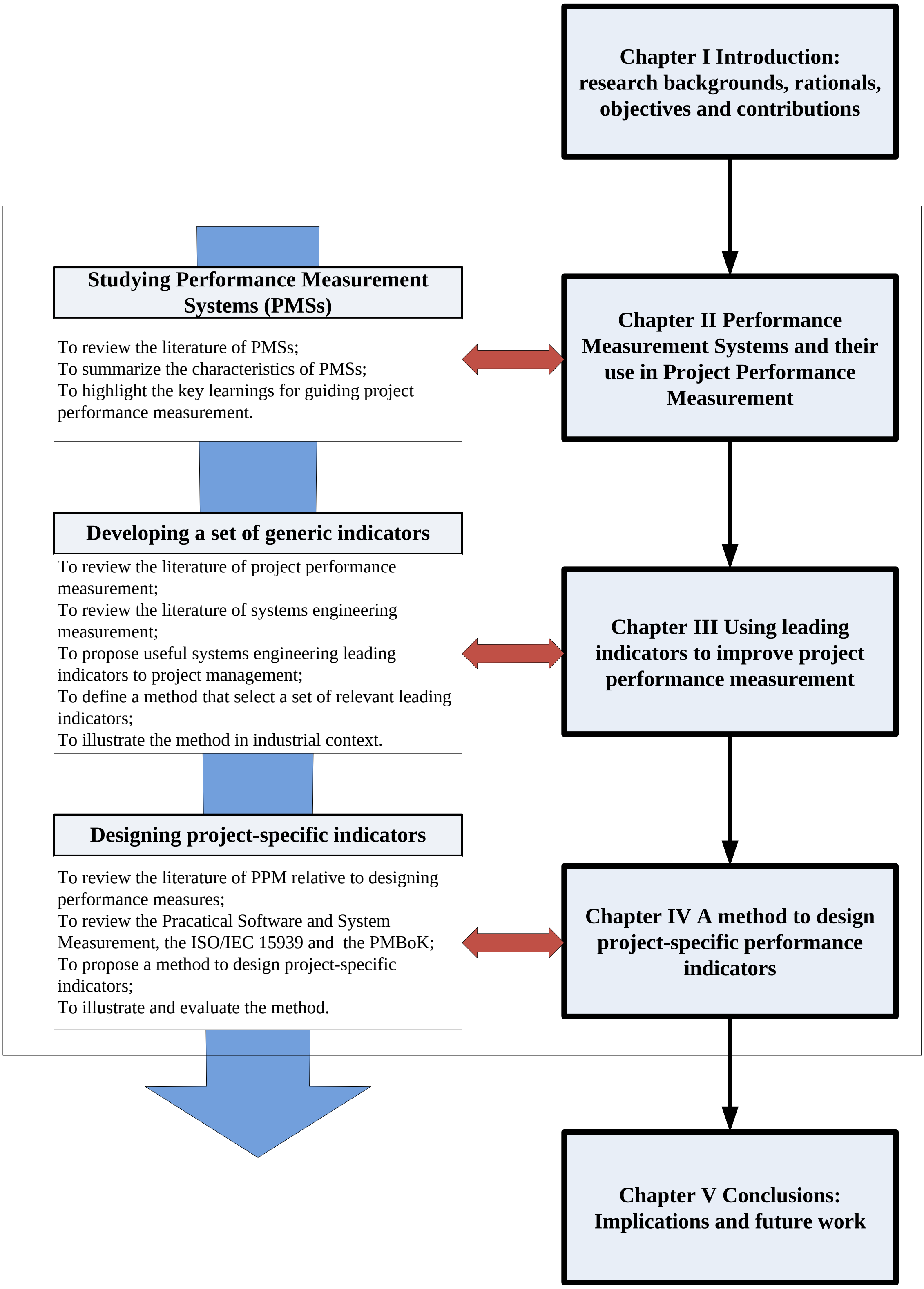

Figure I–2 Structure of the report

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Chapter II Performance Measurement Systems and their use in Project Performance Measurement

Performance measurement systems (PMSs) have got revolutionary changes since the 1980s. It has also had remarking development from classical PMSs to a broad diversification of PMSs. This chapter presents the basic concepts and the definitions in the literature of PMSs and conducts a survey on performance measurement models and frameworks to illustrate the development and evolution of PMSs research. It also analyses how these research results are implemented, or not, into software tools available on the market. It thus points out the gap between academic research results and supporting tools in the domain of the performance measurement and management. The definitions of terms and concepts such as “performance” and “performance measurement” in the PMSs enable us to have a better understanding of project performance measurement. In addition, recent studies in PMSs provide recommendations for tackling the issues of project performance measurement, with a focus on issues relative to project performance measurement, such as the scope and type of performance measures or the design of performance measures.

1. Introduction

Having a relevant performance measurement system in a company has become crucial since the 1980s so that, from that time, research has been developed on several performance measurement systems (PMSs). For the classical performance measurement systems (CPMSs), some features like “balanced”, “integrated” and “strategy-relevance” have been elaborated; a set of methods was quickly adopted in the industry (Bititci, Trevor and Begemann 2000) (Yadav and Sagar 2013), like Performance Pyramid System (Lynch and Cross 1991) or the Balanced Scorecard (Kaplan and Norton 1992, 1996). The latter became very popular because it considered both financial and non-financial measures (Choong 2013) (CIMA 2009).

Concurrently, with the advanced information technology, supporting software tools for performance measurement appeared on the market; many software suppliers sold their products asserting that they help companies evaluating the effective performance of their management. However, a survey we made on theoretical proposals in research on the one side, compared to available tools on the market on the other side, revealed that a wide gap existed between the techniques supported by those tools and the performance measurement models and frameworks elaborated by researchers. Hence the objectives of this chapter are:

- Presenting this survey that analyses both academic researches and supporting software tools in the domain of performance measurement and management;
- Making a gap analysis to establish the differences between “features” that the academic research is presenting and “features” that software vendors are delivering;
- Highlighting the characteristics summarized from the PMSs and their theoretical and methodological recommendations for project performance measurement;

- Demonstrating some issues addressed in PMSs, relative to the limitations of current project performance measurement systems, such as the balanced use of leading and lagging indicators and the design of context-matched performance measures.

This chapter is organized as follows (depicted in Figure II–1). Section 2 reviews the literature on performance measurement models and frameworks, especially demonstrating the definitions of key concepts and terms in this domain. Section 3 presents the survey on software supporting tools. Section 4 makes a gap analysis between academic research and supporting software functions. Section 5 presents the key learnings from the PMSs, the evolution of PMSs and its insights for project performance measurement.

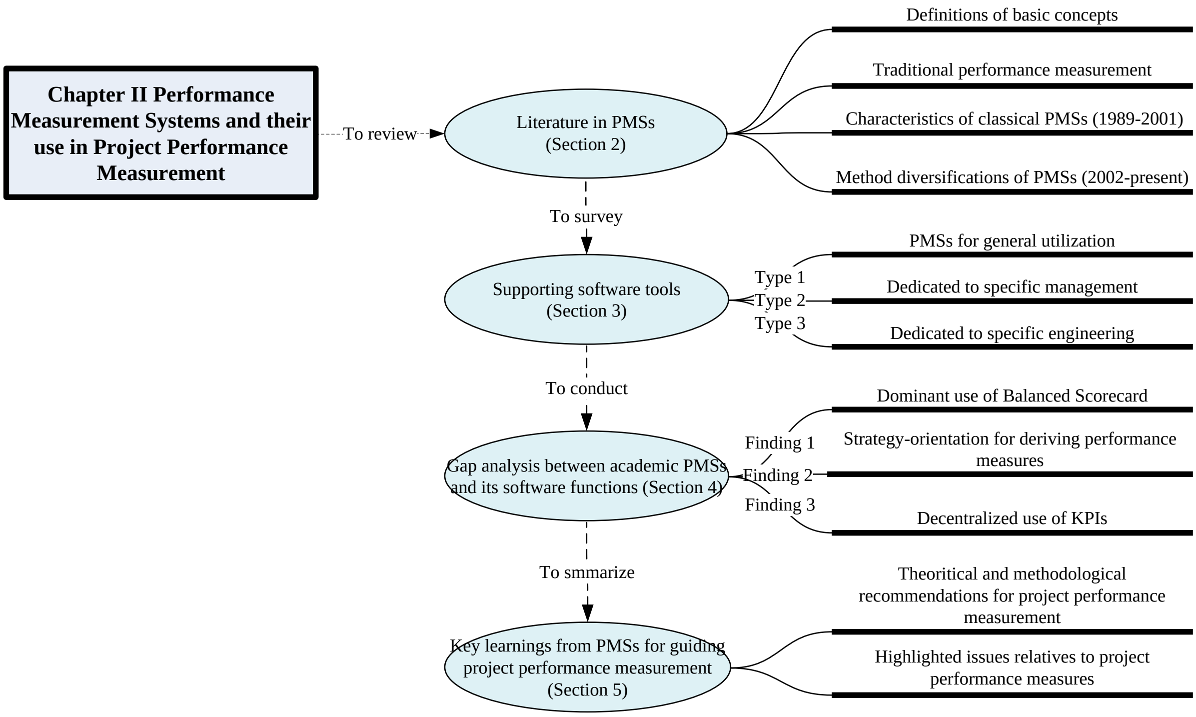

Figure II–1 The mind mapping for Chapter IV

2. Literature review on Performance Measurement Systems

Performance measurement has its long history that dates back to the early nineteenth century (Yadav and Sagar 2013). The definitions of basic terms and concepts have been elaborated from various perspectives by different authors, which will be illustrated in section 2.1. After a brief introduction to traditional performance measurement (depicted in Section 2.2), the section focuses on its recent history, where we identify two important periods, 1989 to 2001 and 2002 to present, when 1989 corresponds to the birth of integrated Performance Measurement Matrix (Keegan et al. 1989) and 2002 to a broad diversification of PMSs.

2.1. Basic concepts and definitions in PMSs research

In this section, several basic concepts and their definitions will be presented according to some representative studies. Definitions of terms and concepts like “performance” and “performance measurement” have never come to an agreement among researchers in this domain. Several representative definitions that get relatively high recognition are given below to offer a global view and knowledges.

2.1.1. *Performance*

Several definitions of performance selected in this study are representative of a considerable body of knowledge about performance measurement pertaining to the PMS research:

"Performance is about deploying *and managing well the components of the causal model(s) that lead to the timely attainment of stated objectives within constraints specific to the firm and to the situation."* (Lebas 1995)

"The level of performance a business attains is a function of the efficiency and effectiveness of the actions it undertakes." (Neely, Gregory and Platts 1995)

"Performance is the efficiency and/or effectiveness of an action." (Bititci 2015, p 34)

2.1.2. *Performance measures*

"Measure can, by definition, only be about the past, even if we are talking of measures about capability." (Lebas 1995)

"A performance measure can be defined as a metric used to quantify the efficiency and/or effectiveness of an action" (Neely, Gregory and Platts1995).

"A performance measure/indicator/metric is the qualitative or quantitative assessment of the efficiency and/or the effectiveness of an action." (Bititci 2015, p 34)

2.1.3. *Performance measurement*

"Performance measurement can be defined as the process of quantifying the efficiency and effectiveness of action." (Neely, Gregory and Platts1995)

"Performance measurement is the process of collecting, analysing and reporting information regarding the performance of an action." (Bititci 2015, p 34)

2.1.4. *Performance measurement systems*

"A performance measurement system can be defined as the set of metrics used to quantify both the efficiency and effectiveness of actions." (Neely, Gregory and Platts 1995)

"A performance measurement system is the process (or processes) of setting goals, developing a set of performance measures, collecting, analysing, reporting, interpreting, reviewing and acting on performance data." (Bititci 2015, p 34)

2.2. Traditional performance measurement

According to Ghalayini and Noble (1996), the literature concerning performance measurement has had two major phases: (1) traditional performance measurement that focused on financial measures (from the late 1880s through the 1980s); and (2) non-traditional performance measurement systems (from the late 1980s).

Traditional performance measurement has been primarily based on management accounting systems and thus performance measures were developed to provide financial performance (Ghalayini and Noble 1996).

Limitations of traditional performance measurement

Some representative financial measures in traditional performance measurement, such as “return on investment” and “market share”, are historical in nature. Ghalayini and Noble (1996) summarized 8 most commonly limitations: the basis of traditional management accounting systems, lagging metrics, not incorporated strategy, less relevance to practice, inflexible, expensive, conflict with continuous improvement, and no longer useful to meet customer requirements and management techniques.

Traditional performance measures received many critics. Anderson and McAdam (2004) demonstrated several cited limitations discussed in (Bourne et al. 2000) (Manoochehri 1999) (Neely 1998). They are respectively:

- encouraging short termism;
- lacking strategic focus;
- encouraging local optimisation;
- providing misleading signals for continuous improvement and innovation; and are not externally focused in relation to customers and competitors.

The limitations of traditional performance measurement make them less applicable in a more complex organizational management and more competitive market environment. Thus attentions have been shifted to seek a more comprehensive performance measurement methodology that can overcome the limitations of traditional performance measurement and incorporate some new elements to enrich performance measurement systems. A turnover in performance measurement research occurred in the late 1980s under the need of a new performance measurement practice, named as the classical performance measurement systems.

2.3. Classical performance measurement systems (1989-2001): a turnover—addressing the balance between financial and non-financial measures

Since the late 1980’s, performance measurement has experienced a great turnover. The main stake was addressing the need for a balance between financial and non-financial measures (Giannopoulos 2013) (de Lima et al. 2013). Developing a better integrated, relevant, strategy-oriented and dynamic performance measurement system became a recurrent goal in the field. In this period, most of the results are model bound and are presented as performance measurement systems (PMSs). Among the most successful ones, this paper analyses and compares 6 classical PMSs: Performance Measurement Matrix (Keegan et al. 1989), Performance Pyramid System (Lynch and Cross 1991), Result and Determinants Framework (Fitzgerald et al. 1991), Balanced Scorecard (Kaplan and Norton 1992, 1996), Dynamic Performance Measurement System (Bititci, Trevor and Begemann 2000) and Performance Prism (Neely, Adams and Crowe 2001). Detailed descriptions for these individual PMSs are demonstrated in the following sections. The perspectives and the characteristics of these PMSs are presented in Table II–2.

2.3.1. *Performance Measurement Matrix*

The Performance Measurement Matrix Framework (Keegan et al. 1989) took a lead in considering and integrating different business performance dimensions—financial and nonfinancial, internal and external, where performance measures tended to become balanced. This matrix, however, has not developed the balance of indicator types as to leading and lagging indicators.

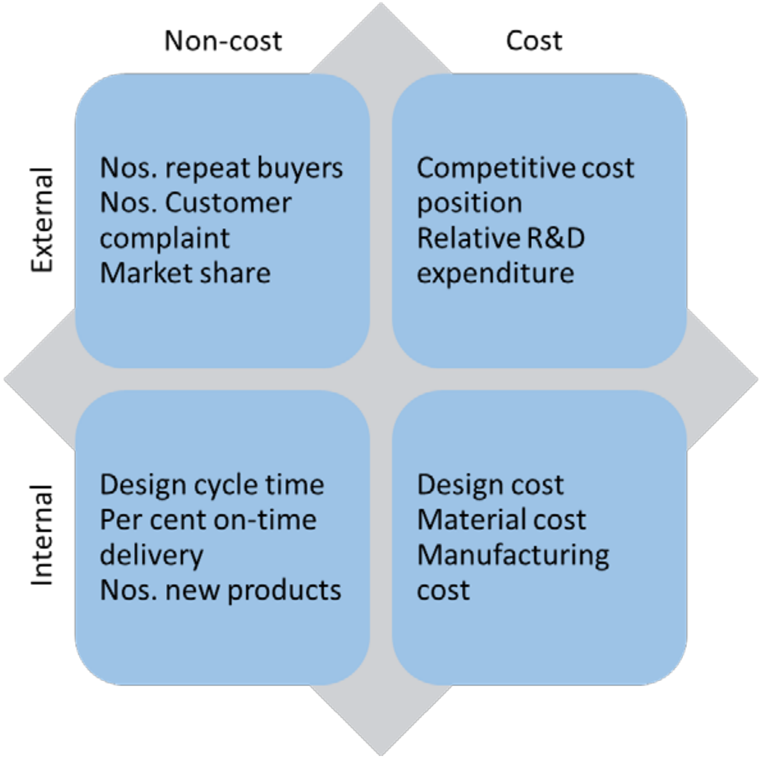

Figure II–2 The performance measurement matrix framework (Keegan et al. 1989)

2.3.2. *Performance Pyramid System*

There are, however, several frameworks which encourage executives to pay attention to the horizontal flows of materials and information within the organization, i.e. the business processes. Most notably of those is the Performance Pyramid System proposed by Lynch and Cross (1991).

The pyramid is built of four levels structuring the different objectives and measures. As the strategy is diffused vertically from the top down, it is transformed into operations. Conversely, the measures are then assigned to the objectives from the bottom up. The core part of this pyramid is at its top, where the senior management develops a vision for the organization. The lower level splits the vision into business units, where objectives are set in term of market and financial terms. One lower level is the Business operating systems, where operating objectives can be focused on for major support of the business strategy. Last, the basement level includes quality, delivery, cycle time and waste.

This model contributed to extending the vision of organizational performance, and digging the deep causes for performance effect. It also considered different measure types according to different organizational functions (Business units, Business operating system, and Department and work centres).

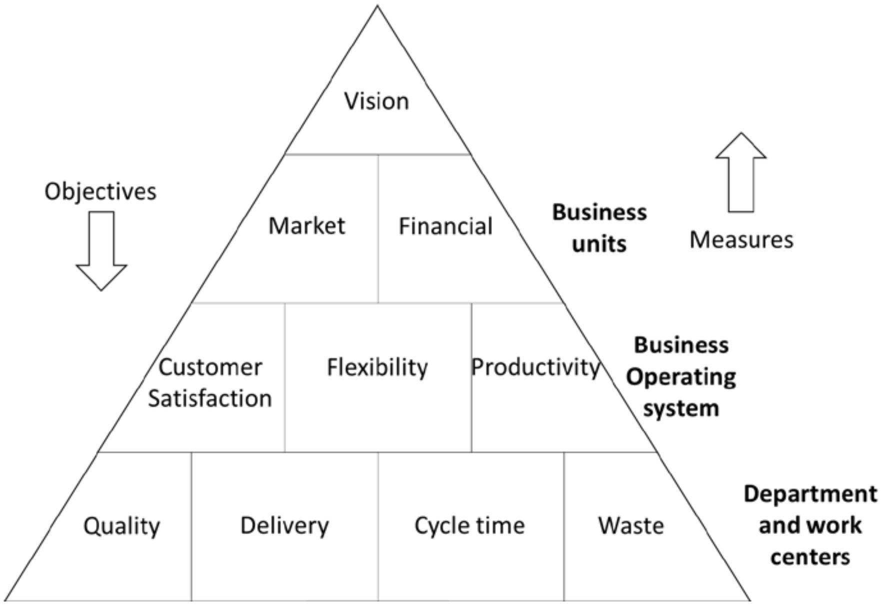

Figure II–3 The performance pyramid system

2.3.3. *Result and Determinants Framework*

Result and Determinants Framework (Fitzgerald et al. 1991) presented the balance of measures between "result" of performance and "determinants" of performance. This framework took a lead in incorporating leading and lagging indicators in the PMSs research. In their study, they assumed that there are two types of performance measures in an organization: one is related to results and the others are the determinants of results. The framework conceptualises the results-related measures as lagging indicators which reflect the ultimate objectives of an organization whereas determinants-related measures are conceptualised as leading indicators that reflect the impact factors of the ultimate performance of the organization.

Table II–1 The Result and Determinants Framework (Fitzgerald et al. 1991)

Categories	Indicators of performance	Dimension of performance
Results	Lagging indicators	Competitiveness
		Financial performance
Determinants	Leading indicators	Quality of service
		Flexibility
		Resource utilisation
		Innovation

2.3.4. *Balanced Scorecard*

Performance measurement has evolved with addressing that business or organizational performance could be enhanced with the help of a balanced set of measures. The Balanced Scorecard (Kaplan and Norton 1992, 1996) has been developed in this context and becomes one of the most widely recognised performance measurement frameworks of today (Neely et al. 2000). This model addresses that the best performance measures are those linked to a firm's strategy. There are 4 perspectives where measures are developed in this model (Figure II–4). These perspectives are:

- Financial perspective: how do we look to our shareholders?
- Customer perspective: how do our customers see us?
- Internal perspective: what must we excel at?
- Innovation and learning perspective: can we continue to improve and create value?

Some researchers have interpreted the "balance" in BSC as the consideration of financial and non-financial measures, leading and lagging indicators and short- and long-term measures (Ahn 2001) (Yadav and Sagar 2013). In spite of its popularity in both academic and industries, several shortcomings have been highlighted in the literature, such as the lack of stakeholder focus (Neely, Adams and Crowe 2001) and the difficulty of implementation (Neely and Bourne 2000).

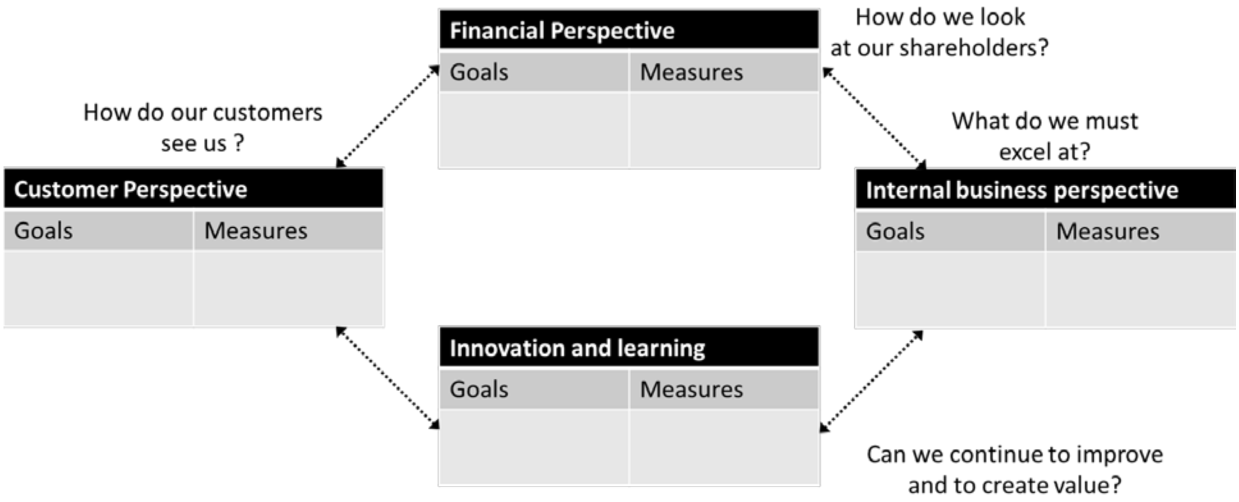

Figure II–4 The Balanced Scorecard model (Kaplan and Norton 1992, 1996)

2.3.5. *Dynamic PMS*

This model (depicted in Figure II–5) emerged from the realization that a performance measurement system needs to be dynamic, including some characteristics such as being sensitive to environmental changes and reviewing and reprioritising internal objectives when changes are significant (Bititci, Trevor and Begemann 2000). Thus a dynamic performance measurement system should have:

- An external monitoring system, which continuously monitors developments and changes in the external environment
- An internal monitoring system, which continuously monitors developments and changes in the internal environment and raises warning and action signals when certain performance limits and thresholds are reached.
- A review system, which uses the information provided by the internal and external monitors and the objectives and priorities set by higher level systems, to decide internal objectives and priorities.
- An internal deployment system to deploy the revised objectives and priorities to critical parts of the system.

The model was extended in the form of a requirements specification, which was used to test the maturity and suitability of existing knowledge in the field to create dynamic performance measurement systems.

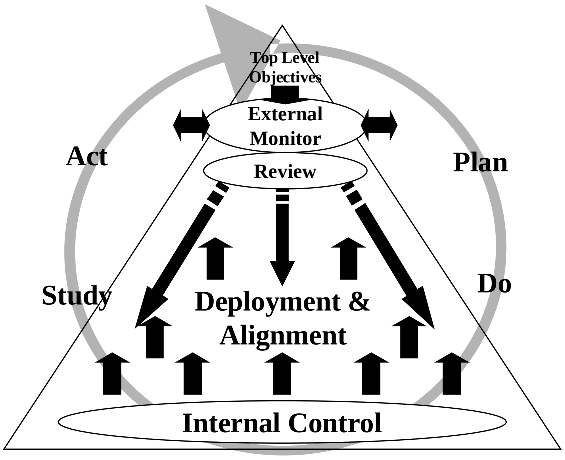

Figure II–5 A dynamic PMS model (Bititci, Trevor and Begemann 2000)

2.3.6. *Performance Prism*

This framework addressed the shortcomings of many of the existing PMSs. Different from most of PMSs that have strategic orientation, The Performance Prism, having stakeholder focus, encourages executives to consider the wants and needs of all the organisation's stakeholders, rather than a subset, as well as the associated strategies, processes and capabilities (Neely, Adams and Crowe 2001).

The performance prism consists of 5 interconnected facets (cf. Figure II–6), they are detailed as follows:

- Stakeholder Satisfaction: Who are the stakeholders and what do they want and need?
- Strategies: What are the strategies we require to ensure the wants and needs of our stakeholders are satisfied?
- Processes facet: What are the processes we have to put in place in order to allow our strategies to be delivered?
- Capabilities facet: What are the capabilities we require to operate our processes?

- Stakeholder contribution: This facet explores the relationship of an organization and its stakeholders, aiming to involving the stakeholders contributing to the organisation.

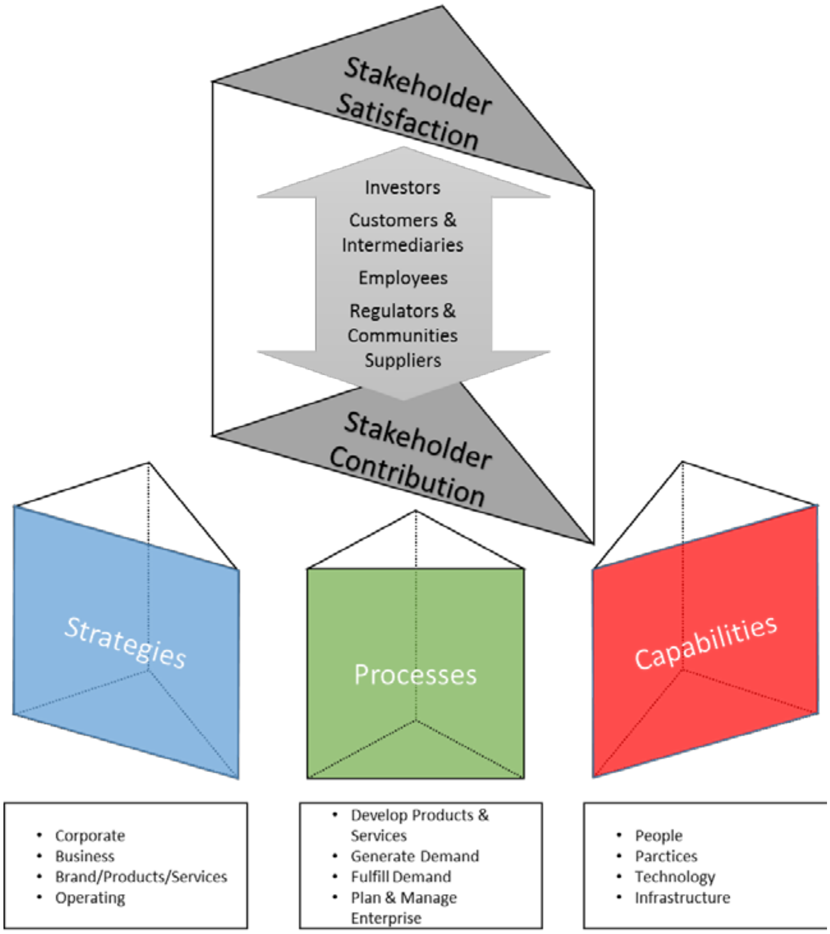

Figure II–6 The performance PRISM model (Neely, Adams and Crowe 2001)

2.3.7. *The characteristics of the classical PMSs*

The preceding literature review provides a global view of classical performance measurement models and frameworks. To summarize these models and frameworks, we use a table with 3 main classifications consisting of the "perspectives", "main pillars" and "characteristics" (Table II–2).

The "perspectives" represents the dimensions or areas of "performance" in a PMS. For example, as illustrated in Section 2.3.4, the Balanced Scorecard (Kaplan and Norton 1992, 1996) consists of 4 performance perspectives, considering some most essential performance dimensions in an organization such as the finance, the innovation and learning, the internal processes, and the customers. The "main pillars" illustrates the main considerations or main parts of the methodology inherent in each PMS to improve organizational performance. For example, "Identify stakeholders" from PRISM model, named as one of the five identified pillars in Table II–2, is the first part of Neely, Adams and Crowe's (2001) methodology.

Indeed, each PMS has its "perspectives" to show that different researchers have their individual points of view of what performance consists of; and the "main pillars" reveals the main parts of the methodology in each PMS.

Both "perspectives" and "main pillars" have been illustrated in the proceeding sections (cf. Section 2.3.1-2.3.7). For the purpose of this report, we need to proceed specifically to the "characteristics" revealed in the PMSs with the development and evolution. Synthetizing the characteristics is important because these characteristics represent their differences from traditional performance measurement, meaning more effective performance measurement. Thus they should be highlighted. The following paragraphs depict them respectively.

"Balanced" represents the equilibrium of the performance measure types, which has been classified from different perspectives. For example, the Balanced Scorecard (Kaplan and Norton 1992, 1996) highlights the financial and nonfinancial measures, while the Performance Measurement Matrix Framework (Keegan et al. 1989) underlined the balance between cost and non-cost measures and between internal and external measures. In addition, some PMSs models referred to the balanced utilization of leading and lagging indicators of performance. For example, the Result and Determinants Framework (Fitzgerald et al. 1991) (Fitzgerald and Moon 1996) took a lead in incorporating leading and lagging indicators in the PMSs research. In this regard, (Grady 1991) gave a good explanation: "Performance measures need to be balanced. Balance includes internal measures with external benchmarks, cost and non-cost measures, result measures to assess the degree goals are achieved, and process measures to evaluate critical tasks and provide early feedback."

"Integrated" represents the integration, both hierarchical and across the business functions. Suggestions on how to do this have been discussed in academic field (Neely et al. 2000).

"Strategy-oriented" has been a dominant practice in deciding what to measure (Neely, Adams and Crowe 2001). It becomes a common consensus among scholars that it is the strategies that direct what to measure (Keegan et al. 1989) (Lynch and Cross 1991) (Kaplan and Norton 1992, 1996). It means that the first thing involved in considering the sources of performance measures is to look to strategy—setting the organizational strategical objectives and then quantifying goals for achieving these objectives.

"Multiple-perspectives" is one of the most remarkable characteristics of the classical PMSs, as single dimension focusing on financial aspect of performance measurement was criticized to fail in meeting customers' requirements (Bourne et al. 2000) (Manoochehri 1999) (Neely 1998). It can be seen from Table II–2 that all the classical PMS models are constituted by different performance perspectives, focusing more on non-financial performance. For example, five facets (stakeholder satisfaction, strategies, processes, capabilities, and stakeholder contribution) are demonstrated in the Performance Prism.

"Stakeholder focus" provides a complementary for the dominant "strategy-oriented" practice in PMSs. With the development of the PMSs research, people come to realise that although the strategies and objectives of an organization plays an important role in deciding what measures can be adopted, the ignorance of stakeholders' satisfactions impact directly the performance success (Neely, Adams and Crowe 2001).

"Dynamic" of a PMS has been addressed to explore whether the existing PMSs models are sufficiently advanced to create a truly dynamic performance measurement system when the external and internal environment of an organisation is not static but is constantly changing (Bititci, Trevor and Begemann 2000).

Table II–2 Towards a balance between financial and non-financial measures

PMSs: classical Performance Measurement Systems (1989-2001): a turnover—addressing the need for a balance between financial and non-financial measures; better integrated performance measurement systems						
Name of PMSs models and framework	**PPM**: Performance Measurement Matrix	**PPS**: Performance Pyramid System	**RDF**: Result and Determinants Framework	**BSC**: Balanced Scorecard	**DPMS**: Dynamic PMS	**PP**: Performance Prism
Perspectives	External/cost; External/non-cost; Internal/cost; Internal/non-cost	Vision; Market, Financial; Customer Satisfaction, Flexibility, Productivity; Quality, Delivery, Cycle time, Waste	Results--competitiveness, financial performance; Determinants--quality, flexibility, resources, and innovation	Financial perspective; Internal business perspective; Innovation/learning perspective; Customer perspective	An external monitoring system; An internal monitoring system; A review system; An internal deployment system	Stakeholder satisfaction; Strategies; Processes; Capabilities; Stakeholder contribution
Main pillars	1.Performance measures must be derived from strategy; 2.Performance measures integrated vertically and horizontally; 3.Performance measures supporting the multidimensional environment; 4. Performance measures based on cost relationships and behavior.	1.Putting corporate vision in focus; 2. Linking corporate strategy to operation; 3. Ensuring correct direction by the vertical and horizontal alignments.	1. Incorporating that results are lagging indicators; 2.Determinants are leading indicators; 3. Defining carefully the performance indicators needed to achieve the performance objective.	1. The balanced scorecard is based on four perspectives surrounding the company's vision and strategy; 2. No pre-defined measures, measures rely on cases; 3. Goals and measures are bounding together.	1. Adopt a broader definition for performance measurement; 2. A control loop to include corrective action; 3. Numerous interrelated performance measures; 4. Review mechanism.	1. Identify stakeholders; 2.Make the strategies to satisfy stakeholders; 3.Put the processes in place to deliver the strategies; 4. Identify capabilities to operate processes; 5. Propose the want and need from stakeholders.
Characteristics	Balanced, integrated, strategy-oriented, multi-perspectives, dynamic and stakeholder focus					

2.4. Performance measurement systems (2002-present): Towards a broad diversification of methods for performance management

After the classical PMSs addressing the balanced, integrated and dynamic system, it seems that broader avenues for this domain were opened by researchers since 2002. Researchers from different disciplines have brought fresh blood into the PMSs research by blending the methods of system dynamics, total quality management, supply chain management and so on into the research of PMSs. In this trend, several different directions are identified: BSC-related approaches, Visual Performance Measurement Systems (VPMS), Project Performance Measurement Systems (PPMSs), Supply-Chain Performance Measurement Management (SCPMM), Quantitative Models for PMSs (QM-PMSs), PMSs for SMEs, and IT-PMS implementation (cf. Table II–3), and some general characteristics are synthesized from these various directions:

- Multi-crossed disciplines. Many methods and theories of other disciplines are brought to extend the performance measurement and management.
- Toward case-analysis. Researchers present their PMSs by a more empirical analysis with the combination of quantitative and qualitative methods.

- Extend and go beyond the classical BSC framework. The BSC model has presented some shortcomings when implemented in enterprise environment during a decade; some researchers extended and went beyond the BSC approaches to emphasize the issues.
- Collaborate between academic and practice for "knowledge transfer". Some researchers owning management consulting enterprises have proposed their concepts of performance measurement, concurrently developed a supporting software tool for performance measurement and completed it with case companies (Busi and Strandhagen 2004). On the other hand, some other researchers who did not design a software tool for testing their theory, but shifted the challenge from designing an expensive intra-software to buying a commoditized, high quality and inexpensive model from software vendors (Meekings, Povey and Neely 2009).

Table II–3 Towards performance management with the diversification

Directions	Main contributions		Characteristics
BSC-related approaches	BSC-TQM	Kanji's business scorecard: Kanji and Sá (2002)	It integrates the total quality management principles and critical success factors with the BSC model.
		TQM–BSC Linkage: Hoque (2003)	TQM–BSC linkages; TQM–BSC linkage issues matrix;
	Beyond-BSC	Dynamic multi-dimensional performance framework: Maltz et al (2003)	It breaks the limitation of BSC and takes five dimensions into the framework: Financial performances; Market/customer; Process; People development; Future.
	BSC-SDM	System dynamics-based balanced scorecard: Barnabe (2011)	Matching the dynamics principles with the BSC framework
		Proactive balanced scorecard: Chytas et al. (2011)	It has used fuzzy cognitive map and simulation to improve the implementation of BSC framework
	BSC-SCM	A balanced scorecard approach for supply chain performance: Bhagwat and Sharma (2007)	It considered the use of a BSC framework to measure and evaluate SCM with specific metrics for each of the perspectives;
Visual Performance Measurement Management (VPMM)	Visual strategy and performance measurement techniques for organizations: Bititci, Cocca and Ates (2015)		End-to-end visual strategy and performance management approaches are proposed to case companies and are found effective.
	Visual management function identification: Tezel, Koskela and Tzortzopoulos (2009)		Based on the Identification of main functions of visual management in different disciplines, an idea of completing a visual management framework for construction organizations is proposed.
Project Performance Measurement Systems (PPMSs)	A multi-dimensional project performance measurement system: Lauras, Marques and Gourc (2010)		It focused on 3 particular axes for the analysis of project performance: project task, performance indicator categories, and a breakdown of the performance triptych (effectiveness, efficiency, relevance).
Supply-Chain Performance Measurement Management (SCPMM)	A framework for supply chain performance measurement: Gunasekaran, Patel and Mc Gaughey (2004)		It considers the four major supply chain activities: plan, source, make/assemble, and deliver); every activity consists of metrics classified at strategic, tactical and operational.
	Green supply chain management on performance: Green Jr et al. (2012)		A comprehensive GSCM practices performance model is proposed and empirically assessed;
PMSs in SMEs	Key contingency factors for PMS in SMEs: Garengo and Bititci (2007)		Corporate governance structure, advanced information practices, a change in a firm's business model and an authoritative management style are four key contingency factors for PMS in SMEs.
Quantitative Models for PMSs (QM-PMSs)	Performance improvement based on a Choquet integral aggregation: Berrah, Mauris and Montmain (2008)		It designed a method for quantifying the causal relationship between the various criteria based on a Choquet integral aggregation operator.
IT-PMS implementation	Monitoring extended enterprise operations using KPIs and a performance dashboard: Busi and Strandhagen (2004)		It combined the concepts of KPIs, dashboards, and ICT to support extended enterprise performance management self-developed software.
	Performance plumbing: Meekings, Povey and Neely (2009)		It includes 4 key elements-performance architecture, performance insights; performance focus and performance action with Suggesting Commodity software for supporting the implementation of performance measurement framework.

3. Supporting software tools survey

According to the Balanced Scorecard Institute (BSI), there are over a hundred balanced scorecard and/or performance management automation development companies (BSI 2015). We have analysed these companies who develop software for providing performance measurement. It shows that some of them have no dedications and develop their software tools with general utilization. Some of them are dedicated to performance management for certain departments or industries. Others develop specifically tools which are primarily designed for specific engineering, for example, systems engineering. According to these, we have distinguished several criteria in our survey: "PMS for general utilization", "Dedicated to specific management" (such as project management, asset management; supply chain performance management), "dedicated to specific Engineering" (for example Systems Engineering). Getting through hundreds of websites that claim to provide supporting software for performance measurement, we have selected 6 software vendors for "PMS with general utilization", 4 for "dedicated to specific management", and 3 for "dedicated to specific Engineering" which have common characteristics of popularity and professionalization for software development. They are depicted in Table II–4.

Table II–4 Supporting software tools for performance measurement

Supporting software types	Software/ Enterprise/ Users	About KPIs/ Visual tools and functions	Modules and Main features
General utilization	Cognot BI/ IBM/ Every level of employees	KPIs-based/ Scorecards and strategy maps	Its Metric Studio provides a comprehensive performance monitoring.
	BSC designer/ Top-managers and CEOs	KPIs-based Leading indicators and lagging indicators/ Strategy map and Balanced scorecard with alerts function;	Strategy map design; KPIs design; Track strategy execution and monitor current performance with KPIs; Cascading scorecards by business goals or by KPIs.
	Necto /Panorama/ Inter-and intra-organization	No reference about KPIs/ Dashboards & simplified infographics with alerts function and easily connected to multiple data sources;	Collaborating and sharing knowledge (integration); Data discovery and analytics; Creating a workboard; Automated tools to share insights and alerts.
	Signalsfromnoise/ Lightfoot/ Front-line staff; Supervisors; Managers.	No reference about KPIs/ Intuitive *sfn* dashboards and SPC chart format with alerts function;	Easy installation; flexibility to extend and add data sources from providers along with a service journey; availability across the whole organization; easy integration with multiple operational systems; up-to-the-minute information.
	Visual KPI/TRANSPARA/ Decision makers, Executives; Operations	A go-to rapid prototyping tool for testing KPIs/ Dashboards with alerts & analytics function;	Designed for real-time operations; Find problems before they find you; Lightweight analytics on your phone; using the Microsoft Excel-based Visual KPI Designer and focusing on rapid prototyping and changes.
	EPM Suite/ Corporater business in control/all levels of the organization	highly flexible and powerful metrics management functionality/ Dashboards	Dashboards and KPIs; Strategic Initiative & Projects; Budgeting and Planning; Performance Reporting.
Dedicated to specific management	QuickScore /Spider strategies/ No referred	It helps find metrics and KPIs flexibly/ Dashboards	Create beautiful strategy maps; Scoring your metrics; Many ways to update; Instant aggregation; Calculated metrics; Track goals over time.
	Maximo asset management /IBM/ Asset management	No reference about KPIs/ Dashboard	6 modules: asset, work, service, contract, materials, and procurement management.
	Cognos Supply Chain Performance Procurement Analytics(SCPPA) /IBM/ Supply chain management	It measures supplier performance across a range of KPIs/ Dashboard	Analyze spending to ensure goods are purchased from cost-effective sources; Analyse buying patterns, deliveries and how well different suppliers respond to your needs; Compare supply chain needs to sales trends and future product plans.
	Quickbrain/ CRAZYLOG/ Plant Life Cycle Management	No reference about KPIs/ Screenshots and Smart-drawings with Pack e-CMMS and Pack e-DMS.	10 modules: DOC; MAINT; COMS; EVENT; STOCK; ILS; BI; DRAW-E; PID-SCAN; Screenshots.
Dedicated to specific Engineering	Squore/Squoring/ Project managers; Systems engineers	It provides KPIs or integrate existed KPIs in enterprises/ Squore decision-making dashboard; Software and systems project management dashboards;	"Custom"--Help define KPIs; "technical debt"—optimize the quality of software development; "acceptance"—secure and rationalize acceptance processes; "automotive"—manage embedded systems projects; Systems engineering—manage the performance of systems engineering projects.
	Ajera /Deltek/ Project managers and Accountants	Ajera dashboards (no alert function)	role-based: For a principal—improve profit margins; For department manager—improve visibility and decision making; For project manager—manage client relationships; For controller—increase department efficiency.
	arKItect /Knowledge Inside/ Systems engineer	A graphic editor	2 products: SEA and Designer. SEA offers an easy-to-use environment for modeling multi-disciplinary systems and specifications and work products; ArKItect Designer can customize the tool according to customer own needs.

Visualizing such diversifications of functions provided by these tools, a concerned question has arisen to us: "Are these tools delivering completely the value of academic research of performance measurement?" In the following section, a gap analysis will be conducted to address it.

4. Gap analysis between academic research and its software functions

For doing the gap analysis, we chose 13 software vendors with a classification of "PMS for general utilization", "dedicated to specific management" and "dedicated to specific engineering" in the first vertical column of Table II–4. To visualize this gap, we have chosen respectively some common and specific characteristics from the two different periods of performance measurement models and frameworks as analysis indicators to measure the fitting between academic and practice. In the period of classical performance measurement systems (1989-2002), there are some common focuses including balanced, integrated, strategy-relevance, and multi-perspectives; concurrently the characteristics of dynamic and stakeholder-focus are specifically referred in certain researches (Bititci, Trevor and Begemann 2000) (Neely et al. 2001) (cf. Table II–2). In the second generation of performance measurement models and frameworks (2002-present), we have chosen 6 main different development directions, and two topics such as "KPIs-based" and "connected to multiple data sources" as analysis indicators (cf. Table II–3).

(1) Fitting rate analysis

With the fitting depicted in Table II–6, we find that academic results of performance measurement models and frameworks have been focused differently in the practices of supporting software development. Some characteristics like "balanced", "strategy relevant" and "integrated" addressed widely in academic are not receiving the attention of software vendors; inversely some not well-referred concepts like "connected to multiple data sources" and "visualization" have been addressed very well by a 100% fitting in the sample software tools. It seems that software development has advanced a little more in some aspects than academic research (cf. Table II–5).

Table II–5 Fitting rate analysis between software tools and academic researches

Characteristics	Fitting rates
Multi-perspectives; Connected to Multiple data sources; VPMM; KPIs-based.	High fitting rates (≥ 60%)
Balanced; integrated; strategy-relevant; stakeholders focus; Dynamic; PPMS; SCPMM; QM-PMSs; PMSs for SMEs.	Low fitting rates (<60%)

(2) Main findings from the fitting rate analysis results

Firstly, for several classical PMSs, only the Balanced Scorecard has been used across the world, whereas many other frameworks have tended only to have regional appeal, many vendors developed their software tools for supporting enterprise performance measurement with consideration of the famous scorecard, but ignoring the advantages of other PMSs; as a result, developed software tools based on Balanced Scorecard exposed some disadvantages. For example, theoretically the Balanced Scorecard was conceptualized as a controlling tool for senior managers and not as an improvement tool for factory operation levels, addressing the importance of concentrating on a few of critical performance indicators; However some software vendors claim to be able to provide unlimited indicators.

Table II–6 The academic research on performance measurement vs. supporting software tools

Analysis indicators / Analysis objects		CPMSs: Classical Performance Measurement Systems (1989-2002)						PMSs: Performance Measurement Systems (2002-present): Towards performance management							
		Characteristics				Specific characteristics		Different research directions						Topics	
Subjects	Software	Ba.	In.	St.-re.	Multi-pe.	St. fo.	Dyn.	BSC Re.	VP-MM	PP-MS	SC-PM-M	QMP MSs	PMSs for SMEs	KPIs-based	CM.
General utilization	Cognot BI	X	X	X	X				X				X	X	X
	BSC designer	X	X	X	X			X	X				X	X	X
	Necto		X		X				X					X	X
	Signalsfromnoise		X		X				X						X
	Visual KPIs								X					X	X
	EPM Suite	X	X	X	X			X	X	X				X	
Dedicated to specific management	QuickScore	X		X	X			X	X				X	X	
	Cognos SCPPA										X			X	X
	Maximo Asset management							X							X
	Quickbrain				X			X					X		X
Dedicated to specific engineering	Squore		X		X			X	X					X	X
	Ajera		X		X			X	X					X	X
	arKItect				X			X	X						X
Fitting rate		30%	54 %	30%	91%	0	0	22%	100%	44%	11%	0	22%	70%	100%

Notes: Ba. refers to Balanced; In. for integrated; St-re. is for strategy-relevance; Multi-pe. is for multi-perspectives; St. fo. is for stakeholders focus; Dyn. for Dynamic. BSC Re. is for BSC related; Well-ref. is for well referred; CM. is for Connected to Multiple data sources.

Secondly, "Performance measures must be derived from strategy" dominated the direction of relevant software development; however the PRISM proposed by some scholars (Neely, Adams and Crowe 2001) has denied the traditional opinion that measures should be derived from strategy. Instead, they thought that the starting point should be: "Who are the stakeholders and do they want and need?" However, this proposal has not been followed by main software vendors. Similarly, DPMS model (Bititci, Trevor and Begemann 2000) has identified that current knowledge and techniques are sufficiently mature to create the DPMS, not having received the attention of software vendors yet.

Thirdly, the classical PMS—Balanced Scorecard (Kaplan and Norton 1992, 1996) provoked to minimize information overload by limiting the number of measures used. It keeps adding new measures whenever an employee or a consultant makes a good suggestion, enabling managers to focus on the handful of measures that are most critical. Indeed, in the market of developing BSC-related software, the vendors and developers did not focus on the critical measures. They proposed to use KPIs, but these KPIs seemingly are decentralized with a lot of elements.

5. Key learnings from the development and evolution of PMSs and its implications for project performance measurement

Up to this point, we have globally reviewed the development and evolution of the PMSs. The preceding work enables us to obtain a general view of performance measurement and management. Based on the whole vision, some characteristics have been summarized, and these characteristics could be used as general guidance to develop project performance measurement approaches. Such discussions are presented in Section 5.1. Then we focus specifically on the performance measures of PMSs. The essence of performance measures have been addressed widely in the literature of PMSs, especially the use of leading and lagging indicators, demonstrated in Section 5.2.1, and the methods of designing appropriate measures, presented in Section 5.2.2.

5.1. The characteristics of classical PMSs and recently developed frameworks

Based on the literature review (cf. Section 2.3), a classical PMS was addressing the characteristics such as "balanced", "integrated", "strategy-oriented", "multiple-perspective" and "dynamic". This set of characteristics is considered as key recommendations in developing PMSs models and approaches, which has revolutionarily changed the way performance is measured. Some of the characteristics have led us to think of what we can take from them to develop performance measurement approaches for projects. For example, the characteristic "dynamic" has been addressed for a performance measurement system, providing the benefits of responding quickly to external and internal environmental changes. In this regard, how to design "dynamic" project performance measurement system is worthy exploring. It is also important to bear in mind that PMSs have been widely developed in business context and some possible inappropriateness should be reckoned when considering the recommendations obtained from PMSs for project performance measurement. For example, the "strategy-oriented" for deriving performance measures may be not appropriate for a project.

PMSs have got rapid development with new models and frameworks developed for addressing performance management (2002-present). Some characteristics have been synthesized from the literature of this period (cf. Section 2.4). They are respectively "Multi-crossed disciplines", "Toward case-analysis", "Extend and go beyond the traditional BSC framework" and "Collaborate between academic and practice for 'knowledge transfer'". These characteristics reveal the evolution of this domain, which can provide some methodological guide to improve project performance measurement. For example, the characteristic "Multi-crossed disciplines" contributes to extending PMS approaches and complementing the theories of the field by encouraging learning from other disciplines. This leads us to think to improve current project performance measurement based on good practices from other disciplines, not limited to seeking solutions from the literature on project performance measurement itself.

5.2. The essence of performance measures as part of an overall system

Various organizational performance measurement models and frameworks have been developed over the years to help management visibility and control. According to the preceding review it is clear that performance measures are the most essential part of a performance measurement system. Indeed various related themes have been raised and discussed by researchers. For example, the selection of performance measures has been widely discussed; and approaches for developing indicators have been well focused as well. Indeed, these are relative to the issues in project performance measurement that we are addressing in this report, such as the need to extend the scope and type of indicators, the need to balance lagging indicators (to control) with leading indicators (to monitor), and the need to construct performance indicators that are relevant to project-specific information needs (cf. Chapter I). Thus, our motivation in this section is to highlight some issues of the PMSs especially relative to the limits of current project performance measurement.

5.2.1. *Type of performance measures*

Generally a PMS are multiple perspectives. Once the "perspectives" (sometimes named as "performance dimensions" or "performance areas") have been developed, a set of performance measures should be elaborated for every perspective. Performance measure types could be various for different functions. A clear understanding of the types of measures is necessary and important. With decades of year's development of PMSs, the types of performance measures have been discussed widely in literature. One of critical issues addressed in the PSMs over the type of measures is a balanced use of leading and lagging indicators, which will be presented from the various points of view according to different authors as follows.

As presented previously, the Result and Determinants Framework (Fitzgerald et al. 1991) (Fitzgerald and Moon 1996) took a lead in incorporating leading and lagging indicators in the PMSs research. The framework conceptualises the results-related measures as lagging indicators which reflect the ultimate objectives of an organization whereas determinants-related measures are conceptualised as leading indicators that reflect the impact factors of the ultimate performance of the organization.

The popular Balanced Scorecard includes 4 perspectives (Kaplan and Norton 1992, 1996). In their books, the authors thought that there were causes and results between the 4 perspectives and the internal processes are leading indicators of financial perspectives.

Ghalayini and Noble (1996) reviewed the limitations of traditional performance measures and presented one of the most important limitations is financial reports were usually closed monthly and they were lagging metrics that are a result of past decision, which were considered too old to be useful for performance assessment.

Beatham et al. (2004) stated:

"Leading measures do offer the opportunity to change. They are measures of performance whose results are used either to predict future performance of the activity being measured and present the opportunity to change practice accordingly, or to enable future decisions to be made on future associated activities based on the outcome of previous activities."

"Lagging measures are used to assess completed performance results. They do offer the opportunity to change performance or alter the result of associated performance. They are used only as a historic review."

Anderson and McAdam (2004) demonstrated that leading indicators that could be forward looking and predictive would have to be developed. In their critics, they have presented the shift of performance measurement from financial measures, also named conventional measures, traditional performance measures or lagging indicators.

In the study of Beatham et al. (2004), it is thought "*the sub process KPO (key performance outcomes) can be seen as a leading measure in the context of the overall result.*"

In this regard, it can be seen that this stream of studies in the PMSs is highlighting the relationship of leading and lagging indicators, especially addressing the importance of leading indicators. To summarize, we use the statement of Peng et al. (2007): "*leading indicators are very powerful metrics in that they possess not only the predictive and insightful causal relationship(s) within the business process(s), but also enable the actionable course for continuing process improvement.*"

In spite of the various definitions stated above, how to develop a balanced set of leading and lagging indicators stays still a key issue in the PMSs research. Lagging indicators are backward-focused or "trailing"—they measure performance data already captured; they help assessing whether your goals are achieved. These indicators, used to measuring results and based on outputs and outcome, are easy to measure and accurate, but hard to improve or influence; it is an after-the-event measurement, essential for charting progress but useless when attempting to influence the future. However, leading indicators signal future events; they are input oriented, hard to measure and easy to influence. They are generally seen as precursors to the direction something is going. Because leading indicators come before a trend, they are considered as drivers. However, they are more difficult to determine than lagging indicators but they can improve organization's decision making ability, and lay out what is working and what is not working within the organization and help guiding the management focus on the right directions.

What has become clear over years of PMSs research is that a combination of leading and lagging indicators result in enhanced business performance overall: A lagging indicator without a leading indicator will give no indication as to how a result will be achieved and provide no early warnings about tracking towards a strategic goal; a leading indicator without a lagging indicator may make you feel good about keeping busy with a lot of activities but it will not provide confirmation that a business result has been achieved. A 'balance' of leading and lagging indicators is required to ensure the right activities are in place to ensure the right outcomes. Especially, incorporating leading indicators into the dominant system of lagging indicators can broaden the scope, type and number of the existing indicators. In this regard, we seek to know: **To what extent has the topic of leading and lagging indicators already been developed in project performance measurement? Is it possible to improve project performance measurement by considering a balanced use of performance indicators (leading indicators to monitor and lagging indicators to control)?** The study in Chapter III is to address these questions.

5.2.2. *Designing an appropriate set of performance measures*

The importance of an appropriate set of performance measures have been highlighted in the PMSs, which can be proved by the developed measures under each framework or model in the literature review (cf. Section 2.3). Although some available measures proposed in those PMSs, it has been proved that the uncertainty about what to measure has been one of five mains problems faced in industrial practice (Lohman 2004). Identification, quantification, valuing and implementing measures have been a big difficulty in the use of PMS (Bourne et al.

2000). Dysfunctional behaviour can be possibly caused if the inadequate measures are designed (Neely et al. 1997).Thus one of the key streams in PMSs research is to seek an approach to design an appropriate set of performance measures. Many authors have shown their interests in it, presenting some rules and guides to the selection of performance measures (Lea and Parker 1989) (Globerson 1985), or suggesting a process to decide what to measure (Keegan et al. 1989). However, Neely et al. (2001) thought that the process to design performance measures at a rather superficial level.

According to Bourne et al. (2000), the development of performance measurement systems can be divided into 3 main processes, including:

- the design of the performance measures (design phase);
- the implementation of the performance measures (implementation phase);
- the use of the performance measures (use phase).

In their method, the design phase is the beginning of a PMS development, consisting of two activities—identifying the key objectives to be measured and designing the measures. The implementation phase focuses on systems and procedures to collect and analyse performance data regularly. The use of performance measures is subdivided into "assessing the implementation of strategy" and "challenging the strategic assumptions". The three phases corresponds with the three of Neely et al.'s (2000) processes for developing performance measurement system (the design, implementation and use processes). All of them addressed the importance of designing an appropriate set of performance measures. In literature of PMSs, the design of performance measures has been taken as a complex process (Neely et al. 1997), a process to decide what to measure (Neely et al. 2000).

Neely et al. (2000) cited the arguments from Keegan et al. (1989) who thought that the process consisted of 3 steps, including:

- looking to strategy,
- deriving an appropriate set of measures, and
- instilling the performance system into management thinking.

For designing performance measures, Neely et al. (1997) have proposed a framework—the performance measurement record sheet consisting of 10 elements:

- Title: title of a measure should be defined clearly (Element 1)
- Purpose: performance measures should be relevant and have an explicit purpose (Element 2)
- Relates to: performance measures should be related to business objectives (Element 3)
- Target: performance measures should have pre-set targets (quantities that can be benchmarked) (Element 4)
- Formula: the way performance is measured (Element 5)
- Frequency: performance should be recorded and reported in a certain frequency (Element 6)

- Who measures: the person who collect and report the data should be assigned (Element 7)
- Source of data: it is important to identify the source of the raw data (Element 8)
- Who acts on the data (Element 9)
- What do they do: the element suggests defining the general management process to follow if the performance appears to be either acceptable or unacceptable (Element 10)

Although the 10 elements in the framework of Neely et al. (1997) seems various, actually they can be regrouped and correspond to the 3 steps of Keegan et al. (1989). For example, the Element 1, 2 and 3 are telling one thing, as the first step of Keegan et al. (1989), that is to look to strategies (or objectives) as the sources of measures; Element 4, 5 and 6 are addressing one measure itself (quantitative part); and Element 7, 8, 9 and 10 are addressing how to make full use of the organizational management system to collect, analyse and report the data. To summarize and interpret, according to the proposals of Keegan et al. (1989) and Neely et al. (1997), 3 steps could be considered for the design of an appropriate set of performance measures relevant to organizational context. These are:

- Step 1 Deciding the sources/origins of performance measures;
- Step 2 Defining and constructing performance measures;
- Step 3 Instilling the developed indicators into management thinking.

The three steps summarized here will be a guide to designing project-specific performance measures in Chapter IV, in a way to check the development of each of the three steps in literature of project performance measurement, enabling us to have a vision of current status and possible issues in the concerned field.

6. Conclusion

This chapter reviewed the literature of PMSs and showed its development and evolution from classical PMSs to the diversification of PMSs. It illustrated key learnings from the PMSs. Indeed, the basic definitions of performance and performance measurement enable us a better understanding the nature of this discipline and deepen our knowledge of project performance measurement. The characteristics of PMSs provide theoretical and methodological recommendations for project performance measurement approaches that concern to us in this report. Especially, we identified some highlighted issues in PMSs, relative to the limitations of current project performance measurement systems, such as the need to extend the scope and type of indicators, the need to balance lagging indicators (to control) with leading indicators (to monitor) and the need to construct performance indicators that are relevant to project-specific information needs. Chapter III will focus on the issue of the unbalanced use of leading and lagging indicators in project performance measurement.

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Chapter III Using leading indicators to improve project performance measurement

Chapter I demonstrated the need to extend the scope, type and number of performance measures for effectively managing complex projects. Chapter II concluded that a balanced use of leading and lagging indicators resulted in enhanced business performance overall. This chapter thus seeks to explore the use of indicators in project performance measurement: To what extent has the topic of leading and lagging indicators already been developed in project performance measurement? Is it possible to improve project performance measurement by considering a balanced use of performance indicators (leading indicators to monitor and lagging indicators to control)? To address these questions, Chapter III first reviews the literature of project performance measurement and highlights the issues. Then a proposal is made to extend the scope, type and number of indicators used in project performance measurement by considering if leading indicators defined in systems engineering measurement can be adapted to this field. To this respect, the methodology proceeds in, first, mapping the systems engineering indicators with the project management activities thus resulting in the identification of a set of potentially useful indicators for measuring the different activities, then, tailoring a selection of these indicators with project-specific data to define a set of most relevant indicators for a given project. This methodology is illustrated on a case study in a manufacturing company.

1. Introduction

In today's highly competitive industrial environment, companies have to find solutions to keep improving their performance and to lead their projects at best (Aziz and Hafez 2013) (Choong 2013a) (Li and Zhao 2016). To reach this objective of increasing performance, there is a need to better control development cycles and manage project progress while maintaining the achievement of objectives (Meredith and Mantel 2011). Decisions all through the project must be taken on reliable information, supported by performance indicators. Thus, to better monitor projects, companies must use the most pertinent performance indicators, relevant to the goals and easily measured and understandable to users (Choong 2013b).

In project management, the focus (the scope) to measure performance usually is on cost and schedule, but not on product requirements performance, meaning for example ensuring that the solution satisfies the customer's requirements, which could be evaluated with a technical progress measure (Carson and Zlicaric 2008). In practice, measuring the performance of a project with a single set of 2 or 3 indicators results in a limited practice for today's complex projects, not satisfying the increasing need of industrial performance. Moreover, indicators used in project management are backward-focused (lagging indicators); they measure performance data already captured (at a milestone, verification focuses on controlling if the project is not running over budget or delay or is close to be). Thus, indicators are useful to control how the project has progressed but of no help to lead the project in the future. An interesting practice would be to complement this set of indicators with indicators able to signal future events, helping the manager to monitor the project towards the achievement of its goals (called leading indicators).

The goal of this chapter thus is to determine if the scope, type and number of indicators to measure performance in project management could be developed and how to proceed to this respect. Observing that the development of performance measurement indicators is more or less advanced according to the disciplines, the research method is to consider how performance measurement is practiced in other disciplines, to evaluate the benefits, and to analyze if the good practices that have been identified there could be transferred to project management. After an analysis of practices in construction engineering (Zheng et al. 2017), this chapter now considers practices in systems engineering.

Analyzing how is implemented performance measurement in systems engineering reveals that this discipline defines 18 general leading indicators, focusing widely on technical performance, staffing, facilities and equipment etc., associated to the different systems engineering processes. Obviously, they have a wider focus compared to the traditional project performance areas to whom only cost and time concern. The immediate question this report tries to answer thus is "Can we transfer some leading indicators from systems engineering to project management?" To this respect, it analyzes if any of the 18 indicators could be associated to the different project management processes. This study results in a matrix that generally indicates what set of indicators among the 18 could be useful to measure the performance of a certain type of project activities (for instance activities related with project quality management or with project time management, or else project cost management). This corresponds to the first contribution of the study.

However, to practically define and implement relevant leading indicators for a project, the analysis must deepen and precisely characterize the processes, data and context of the project, etc. in order to specify and tailor the specifications of a selection of indicators from the set of potentially useful ones to the project context and thus to obtain a subset of most relevant indicators for a given project. For instance, in a project aiming at developing embedded software for aerospace, where certification constraints are strong, documenting processes and products is very important; a special focus will be made on quality plan and quality control, thus resulting in the definition of a performance indicator on the quality of documents. This chapter proposes a method for identifying and tailoring the set of most relevant indicators for a specific project; this corresponds to its second contribution.

The chapter is organized as follows. Sections 2 and 3 respectively introduce the research background in project performance measurement and systems engineering measurement. Section 4 presents the first contribution, the proposal of a methodology to identify if some indicators from systems engineering measurement could be useful to measure the performance of project management activities, thus resulting in a mapping between these activities and the several indicators. Section 5 develops the second contribution, a method to adapt and refine the general results from the interpretation of the previous mapping for a specific project, and illustrates it on a case study. Section 6 concludes on the achievement of our research objectives and gives perspectives about further research. Figure III–1 synthetizes this chapter and illustrates the logical connections between sections.

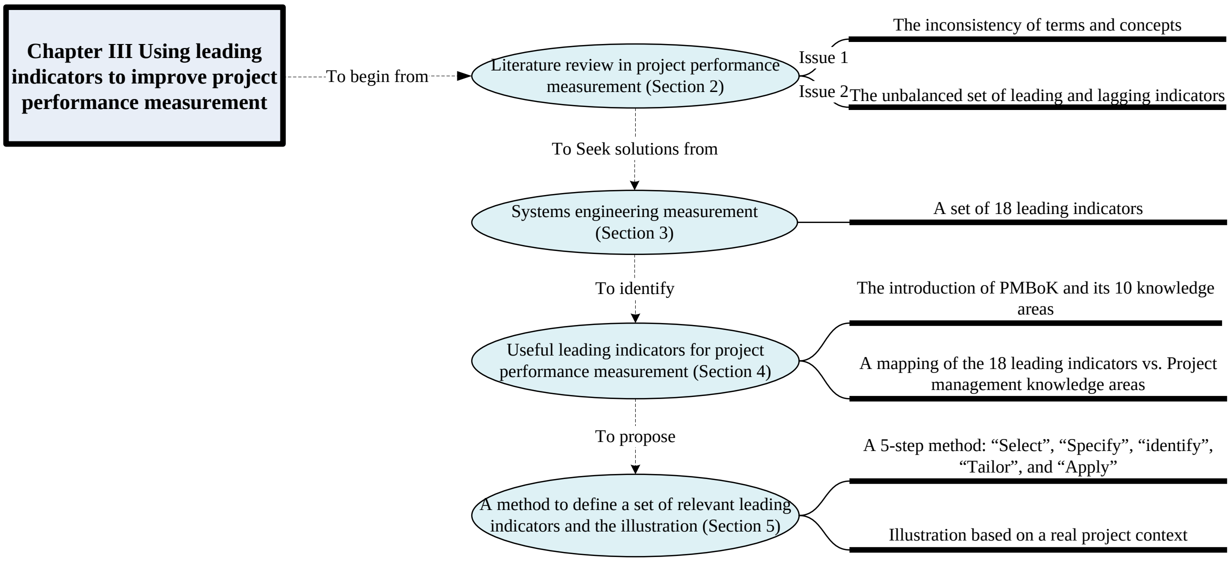

Figure III–1 Structuration of chapter III

2. Research background on project performance measurement

Project performance measurement is a topic of increasing concern both to researchers and practitioners (Lauras, Marques and Gourc 2010) (Zheng et al. 2016). Problems with existing models and frameworks, based on traditional time and cost performance evaluation, have been widely documented. Section 2.1 presents the definitions of project performance measurement and draws the attention to the issues relative to measures of performance. Section 2.2 provides a way to make clear the inconsistent use of measures/metrics/indicators, generates the definitions for the leading and lagging indicators based on cross-discipline learning, and demonstrates specifically the unbalanced use of leading and lagging indicators in project performance measurement.

2.1. Project performance measurement

2.1.1. *Definitions*

According to the representative definitions in the PMSs research (cf. Chapter II), Bititci (2015, p 34) has defined that "Performance is the efficiency and/or effectiveness of an action" in business performance measurement. Effectiveness refers to the extent to which customer requirements are met, while efficiency is a measure of how economically the firm's resources are utilized when providing a given level of customer satisfaction (Neely, Gregory and Platts 2005). "Performance measurement" is defined as the process of quantifying the efficiency and effectiveness of action (Neely, Gregory and Platts 2005). It mainly refers to improving performance goals, detecting variances and taking corrective action if targets were not met (Choong 2014).

Specifically to project context, Morris and Pinto (2010) have defined "Project performance" as a trade-off of several dimensions, specifically what is done (scope and quality) versus the resources (time and cost) used to do the work. Project performance is also recognized as a multidimensional parameter and was viewed as synonymous with its ability to complete the project within the specified time and cost (Pillai, Joshi and Rao 2002).

In the Project Management Body of Knowledge (PMBoK) guide, a popular standard in project management edited by the Project Management Institute (PMI 2013), "Project performance measurement" (PPM) is thought as an assessment about the magnitude of variation from the original baseline (e.g. scope baseline, cost baseline). Following the definition of performance measurement in (Neely, Gregory and Platts 2005), Project performance measurement can be considered as a complex process of quantifying the efficiency and effectiveness of action under project context. To conduct the process, a set of project performance measures are necessary. Next section will identify some highlighted issues in literature.

2.1.2. *Identifying the issues relative to performance measures*

PPM is now the subject of considerable research. One of the key questions that has to be considered during this process is to decide "what" will be measured (Toni and Tonchia 2001), more precisely, to select a system of performance measures. Performance measures can keep project stakeholders informed about the status of the project. They must be carried out by the project manager and the appropriate stakeholders (Kerzner 2011). It has been recognized that inadequate performance measures provide inappropriate information for decision making, thus resulting in bad project results (Thomas and Fernández 2008) (Yun et al. 2016). Highlighting the importance of performance measures in project management, many researchers developed generic performance measures in their study context. Their recommendations about appropriate performance measures for project management were variously expressed, but generally addressing time and cost measures, or the derivatives of time and cost (Kerzner 2011). This can be proved by highly recognized Earned Value Management (EVM) method, or its extension and improvement research.

However, project management has evolved from some aspects, and one most important evolution is that traditional project constraints (e.g. time and cost) have been extended as projects become larger and more complex. Customer satisfaction must be considered, other (or secondary) factors (e.g. corporate reputation and image) must be considered, value component should be considered, and business component should be considered as well (Kerzner 2011). So project performance areas have been extended from sole consideration of time and cost constraints to addressing some more constraints (e.g. customer satisfaction, safety and team staffing) and thus performance measures used to provide supporting information for project performance areas have been extended.

Developing a wider set of generic performance measures has received considerable interest from academic field, but different from one study to another. Some researchers argue that performance measures should be developed differently for major project phases to evaluate performance outcomes (Yun et al. 2016). Other researchers highlight the importance of project types, for example, the set of measures for research & development projects must be different from those in construction projects (Henttonen, Ojanen and Puumalainen 2016). The topic about the relative importance of the performance indicators have been considered (Cha and Kim 2011). Thomas and Fernández (2008) have developed measures that describe the outcomes of a project and the input characteristics that impact outcomes. Thus we can see that studies relative to performance measures have been conducted to address the types of project, the project phases, inputs and outputs of projects; however, the types of performance measures themselves have not been well addressed.

For types, several frequent classifications are used: internal and external measures, result indicators and performance indicators, leading and lagging indicators. Internal and external measures have been addressed in the Performance Measurement Matrix Framework (Keegan et al. 1989), result indicators and performance indicators have been well analyzed by Parmenter (2015). Few researchers have advocated the importance of leading indicators (Kerzner 2011); the difficulty to find literature on this issue in PPM shows that this topic has not been deeply developed. Next section will specifically proceed to this concerned subject, and demonstrates the current issues about the use of leading and lagging indicators from the literature.

2.2. Leading and lagging indicators: definition, state of practices and literature, and research opportunity

Before analyzing the literature with regard to the use of leading and lagging indicators in PPM, Section 2.2.1 deals with the troubles caused by interchangeable use of measures/metrics/indicators. To get an effective communication, a standardized way for defining these terms has been adopted. Then Section 2.2.2 focuses on the definition and comparison of leading and lagging indicators, with an extensive review of literature on leading and lagging indicators in different disciplines, including: safety engineering, civil engineering, systems engineering, and business performance measurement. This enables us to redefine the leading and lagging indicators in the context of project performance measurement. Section 2.2.3 shows the research opportunity to improve project performance measurement by using a balanced set of leading and lagging indicators.

2.2.1. *Measures/metrics/indicators—terminology problem*

In project performance measurement, measures, metrics and key performance indicators are often regarded as a same concept in many general discussions. Indicators are used interchangeably with metrics. For example, Kerzner (2011) made no difference between metrics and indicators, writing in his book: *metrics and project performance indicators are established for those critical activities that can have a direct impact on the success or failure of the project*. Measures are used interchangeably with metrics. For example, Neely, Gregory and Platts (2005) defined “A performance measure” as *a metric used to quantify the efficiency and/or effectiveness of an action*. Some researchers made some efforts to distinguish the three terms, addressing that they are distinct (Trochim 2006) (Choong 2013b). For example, Choong (2013b) cited the statements from Trochim (2006), defining: A measure is a quantitative expression—that composes of a number; a metric is defined as a quantitative expression and it is based on a standard or unit of measurement, like cost per unit; an indicator consists of a combination of qualitative and quantitative attributes, collected and processed using multidimensional scaling and cluster analysis to create an unambiguous and valid tool to inform users of direction or measure.

The lack of the consistency on the definitions of basic terms in performance measurement brings a potential source of uncertainty and confusion for users in both practice and academic. In our study, for the purpose of clearance of illustration and effective communication among the researchers and users, we adopt a consistent terminology used in some measurement standards of engineering disciplines like systems engineering measurement and software measurement. The following paragraphs present the standardized definition.

A standardized way to define measures

There are three important concepts that reflect the data nature in the ISO/IEC 15939 (ISO/IEC 2007): base measure that represents basic raw data, derived measure that is generated from base measures, and an indicator that is generated from base measure or/and derived measures. Detailed definitions and characteristics for the three concepts are presented in Table III–1. The definitions and characteristics are extracted from the ISO/IEC 15939. A measure is a variable to which a value is assigned as the result of measurement; however the term "measures" may be used collectively to refer to base measures, derived measures, and/or indicators according to the definition of this standard.

Table III–1 The definitions and characteristics of base measure, derived measure and indicators

	Definition	Characteristics	Examples
Base measure	A measure defined in terms of an attribute and the method for quantifying it.	Tied to specific entities which tend to be relatively persistent; Functionally independent of all other measures; Used to capture information about a single attribute	Number of defects; Number of code lines
Derived measure	A measure that is defined as a function of two or more values of base measures.	Used to capture information about more than one attribute or the same attribute from multiple entities.	Defect density (divide the defects found by the code lines)
Indicator	A measure that provides an **estimate** or **evaluation** of specified attributes derived from a model with respect to defined information needs.	Tied to information needs which tend to change frequently; the basis for analysis and decision-making what should be presented to measurement users	Control chart of defect density in code inspections

2.2.2. *Lagging and leading indicators for performance measurement in various disciplines: characteristics and definitions*

Few studies in PPM deliberately defined the leading and lagging indicators. Kerzner (2011) thought that a leading indicator is actually a key performance measure (KPI) that measures how the work you are doing now will affect the future. According to the research leading indicators thus are classified into KPIs. However what are lagging indicators has not been well defined and explained in his study. To have a better understanding about the concepts, we review some available definitions for leading and lagging indicators in other disciplines, which enables us to get a clear picture of the nature of these two types of indicators and their characteristics.

To obtain the knowledge of the nature and characteristics of leading & lagging indicators to thus generate a comprehensive definition for them in project context, we did a cross-disciplinary review. They are analyzed and summarized in Table III–2.

Table III–2 Leading and lagging indicators in various disciplines

Disciplines	Definitions in some representative research	Lagging indicators characteristics	Leading indicators characteristics
Systems engineering	A ***conventional measure*** provides insight into the issue area of interest to management using historic and current status information (Roedler et al. 2010). A ***leading indicator*** is a measure for evaluating the effectiveness of a how a specific activity is applied on a project in a manner that provides information about impacts that are likely to affect the system performance objectives (Roedler et al. 2010).	To provide a backward looking perspectives; To report past and current status of projects	To provide a forward looking perspective; To deliver early performance information; To predict the future behavior of another process or sub-process
Environment, health and safety (EHS)	The term ***lagging*** typically refers to injuries and fatalities in terms of personal safety, whereas for process safety, ***lagging indicators*** are direct measures of harm and failure and do not have the ability to provide information about the current state of the environmental, health and safety management system (EHSMS) (Hopkins 2009). ***Leading indicators*** are proactive, preventative, and predictive measures that monitor and provide current information about the effective performance, activities, and processes of an EHS management system that drive the identification and elimination or control of risks in the workplace that can cause incidents and injuries (Sinelnikov, Kerper and Inouye 2013).	To report the injuries results; To measure harm and failure;	To give advanced warning of potential problems; To identify risks that can cause incidents and injuries; To predict; To provide information about current status; To be proactive
Civil engineering	***lagging performance indicators*** focus on cost, schedule, changes, safety, and productivity, usually only obtained after project completion (Yun et al. 2016) ***Leading indicators*** are fundamental project characteristics and/or events that reflect or predict project health. Revealed in a timely manner, these indicators allow for proactive management to influence project outcomes (Choi 2007)	Not provide managers a chance to make changes	To provide proactive management; To help improving performance; To predict future results
Business performance management	***Lagging indicator*** is a performance indicator that communicates the performance outcome of a past action. In practice, all performance measures are lagging indicators with respect to the action they report. ***Leading indicator*** is a performance indicator that could be used to predict the future performance outcome of a process. In practice, leading indicators tend to be in-process or input measures to the process.	To communicate the performance outcome of a past action.	To predict the future performance outcome of a process;

Even though various definitions of leading and lagging indicators have been adopted in different disciplines, the basic concept is identical, leading indicators are proactive measures while lagging indicators are reactive measures. From the key characteristics outlined in Table III–2 by analyzing the definitions provided in various sources (i.e., systems engineering, civil engineering and safety engineering), we conclude the common characteristics of lagging indicators are:

- To look at the past and current performance outcome;

- To communicate a result based on past and current data;
- To be reactive.

However the characteristics of leading indicators could be:

- To look at the future performance outcome;
- To draw trend information based on past and current data;
- To predict a result;
- To give advanced warning;
- To be proactive.

Based on the features identified in table III–2 and considering the performance measurement under a project context, we propose the following definitions of leading and lagging indicators in PPM for a use of this report:

- A lagging indicator provides insight into the past and current state of project performance to management by using data information that already exists; a classical indicator in PPM, for instance, is the status of Actual Cost of Work Performed (ACWP).
- In contrast, a leading indicator obtains the trend information based on past and current to predict future state of project performance; for example, in Earned Value Project Management, Schedule Performance Index (SPI) provides the insight of the project schedule performance (greater than 1 is good/favorable).

2.2.3. *Research opportunity in PPM: using a balanced set of leading and lagging indicators*

Based on the above literature review, leading indicators have received wide focus and development in many engineering disciplines (e.g. systems engineering, civil engineering and safety engineering) as they can provide many more advantages in ensuring a successful project than lagging indicators. Our research interest is thus to survey the development and evolution of the leading and lagging indicators in project performance measurement in academic research, to finally get some useful implications for industrial practices.

(1) Lagging indicators in PPM

Literature review in project performance measurement demonstrated that people come to the realization that it is the time to go beyond time and cost. However focus has only been given to extend performance area, not on balancing the performance measure types. The existing literature demonstrated that lagging indicators that provide past and current project status are still dominating the practice. The following paragraphs show several streams of studies that stress the lagging indicators.

One stream that has been addressed widely in literature is to evaluate whether a project is success or a fail when the project completes, named as post-project success evaluations. In this respect, measurement is deployed from project efficiency (focus on Iron-Triangle), project effectiveness (focus on the objective obtainment) and so on. Over the last nearly 70 years, the Iron Triangle (cost, time and quality) have been regarded as the cornerstone of evaluating whether a project has been a success or a failure (Atkinson 1999). With economic globalization, virtual organizations, great competition and environmental focus, many traditional theories have been challenged and showed their limits in practices for obtaining success. Atkinson (1999) has proposed a new framework to suggests the Iron Triangle could be developed to become the Square-Route of success criteria including not only “cost, time and quality” but also the information system, benefits of organization and benefits of stakeholder community. (Zidane, Johansen and Ekambaram 2015) have proposed a holistic framework for project evaluation, in which Project efficiency, Effectiveness, Impacts, Relevance and Sustainability are considered at the same time and all elements and interdependencies are showed.

Another stream is to develop measures for project status monitoring. For example, a web-based project performance monitoring system has been developed to provide project managers timely signaling of project problems (Cheung, Suen and Cheung 2004). Automated Data Collection (ADC) technologies have provided powerful tools for measuring the status of project life cycle (Navon 2007). However the timely monitoring of project status does not provide prediction of future project performance.

It also was proposed that the use of a combined Balanced Scorecard and stage-gate framework is likely to provide more effective project governance in project life cycle though providing key support for decision-making gates (Kakar and Thompson 2010). However, the measures proposed in their framework were still lagging indicators, backward-looking.

Some methods like benchmarking have been proposed to monitor the projects performance (Luu, Kim and Huynh 2008). But benchmarking has its drawbacks, and it cannot address problems that have not been previously recognized or encountered (Barber 2004). It was stressed that the use of benchmarking should be extended beyond the comparison of lagging indicators (Anderson and McAdam 2004).

Cao and Hoffman (2011) developed a new project performance evaluation systems based on a case study approach; engineering productivity metrics (input and output variables) were developed to evaluate project performance. Input variables also called input measures in their study included efforts, project staffing, priority, number of engineers and complexity. The authors thought that adjusting the inputs variables without changing output values (project duration) can make inefficient projects into efficient projects. However, project duration is the key category of project performance measures for their case company, other measures, such as quality and customer satisfaction not being concerned. And this evaluation is in a backward-looking way to monitor project performance, which means first the project efficiency is evaluated, if the efficiency ratio is less than one, and then further calculation about the inputs variables is conducted to find the inefficient causes and thus improve performance by adjusting the input variables.

Even though these results have great contributions to the economic development and enterprise competitions, it seems that most studies are still limited in developing lagging indicators (to measure past and current performance status), used to track how the project progresses and be able to confirm that something is occurring or about to occur (Atkinson 1999) (Zidane, Johansen and Ekambaram 2015) (Anderson and McAdam 2004) (Luu, Kim and Huynh 2008) (Kakar and Thompson 2010). These lagging indicators are backward-focused, or “trailing”. They measure performance data already captured but not draw trend information from the data. In project management, they help assessing whether goals are achieved, easy to measure and accurate but hard to improve or influence; it is an after-the-event measurement which is essential for charting progress but useless when attempting to influence the future.

(2) Leading indicators in PPM

The earned value project management (EVPM) methods have been selected as it has been recognized as the most popular model in project performance measurement. It provided methods for predicting the final cost for projects (Anbari 2003) (Lipke et al. 2009). A project manager could benefit from receiving an early warning cost signal in time to alter the ultimate direction of a project (Fleming and Koppelman 2006). Based on the main thoughts of EVPM, considerable research on the extensions and applications of EVPM are published, for example, some scholars have proposed to improve the use of planned value (Chen, Chen and Lin 2016); others have integrated EVPM and Project Risk management methodologies (Pajares and Lopez-Paredes 2011). EVPM has become an important component of successful project management by helping monitor and predict project performance. It shows that EVPM outcome prediction for cost is reasonably reliable for the measurement of projects performance, but it is striking that all related EVPM researches are geared towards cost and schedule measures. For example the calculations for the cost performance index (CPI) and schedule performance index (SPI) are used to measure trends for forecasting.

- EVPM methods focus on time and cost basically, and most of the other metrics being reported are derivatives of time and cost.
- Other level consideration such as quality improvement, customer satisfaction or project team members' performance cannot be predicted.

EVPM has got its recognition in both academic and practices. It is very important to pay attention to time and cost in project management; but additional measures are needed. Project performance cannot be measured from just time and cost alone (Kerzner 2011).

(3) The importance of a balance of leading and lagging indicators in PPM

Based on the literature review of (1) and (2), it is obvious that relatively few studies focus on prediction-based project performance measurement (Grabowski et al. 2007) (Juglaret et al. 2011) (Mearns 2009), relying on the use of leading indicators, able to signal future events. Indeed, this kind of indicators, input oriented, are hard to measure and easy to influence. They would be very useful to demonstrate progress that has been made, and to guide and focus the management of the project; however they are more difficult to determine than lagging indicators.

What has become clear over years of research is that both leading and lagging indicators are useful to performance measurement, and that a combination of leading and lagging indicators result in enhanced business performance overall (Kueng et al. 2001). A lagging indicator demonstrates that a business result has been achieved and a leading indicator will provide early warnings about tracking towards a strategic goal. Together they will track progress and success of a project.

Thus, in projects, a 'balance' between leading indicators, supporting prediction-based project performance measurement, and lagging indicators, supporting outcome-based project performance measurement, is required to ensure the right activities are in place to ensure the right outcomes. Prediction-based project performance measurement is forward looking, representing the expectation from the projects; it is used in the initiation, planning and execution stages of a project life cycle (Eilat, Golany and Shtub 2008). Outcome-based project performance measurement evaluates project health status through a backward-looking measurement that represents what has already been accomplished (Eilat, Golany and Shtub 2008).

In synthesis, a balanced set of leading and lagging indicators is needed for measuring different aspects of project performance and to ensure that activities produces the right outcomes. The current dominance of outcome-based project performance measurement based on the lagging indicators must evolve towards a more balanced measurement including prediction-based measurement, and leading indicators needs to be defined and introduced into project performance measurement. Yet, introducing leading indicators to balance measurement is not enough to get a performant measurement because the choice of indicators for project performance measurement greatly differs from project to project depending much on the organization types, project objectives, resources and policies. To be relevant, indicators thus need to be precisely specified and tailored in accordance with the context of the project.

3. Research background in systems engineering measurement

Systems engineering measurement, on its side, has been experiencing a remarkable development with a shift from outcome measurement to predictive measurement, which has resulted to the definition of various leading indicators and to the publication of several guides and standards for measurement. Measurement is a key element in a management feedback control loop that allows for the monitoring of systems engineering processes (INCOSE Measurement Working Group 2010).

For effectively evaluating the health status of systems engineering in a program, many researchers and practitioners have provided some practices relying on the measurement and monitoring of systems engineering processes (Kasser 1994) and theoretical foundation of the systems engineering measurement, which is based on the systems theory (Choong 2013a) (Alter 2013). Several organizations such as the consortium Lean Advancement Initiative (LAI) of the Massachusetts Institute of Technology (MIT), the International Council on Systems Engineering (INCOSE), the International Organization for Standardization (ISO) and the Practical Software and Systems Measurement (PSM) also tackled the question to support effective management of systems engineering. As a result, a series of guidebooks have been developed and published since 1995: Metrics Guidebook for Integrated Systems and Product Development (Wilbur 1995); INCOSE Systems Engineering Measurement Primer (INCOSE Measurement Working Group 1998 2010), Technical Measurement (PSM and INCOSE 2005) and Systems Engineering Leading Indicators (Roedler et al. 2010). Figure III–2 shows how these guidebooks progressively evolved under the influences of different standards from other domains, such as software engineering, towards the definition of systems engineering leading indicators (Roedler et al. 2010).

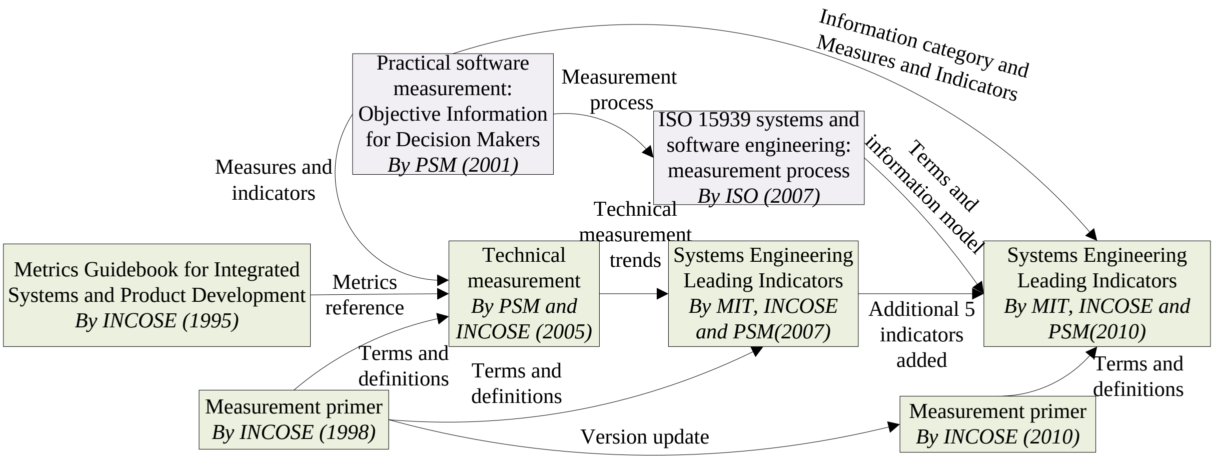

Figure III–2 Evolution of systems engineering measurement

Firstly, from Figure III–2 Metrics Guidebook for Integrated Systems and Product Development (Wilbur 1995) which was the first formal guide for systems engineering measurement published in 1995 by INCOSE, has been prepared for supporting systems engineering program measurement. In this guide, thousands of metrics were collected, categorized, and assessed as candidates; it supports group establishing new metrics program. However, there are some drawbacks about this guide book, 1) it presented only lagging indicators; 2) no detailed guide about how to aggregate the data collected with models or functions.

Then, INCOSE SE Measurement Primer version 1.0 (INCOSE Measurement Working Group 1998) was published with two objectives: 1) define the basic concepts behind measurement and measurement programs; 2) provide requisite background knowledge. To reflect the change in ISO and PSM guidance, it has been revised to version 2.0 (INCOSE Measurement Working Group 2010). However it has only synthesized key guiding principles consistent with the ISO/IEC 15939:2007 Systems and software engineering—Measurement process and the Practical Software and Systems Measurement (PSM) guidebook, no information about how to realize a construct of a SE leading indicators (Rhodes, Valerdi and Roedler 2009).

Technical measurement, version 1.0 (PSM and INCOSE 2005) developed collaboratively by PSM, INCOSE, and Industry, is a set of measurement activities used to provide the stakeholders insight into progress in the definition and development of the technical solution. It has synthesized the metrics references from INCOSE SE Measurement Primer version 1.0 (INCOSE Measurement Working Group 1998), Metrics Guidebook for Integrated Systems and Product Development (Wilbur 1995), Practical System Measurement--Objective Information for Decision Makers (McGarry et al. 2002), and Practical Software and Systems Measurement Guide V4.0c (PSM 2003). It presents the ongoing assessment, mainly for risks and issues associated with technical aspects.

These three guidebooks have been applied in SE practical activities and get general recognition; however, all these are still staying in outcome measurement with lagging indicators, as to how to predict potential risks and issues has only been referred as a concept.

Indeed, systems engineering measurement does not only use lagging measurements but also defines methods to promote leading measurements (Rhodes, Valerdi and Roedler 2009); this way, 18 leading indicators were recently proposed, validated, and finally engineered in a practical guidance, Systems Engineering Leading Indicators Guide (Roedler et al. 2010) (cf. Figure III–2). This guide describes each indicator in details and identifies relationships between the different indicators and the processes activities of the ISO/IEC 15288. Note that even if this standard is a standard for systems engineering evidently describing technical processes, it also describes several project processes, dealing with the management of the technical processes. For example, the “Defect and Error Trends” indicator can be mapped to “Project planning” and “Project assessment and control” processes from the “Project processes” of the ISO/IEC 15288 as illustrated in Table III–3. More precisely Table III–3 shows that this indicator can be used to evaluate the trends associated with defects and errors, which can indicate whether the product will meet the quality objectives and whether a change in the defect discovery process might be of value and thus provide useful insights in the activities “Plan the project technical and quality management”, “Assess the project” and “Control the project”.

Table III–3 Mapping of the “Defect and Error Trends” indicator to some of the processes activities of the ISO/IEC 15288 extracted from the Systems Engineering Leading Indicators Guide.

	Defect and Error Trends
6.3 Project processes	
6.3.1 Project planning process	
6.3.1.3.a Define the project	
6.3.1.3.b Plan project resources	
6.3.1.3.c Plan the project technical and quality management	X
6.3.1.3.d Activate the project	
6.3.2 Project assessment and control process	
6.3.2.3.a Assess the project	X
6.3.2.3.b Control the project	X
6.3.2.3.c Close the project	

From the development and characteristics of systems engineering measurement, some of its advantages can be summarized as follows:

- The history of systems engineering measurement has changed from lagging indicators to a balance of lagging and leading indicators, thus constituting a systemic and effective measurement;
- A set of leading indicators have been collaboratively developed by consortiums such as LAI, INCOSE and PSM to address the need of using leading indicators for evaluating the health of systems engineering in a program;
- The set of leading indicators draw on trend information of conventional measures or significant correlation to provide predicative analysis, which is cost-effective.

The application of systems engineering leading indicators has been conducted by NAVAIR (Naval Air Systems Command) on some aircraft development programs (Roedler et al. 2010) and research effort has also been made to evaluate the potential use of leading indicators on some high speed sled testing programs within one organization (Knorr 2012). Some studies point out the benefits of applying SE leading indicators for technical reviews and audits defined in the United States Defense Acquisition Guidebook (Orlowski et al. 2015). However, the use of these indicators remains limited to the domain of systems engineering and no research ever considered extending the scope to other application domains, such as to project management.

4. Identifying leading indicators useful to project performance measurement

The idea of considering best practices in systems engineering measurement to potentially transfer them to project performance measurement emerged when recent surveys pointing out the industrial need to integrate or at least to align systems engineering and project management practices (Sharon 2011). To bridge the gap between project management and systems engineering management, organizations from both sides such as the INCOSE (International Council on Systems Engineering) and the PMI (Project Management Institute) have launched several surveys and conferences on this issue (Conforto et al. 2013). Recent contributions (Xue et al. 2015) demonstrate that the integration can be improved with the alignment of processes described in standards and norms from the two domains, among a few other options enumerated in (Rebentisch 2017). However, no study until now focused on the alignment of methods and tools for performance measurement.

This chapter considers transferring and adapting the best practices from systems engineering measurement such as described in standards and guides, as well as systems engineering leading indicators, to the practices in project performance measurement as defined in project management guides. The study chose to analyze two of the most popular current references (Xue et al. 2015), the Systems Engineering Leading Indicators Guide (Roedler et al. 2010) on one side, with a set of 18 leading indicators associated to systems engineering processes, and the PMBoK Guide to the Project Management (PMI 2013) defining project processes on the other side.

The PMBoK Guide offers a framework consisting of 47 processes grouped into 5 process groups (cf. Table III–6) and used in 10 Knowledge Areas; each process includes inputs, tools and techniques and output. For example, "Project Quality Management Knowledge Area" includes 3 processes, and one of the three processes is "Control quality management" consisting of Inputs, Tools and techniques and Outputs (cf. Figure III–3).

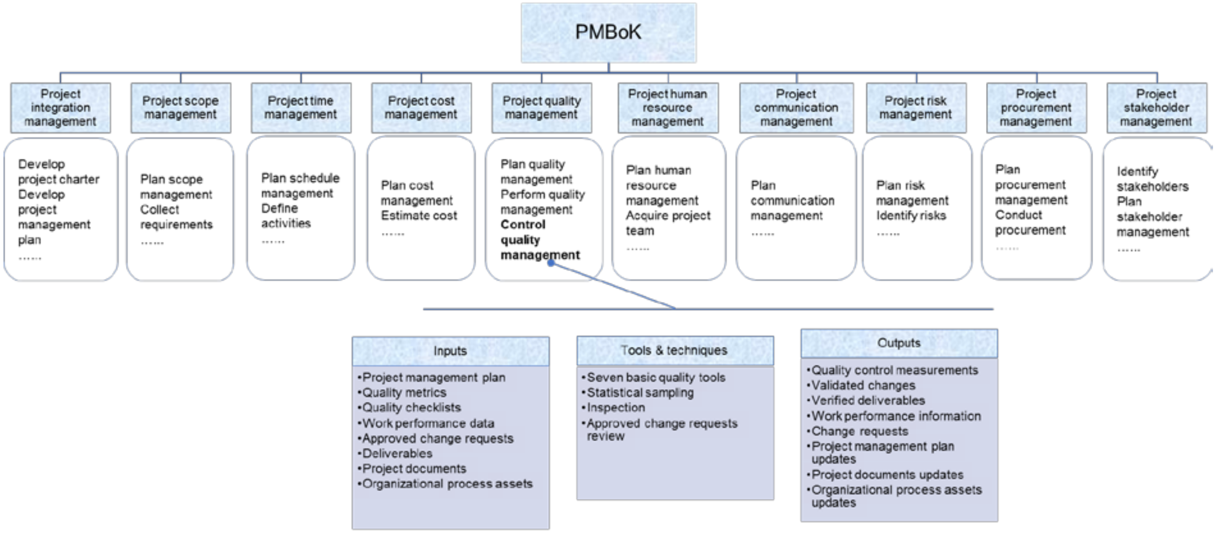

Figure III–3 Structure of the PMBoK

The Systems Engineering Leading Indicators Guide defines each systems engineering leading indicator according to 7 rubrics as demonstrated in Table III–4: “Information need description”, “Measurable concept and leading insight”, “Base Measure Specification”, “Entities and Attributes”, “Derived Measure Specification”, “Indicator Specification” and “Additional Information”. Each rubric provides different information on the indicator. According to the descriptions of the 7 rubrics demonstrated in Table III–4, the rubrics “Information need description” and “Measurable concept and leading insight” are the most useful in (1) deciding what categories are applicable for this leading indicator; and (2) specifying what specific insight the leading indicator may provide. Thus the two rubrics will be referred to map leading indicators to Knowledge Areas of the PMBoK.

To identify which leading indicators from systems engineering measurement could be useful to project performance measurement, the method consists in analyzing the specifications of each indicator, especially the rubrics “Information need description” and “Measurable concept and leading insight” as mentioned above and to determine for each Knowledge Area what subset of the 18 indicators could be associated to. This section explains the method and gives its results in a matrix mapping the systems engineering leading indicators and the Knowledge Areas of the PMBoK.

4.1. Systems engineering leading indicators

As mentioned above the rubrics “Information need description” and “Measurable concept and leading insight” are the most useful information to help deciding if a leading indicator can be mapped to a Knowledge Area. “Information need description” includes two pieces of information: ‘Information need’ and ‘Information category’ (cf. Table III–4). The ‘Information category’ specifies what categories are applicable for a given leading indicator. The ‘Leading insight provided’ included in the rubric ‘Measurable concept and leading insight’ specifies what specific insights the leading indicator may provide in context of the Measurable concept, typically a list of several or more insights (Roedler et al. 2010). Both ‘Information category’ and ‘Leading insight provided’ will help to decide what subset of the 18 indicators (cf. Table III–4) could be associated to each Knowledge Area.

Table III–4 Systems engineering leading indicator general description (Roedler et al. 2010)

{Name of Leading Indicator}	
1. Information need description	
Information need	Specifies what the information need is that drives why we need this leading indicator to make decisions
Information category	Specifies what categories (as defined in the PSM) are applicable for this leading indicator (for example, schedule and progress, resources and cost, product size and stability, product quality, process performance, technology effectiveness, and customer satisfaction)
2. Measurable concept and leading insight	
Measurable concept	Defines specifically what is measurable
Leading insight provided	Specifies what specific insights that the leading indicator may provide in context of the Measurable concept - typically a list of several or more
3. Base measure specification	
Base measures	A list of the base measures that are used to compute one or more leading indicators - a base measure is a single attribute defined by a specified measurement method
Measurement methods	For each base measure, describes the method used to count the base measure, for example simple counting or counting then normalized
Unit of measurement	Describes the unit of measure for each of the base measures
4. Entities and attributes	
Relevant entities	Describes one or more particular entities relevant for this indicator – the object is to be measured (for example, requirement or interface)
Attributes	The function for computing the derived measure from the base measures
5. Derived measure specification	
Derived measure	Describes one or more measures that may be derived from base measures that will be used individually or in combination as leading indicators
Measurement function	The function for computing the derived measure from the base measures
6. Indicator specification	
Indicator description and sample	A detailed specific description and display of the leading indicator, including what base and/or derived measures are used
Thresholds and outliers	Would describe thresholds and outliers for the indicator; this information would be company (and possibly project) specific
Decision criteria	Provides basic guidance for triggers for investigation and when possible action to be taken
Indicator interpretation	Provides some insight into how the indicator should be interpreted; each organization would be expected to tailor this
7. Additional information	
Related processes	Lists related processes and sub-processes
Assumptions	Lists assumptions for the leading indicator to be used, for example, that a requirements database is maintained
Additional Analysis Guidance	Any additional guidance on implementing or using the indicators
Implementation Considerations	Considerations on how to implement the indicator (assume this expands with use by organization)
User of Information	Lists the role(s) that use the leading indicator information
Data Collection Procedure	Details the procedure for data collection
Data Analysis Procedure	Details the procedure for analyzing the data prior to interpretation

Table III–5 18 Systems engineering leading indicators and key insights provided (Roedler et al. 2010)

Leading indicators	Information categories	Insight provided
Requirements	Product size and stability	Rate of maturity of the system definition against the plan. Also characterizes stability and completeness of system requirements which could potentially impact design and

Trends	Product quality Process performance	production.
System Definition Change Backlog Trend	Schedule and progress Process performance Product stability	Change request backlog which, when excessive, could have adverse impact on the technical, cost and schedule baselines.
Interface Trends	Product size and stability Product quality Process performance	Interface specification closure against plan. Lack of timely closure could pose adverse impact to system architecture, design, implementation and/or V&V any of which could pose technical, cost and schedule impact.
Requirements Validation Trends	Product size and stability Product quality Process performance	Progress against plan in assuring that the customer requirements are valid and properly understood. Adverse trends would pose impacts to system design activity with corresponding impacts to technical, cost & schedule baselines and customer satisfaction.
Requirements Verification Trends	Product size and stability Product quality Process performance	Progress against plan in verifying that the design meets the specified requirements. Adverse trends would indicate inadequate design and rework that could impact technical, cost and schedule baselines. Also, potential adverse operational effectiveness of the system.
Work Product Approval Trends	Schedule and progress Product quality Process performance	Adequacy of internal processes for the work being performed and also the adequacy of the document review process, both internal and external to the organization. High reject count would suggest poor quality work or a poor document review process each of which could have adverse cost, schedule and customer satisfaction impact
Review Action Closure Trends	Schedule and progress Product quality Process performance Customer satisfaction	Responsiveness of the organization in closing post-review actions. Adverse trends could forecast potential technical, cost and schedule baseline issues.
Technology Maturity Trends	Technical effectiveness	Risk associated with incorporation of new technology or failure to refresh dated technology. Adoption of immature technology could introduce significant risk during development while failure to refresh dates technology could have operational effectiveness/customer satisfaction impact.
Risk Exposure Trends	Product quality Schedule and progress Resources and Cost	Effectiveness of risk management process in managing / mitigating technical, cost & schedule risks. An effective risk handing process will lower risk exposure trends.
Risk treatment trends	Product quality Schedule and progress	Effectiveness of the SE organization in implementing risk mitigation activities. If the SE organization is not retiring risk in a timely manner, additional resources can be allocated before additional problems are created.
Systems Engineering Staffing and Skills Trends	Resources and Cost	Ability of SE organization to execute total SE program as defined in the program SEP/SEMP. Includes quantity of SE personnel assigned, the skill and seniority mix and the time phasing of their application throughout the program lifecycle.
Process Compliance Trends	Process performance	Quality and consistency of the project defined SE process as documented in SEP/SEMP. Poor/inconsistent SE processes and/or failure to adhere to SEP/SEMP, increase program risk.
Technical Measurement Trends	Technical effectiveness Product quality	Progress towards meeting the Measures of Effectiveness (MOEs) / Performance (MOPs) / Key Performance Parameters (KPPs) and Technical Performance Measures (TPMs). Lack of timely closure is an indicator of performance deficiencies in the product design and/or project team’s performance.
Facility And Equipment Availability Trends	Resources and Cost	Availability of non-personnel resources (infrastructure, capital asset, etc.) needed throughout the project lifecycle.
Defect/Error Trends	Product quality Process performance Product size and stability	Progress towards the creation of a product or the delivery of a service that meets the quality expectations of its recipient. Understanding the proportion of defects being found and opportunities for finding defects at each stage of the development process of a product or the execution of a service.
System Affordability Trends	Product quality Schedule and progress Risk or Confidence	Progress towards a system that is affordable for the stakeholders. Understanding the balance between performance, cost, and schedule and the associated confidence or risk
Architecture	Product quality	Maturity of an organization with regards to implementation and deployment of an

Trends	Process performance Technical effectiveness Customer satisfaction	architecture process that is based on an accept set of industry standards and guidelines.
Schedule and Cost Pressure	Schedule and progress Resources and Cost Risk or Confidence	Impact of schedule and cost challenges on carrying out a project.

4.2. PMBoK framework

The PMBoK provides a complete project matrix framework based on 47 processes that are grouped into 5 Project Management Process Groups, and involved into 10 Knowledge Areas (cf. Figure III–3). Table III–6 presents an extraction of this framework focusing on 5 Project Management Process Groups vs. 10 Knowledge Areas whose intersections contain the 47 process areas.

Table III–6 PMBoK framework structured in 5 process groups, 10 Knowledge Areas and 47 processes (PMI 2013)

10 Knowledge Areas	5 Project Management Process Groups				
	Initiating process group	Planning process group	Executing process group	Monitoring and controlling process group	Closing process group
Project integration management	Develop project charter	Develop project management plan	Direct and manage project work	Monitor and control project work Perform integrated change control	Close project or phrase
Project scope management		Plan scope management Collect requirements Define scope Create WBS		Validate scope Control scope	
Project time management		Plan schedule management Define activities Sequence activities Estimate activity resources Estimate activity durations Develop schedule		Control schedule	
Project cost management		Plan cost management Estimate costs Determine budget		Control costs	
Project quality management		Plan quality management	Perform quality Assurance	Control quality	
Project human resource management		Plan human resource management	Acquire Project team Develop project team Manage project team		
Project communications management		Plan communications Management	Manage communications	Control communications	
Project risk management		Plan risk management Identify risks Perform qualitative risk analysis Perform quantitative risk analysis Plan risk responses		Control risks	
Project procurement management		Plan procurement management	Conduct procurements	Control procurements	Close procurements
Project stakeholder management	Identify Stakeholders	Plan stakeholder management	Manage stakeholder engagement		

In conclusion, based on the analyses of the ‘Information category’ and ‘Leading insight provided’ by the 18 systems engineering leading indicators and of the 10 Knowledge Areas and their processes in the PMBoK, a first conclusion is that it is possible to introduce the systems engineering leading indicators into project management practices to improve the project performance measurement. A deeper analysis then consists in associating indicators to Knowledge Areas.

4.3. Mapping systems engineering leading indicators with PMBoK Knowledge Areas

To make the mapping between indicators and Knowledge Areas the method proceeds in two steps. As mentioned above (cf. Section 4.1), both 'Information category' and 'Leading insight' of one systems engineering leading indicator specification help to decide for each Knowledge Area what subset of the 18 indicators could be associated to. First, it is to verify whether the 'Information category' of the indicator directly corresponds to the Knowledge Area or not. If the direct correspondence exists, then the leading indicator can be mapped to the Knowledge Area. If the 'Information category' does not demonstrate a direct association between the leading indicator and the Knowledge Area, we proceed to the second step to verify whether the 'Leading insight' provided by the leading indicator is useful in one or several processes of one Knowledge Area; if this is possible, then the leading indicator can also be mapped to the Knowledge Area.

To illustrate how the method works, let us take the systems engineering leading indicator "System Definition Change Backlog Trend" as an example. Table III–7 provides two rubrics of this indicator specification.

Table III–7 An extract from "System Definition Change Backlog Trends" indicator

"System Definition Change Backlog Trends" indicator	
Information need description	
Information need	Evaluate the backlog trends of the system definition to understand whether the changes are being made in a timely manner
Information category	1. **Schedule and Progress** – Work Unit Progress 2. Also may relate to **Process Performance** - Process Efficiency 3. Also may relate to **Product Stability**
Measurable concept and leading insight	
Measurable concept	Are changes to the baseline being processed in a systematic and timely manner?
Leading insight provided	• Indicates whether the change backlog is impeding system definition progress or system development quality/schedule. • Indication of potential rework due to changes not being available in a timely manner.

Abstracted from the "System Definition Change Backlog Trend" indicator specification in (Roedler et al. 2010)

From Table III–7, the leading indicator has three Information categories, which are "Schedule and progress", "Process performance", and "Product stability". Obviously, "Schedule and Progress" directly corresponds to the "Project Time Management" Knowledge Area of the PMBoK, so the leading indicator can be mapped to this Knowledge Area. The question here is: "Is this the only Knowledge Area this leading indicator can be mapped to?" To explore whether the indicator can be associated to more Knowledge Areas, we examine the Leading insight provided by the leading indicator in Table III–7. Leading insight indicates "*whether the change backlog is impeding system definition progress or system development quality/schedule*" and "*the potential rework due to changes not being available in a timely way*"; the two pieces of information help in change control. An overview of the processes of the remaining 9 Knowledge Areas demonstrate that the leading insight provided by this indicator can satisfy the information needs of the "Perform Integrated Change Control" process in the "Project Integration

Management" Knowledge Area. Thus the leading indicator can also be mapped to the "Project Integration Management" Knowledge Area (see Table III–8).

Proceeding this way, a preliminary mapping between the 18 leading indicators and the 10 Knowledge Areas of the PMBoK can be obtained. It results in a matrix that indicates what subset of indicators could generally be relevant to measure the performance of a certain type of activities (cf. Table III–8). The identified relationships in this table indicate the Knowledge Areas in which the systems engineering leading indicators are most likely to provide useful insight. Project teams could be inspired from the result presented in the table and through continuous project practices would have useful leading indicators. This method and resulting table constitute the first contribution of the research, answering the need to develop leading indicators in project performance measurement stated at the end of Section 2, and thus get a balanced use of lagging and leading indicators.

Table III–8 Preliminary mapping of systems engineering leading indicators with PMBoK Knowledge Areas

10 PMBoK Knowledge Areas / 18 SE leading indicators	Project Integration Management	Project Scope Management	Project Time Management	Project Cost Management	Project Quality Management	Project Human Resource Management	Project Communication Management	Project Risk Management	Project Procurement Management	Project Stakeholder Management
Requirements Trends		X			X					
System Definition Change Backlog Trend	X	X	X		X					
Interface Trends		X								
Requirements Validation Trends		X			X					
Requirements Verification Trends		X			X					
Work Product Approval Trends			X		X		X			
Review Action Closure Trends			X		X					X
Technology Maturity Trends		X								
Risk Exposure Trends			X	X	X	X		X		
Risk Treatment Trends			X		X			X		
Systems Engineering Staffing & Skills Trends				X		X				
Process Compliance Trends					X					
Technical Measurement Trends		X			X					
Facility and Equipment Availability Trends			X	X					X	
Defect and Error Trends					X					
System Affordability Trends			X	X				X		
Architecture Trends					X					X
Schedule and Cost Pressure			X	X				X		

However, to be relevant in practice, indicators need to be tailored in accordance with the specific context of a given project. It is then necessary to deepen the analysis from the Knowledge Area level to the process level and adapt these general indicators to the project to get more relevance in the definition and use of indicators, by integrating the project-specific data into the analysis and by considering the importance that is given to each process in the project.

5. A method to define a set of relevant leading indicators to efficiently manage a specific project

To implement the result given by the mapping here above for a given project, a subset of relevant leading indicators must be associated to the processes of Knowledge Areas (to their inputs, tools and techniques, and outputs). The objective is to make a reference available for project teams who want to improve the project performance by providing information about which leading indicators could be useful to measure performance of given processes. This advanced analysis consisting in defining, characterizing and implementing leading indicators in project management is useful to determine the very indicators that will be the most relevant for given processes in a specific project.

5.1. Adapting and refining the mapping for a given project: proposal of a methodology

A project team starts from real project needs (e.g. improving practices in a given Knowledge Area), to apply the recommended systems engineering leading indicators in Table III–8 and then conduct a detailed analysis on how the systems engineering (SE) leading indicator integrate with the inputs, tools and techniques, and outputs of processes of the Knowledge Area (KA). We propose 5 steps: “Select”, “Specify”, “Identify”, “Tailor”, and “Apply” to explore the detailed integration of one leading indicator to one Knowledge Area, as presented in Figure III–4.

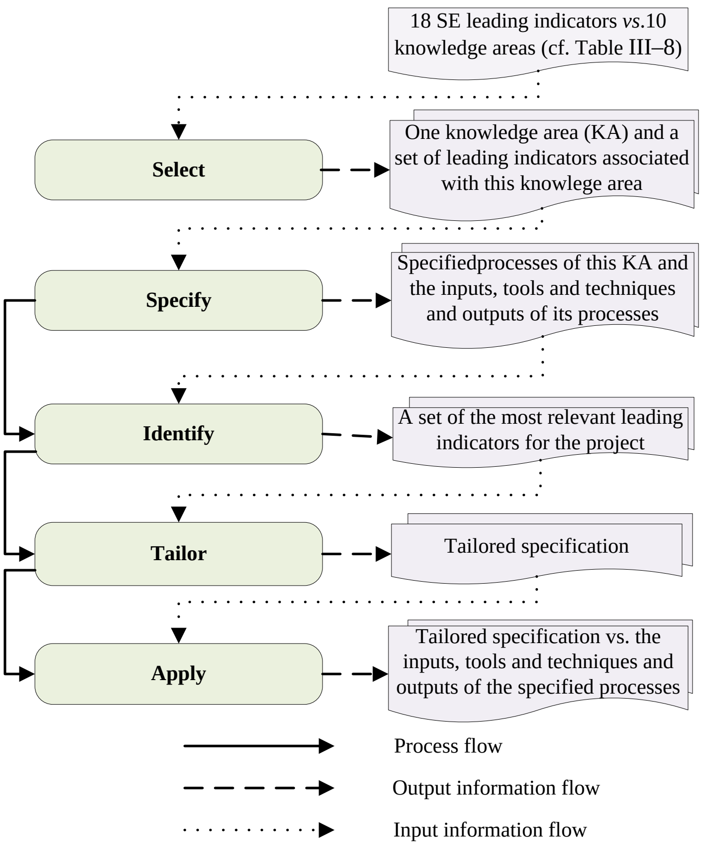

Figure III–4 The 5 steps for integrating a systems engineering leading indicator with processes of a PMBoK Knowledge Area

The detailed description for each step is given here after.

Select: Choice of Knowledge Area to pay attention to based on issues or improvement needs for the project. The mapping of Table III–8 indicates which set {S} of indicators can be useful for this given Knowledge Area.

Specify: Referring to the PMBoK framework where each Knowledge Area includes several processes, the project background data are integrated to the processes to specify them (inputs, technique and tools and outputs of each process) to get a project-specific framework F.

Identify: The project-specific information needs can be generated in this step based on the specified structure of the step above. Then to answer the specified information needs, one or a few relevant leading indicators are chosen among the whole set of potentially useful ones {S}, thus resulting on a reduced sub-set of relevant indicators {Reduced_S} for the project.

Tailor: Referring to the Systems Engineering Leading Indicators Guide to get their precise specification (Information need description, base measure specification, derived measure specification, indicator specification), this step consists in tailoring the specification of each indicator from the {Reduced_S} with regard to the project, thus resulting on a set of most relevant tailored indicators {Tailored_Reduced_S} for the project.

Apply: This step consists in analyzing the {Tailored_Reduced_S} with regard to the specified processes from the project-specific framework of the project F to see how the project-tailored specification of indicators will work with the project- specific framework F.

In conclusion, this 5-step method described in this section allows adapting and refining the generic mapping of systems engineering leading indicators with the different Knowledge Areas of the PMBoK (cf. Section 4.2) for a specific project. It provides a very useful solution to introduce relevant leading indicators in the management of a project.

5.2. Illustration of the method to define relevant leading indicators in a project from the manufacturing industry

Projects have different characteristics: different domains, scopes, stakeholders, objectives, resources, etc. Thus adapting the mapping of Table III–8 to a specific project can result in the definition of different indicators according to the project background. In this paper, a medium-sized equipment manufacturing company in China in the manufacturing industry has been chosen to illustrate the methodology.

Keye Co., Ltd is a high-tech enterprise specializing in design, manufacture and installation of electro-physical and vacuum equipment as well as various general-purpose mechanical products. It closely collaborates with several scientific research units. Each year, between 30 and 50 projects are lead in this company.

The project K** (confidential) is one of the typical projects contracted by the company. It is a new reverse field pinch device. Research and development (R&D) on Keye's products is jointly undertaken by Keye Company and research institutions. The project is characterized by a long research period, a wide set of technical and non-technical requirements, innovative technologies, etc.

To get the most relevant indicators for this project, we apply the 5-step methodology as described in Figure III–5. A detailed description of the steps is provided here after.

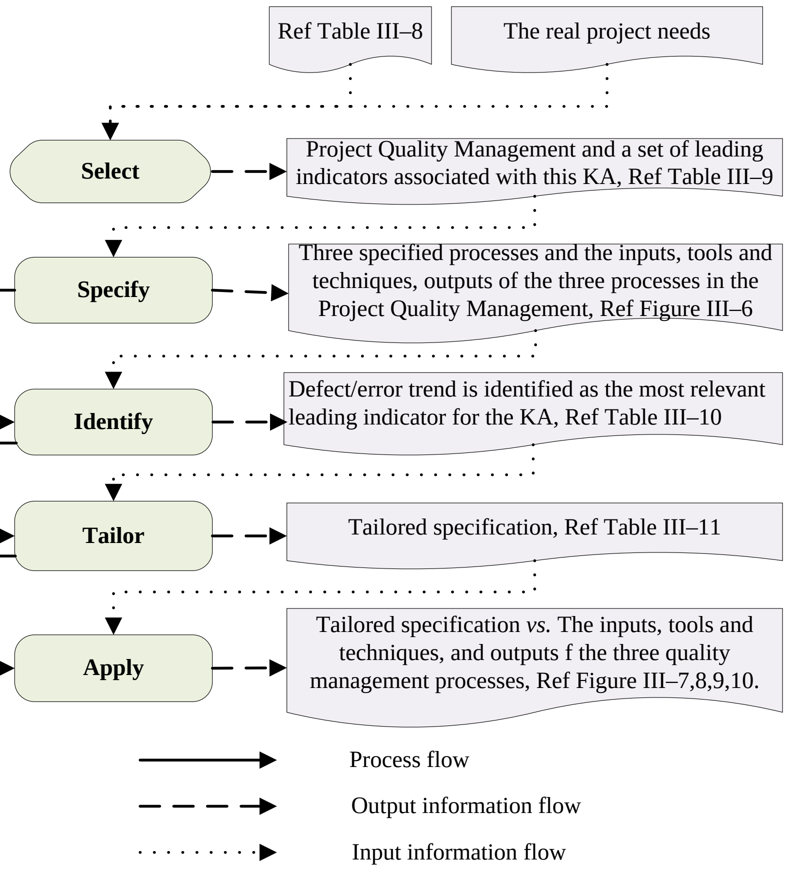

Figure III–5 Steps to follow to integrate the "Defect and Error Trends" indicator into the "Project Quality Management" Knowledge Area

(1) Select: the "Project Quality Management" Knowledge Area is selected based on the real project needs

After several discussions with the project team, it occurs that managers often were perplexed by some issues in quality management:

- The existing quality management process is mainly about quality control records of operational processes and periodic evaluation of the project, which is lagging measurement;
- No available leading indicators for predicting the potential risks caused by quality documents.

Through the above issues, it was agreed that the Project Quality Management" Knowledge Area could be where improvement is most needed. With reference of the preliminary mapping in Table III–8, for the "Project Quality Management" Knowledge Area, 12 systems engineering leading indicators are available (cf. Table III–9).

Table III–9 Selected Knowledge Area and its related leading indicators

	Project Quality Management
Requirements Trends	X
System definition Change Backlog Trends	X
Requirements Validation Trends	X
Requirements Verification Trends	X
Work Product Approval Trends	X
Review Action Closure Trends	X
Risk Exposure Trends	X
Risk Treatment Trends	X
Process Compliance Trends	X
Technical Measurement Trends	X
Defect and Error Trends	X
Architecture Trends	X

(2) ***Specify:*** *Three processes and their data flows of the "Project Quality Management" area are specified*

This step considers the PMBoK framework and the project background to provide a project-specific framework.

First, we need to survey the main issues of Project Quality Management in the project backgrounds. All the information described here was the result of reviewing the project documents and interviewing the project manager. As the original document prepared by the project team was not completed in the framework of the PMBoK Guide (PMI 2013), the collected project information needed to be transformed into three processes according to the structured "Inputs, Tools and techniques, and Outputs" described in the PMBoK Guide: "Plan quality management", "Perform quality assurance" and "Control quality" (cf. Figure III–3). Finally, a project-specific description of the "Project Quality Management" Knowledge Area and its processes has then been specified and generated as shown in Figure III–6.

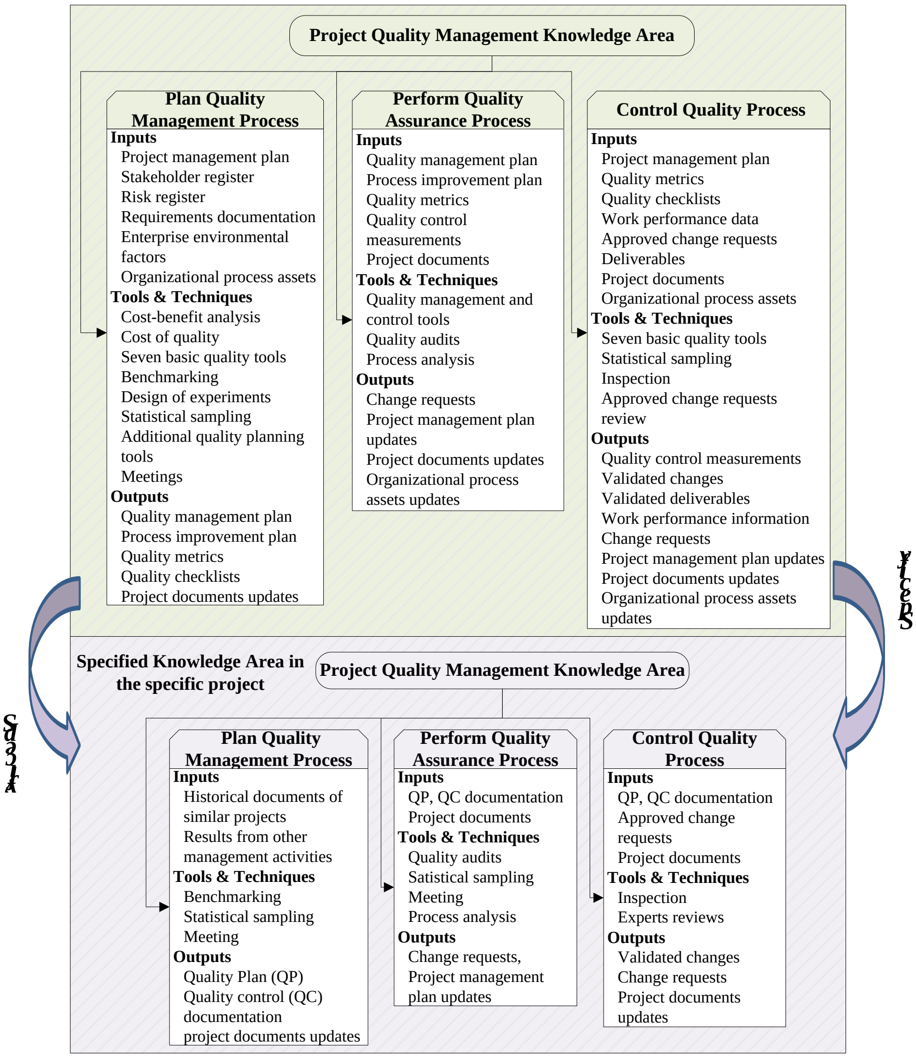

Figure III–6 Specified Project Quality Management Knowledge Area

(3) ***Identify***: *The information needs based on the specified Knowledge Area in the specific project from the previous step are generated to get the most relevant leading indicator*

Based on the specified project-specific framework from the previous step, after several times of discussions with managers, it was identified that the creation and complementation of Quality Plan (QP) and Quality Control (QC) documentation constituted an important effort through the three processes "Plan Quality Management", "Perform Quality Assurance" and "Control Quality" of the "Project Quality Management" Knowledge Area in this project. Generally, Quality Plan and Quality Control documents include quality requirements and standards for the project and its deliverables. There could be various types of defects (e.g. omitted quality requirements) created, but they may not be recognized before the document is completed. Quality Plan and Quality Control documentation helps to ensure project quality, but how to track and ensure the quality of Quality Plan and Quality Control documentation itself? To answer this specific information need, it appeared that the "Defect and Error Trends" (cf. Table III–10) is the most relevant leading indicator to this information need.

Table III–10 Identifying the most relevant leading indicator

	Project Quality Management
Defect and Error Trends	X

(4) Tailor: Base & derived measures and related measurement function of "Defect and Error Trends" indicator are selected

To use the "Defect and Error Trends" indicator appropriately and effectively for this project, it is necessary to tailor it. This indicator provides very detailed information in its specification (cf. Page 80 of the Systems Engineering Leading Indicators Guide, Version 2.0), but not all the information is applicable to the specified project and satisfying information needs, the quality of Quality Plan and Quality Control documentation. The table below provides the tailored specification according to the result in Figure III–6. In this project, one base measure (measure M1), one derived measure (measure M2) and their related measurement function, indicator description, and thresholds and outliers have been chosen. Table III–11 presents the tailored specification of the indicator.

Table III–11 Tailored specification of the "Defect and Error Trends" indicator

Leading indicator "Defect and Error Trends"	Base measures provided
	M1: Number of defects found at each discovery stage
	Derived measure
	M2: Estimated number of latent defects
	Measurement function provided for the derived measure
	Weibull model functions are proposed to fit defect discovery data; and the Rayleigh model is suggested with its application
	Indicator description
	The defect discovery profile includes a fit to defect data as it becomes available and projections to later time intervals.
	Thresholds and outliers
	Range of acceptable values for defect discovery based on past project history
Notes: Based on the practical software and systems measurement (PSM), data for base measures are obtained by direct measurement. Data for derived measures come from other data, typically by combining two or more base measures. An indicator constitutes of a set of base measures and derived measures.	

(5) ***Apply:*** *The detailed application of the measures into the data flows of the processes is obtained, and derived leading indicators for the project are built*

The defect discovery profiles separately for Quality Plan and Quality Control documentation per time interval have been built. The defect discovery profiles include a fit to defect and error data discovered in each time interval and projection to the later phases based on the data fits for earlier phases according to the "Indicator description" in Table III–11. The profiles can reflect whether defect discovery will meet expected results compared with the "Thresholds and outliers" described in Table III–11. A corrective action should be taken with experts when values exceed tolerance in the profiles. The analysis on how the tailored specification is applied into the inputs, tools and techniques and outputs of the specified processes is as follows. New inputs and outputs of the three project quality management processes are marked in bold in addition to existing inputs and outputs in Figure III–7, III–8 and III–9. Tools and techniques for building the derived leading indicator for the project is demonstrated in italics in Figure III–7, III–8 and III–9.

First, the "Inputs, Tools and techniques and Outputs" of the Planning Quality Management process have been demonstrated in Figure III–7 where new inputs and outputs have been bolded and added. In the Inputs, "the specification of Defect and Error Trends in the Systems Engineering Leading Indicators guide" has been added as a new reference in addition to the existing inputs of the project identified in Figure III–6. In the Tools and techniques, some tools like "benchmarking" and "meeting" in the project are useful for building the derived leading indicator, for example, benchmarking will be used to build the thresholds based on the historic data of similar projects. In the Outputs, in addition to the Quality Plan and Quality Control documentation, the "Defects and Errors discovery profiles of the Quality Plan and Quality Control documentation—thresholds and outliers" has been added as a new reference, which will become one of the Inputs of the Performing Quality Assurance process.

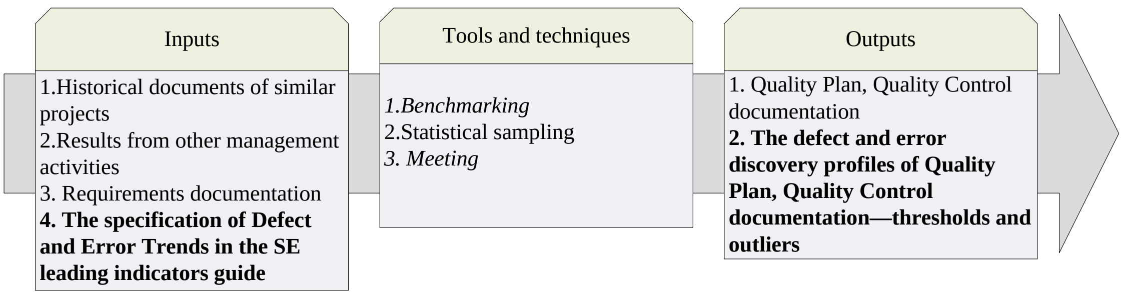

Figure III–7 Integrating the tailored specification of "Defect and Error Trends" indicator into the Inputs, Tools and techniques, and Outputs of the Planning Quality Management process

As a result, the thresholds and outliers of the leading indicator have been planned and built in the Planning Quality Management process. Then we move to the Performing Quality Assurance process where the updated Inputs, Tools and techniques and Outputs have been presented (cf. Figure III–8). New inputs and outputs have been bolded and added. The Quality Plan and Quality Control documentation and the "Defect and error discovery profiles of Quality Plan and Quality Control documentation—thresholds and outliers" created in the process of the Planning Quality Management process become one new input of the Performing Quality Assurance process. Piloting total defects each milestone of the project is started in this process. The Defect and Error Trends could include: spelling mistakes; omitted quality requirements, perspective gaps between the project team and the customers etc. The number of defects discovered at project milestones will be recorded by "quality audits" tools. Measure M1 and measure M2 from Table III–11 will be depicted in the defect and error discovery profiles of Quality Plan and Quality Control documentation that is a new output of this process.

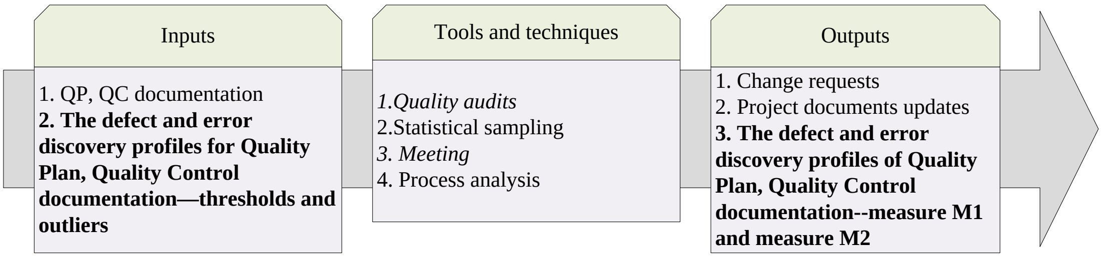

Figure III–8 Integrating the tailored specification of the "Defect and Error Trends" indicator with the Inputs, Tools and techniques, and Outputs of the Performing Quality Assurance process

By tracking the measures M1 and M2 built in the Performing Quality Assurance process, the Controlling Quality Management is updated with some new inputs and outputs demonstrated in Figure III–9. In the Inputs of this process, "the Defect and Error discovery profiles of Quality Plan and Quality Control documentation—measure M1 and measure M2" helps providing insights on deviation. Some analysis should be conducted once unexpected deviation (less than, equal to, or greater than expected tolerance) occurs and some mitigating actions will be taken with the change requests. For example, re-inspecting the QP document can be made by using "expert reviews" in the Tools and techniques. The "corrective actions documents for responding the defect and error discovery profiles of Quality Plan and Quality Control documentation" will be added in the existing Outputs.

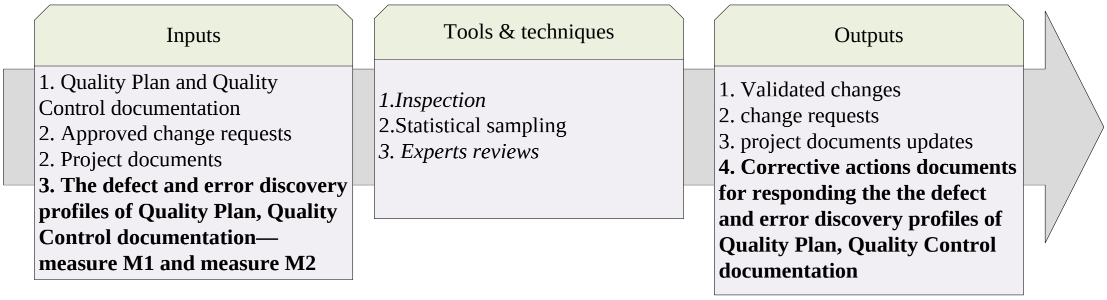

Figure III–9 Integrating the tailored specification of the "Defect and Error Trends" indicator with the Inputs, Tools and techniques, and Outputs of the Control Quality Management process

Through the application analysis, a relative position of M1 (number of defects found at each discovery stage) and M2 (estimated number of latent defects) is presented in Figure III–10. Measure M1 and measure M2 of the "Defect and Error Trends" indicator have been plotted by different time intervals in a project, and measure M2 is estimated numbers of latent time intervals based on the actual measure results of M1; once actual defect data in a project is available, a fit/projection can be built by using measurement functions. For example, the Weibull model function can be used to fit defect discovery data according to Table III–11.

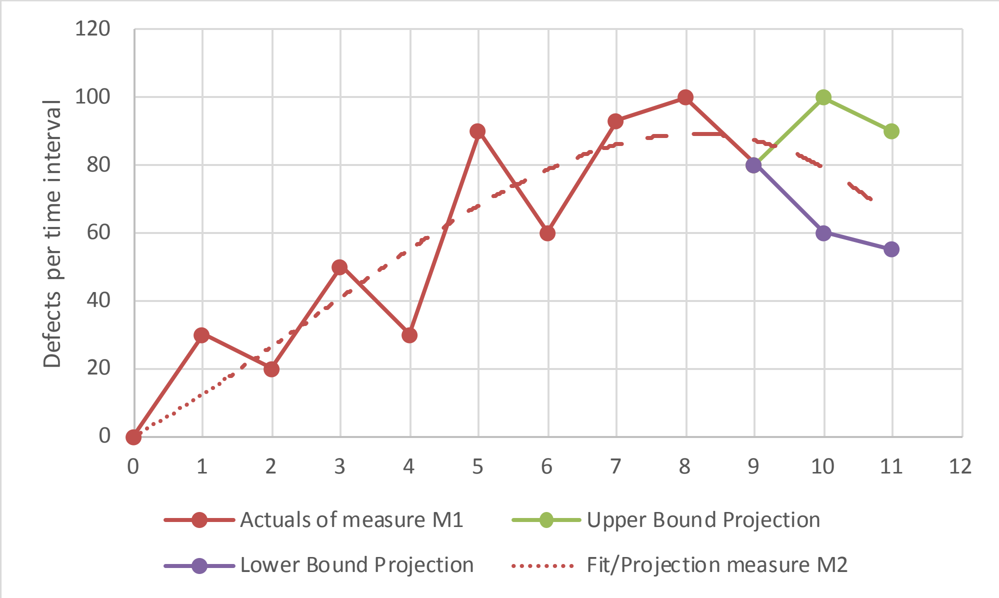

Figure III–10 The relationship between M1 and M2

Through the study, the preliminary mapping results and integrating processes have been conducted and have enabled the project team to apply leading indicators to improve the project performance measurement. It can be concluded that leading indicators could be also very useful in project management while lagging indicators have dominated in practice. Clearly for the project in the small and medium enterprises (SMEs), many challenges face managers for fewer resources and more competitions, the management must be flexible and visible, traditional outcome-based measurement can tell how well or bad they are doing but may not provide information as to the factors or reasons of a potential problem and thus to focus corrective actions to improve the project performance. A balance of lagging and leading indicators in a project can ensure that the right activities are in place to ensure the right outcomes.

6. Conclusion

This chapter addresses the question of improving the performance measurement of engineering projects. Considering the need to balance the use of lagging and leading indicators to evaluate the project health, and that for the moment, in project performance measurement few leading indicator was used, the issue tackled here is to introduce leading indicators to measure the project performance. To this respect, the study provides two major contributions. The first one consists in analyzing the 18 leading indicators that have been defined in systems engineering to determine if any could be useful to measure project performance. This analysis results in a general mapping identifying subsets of leading indicators that could be relevant to measure the performance of the project processes. The second contribution is a methodological proposal to tailor these subsets of leading indicators for a specific project according to the context of the project, its goals and issues, and the importance given to processes. The proposal is illustrated on a project in a manufacturing company. Interviews made with project managers in Great Britain in July 2017 shows that this method is useful and answers a need to have methods and tools to better evaluate the project progress. However, if it is well adapted to project in technical products development, it seems to be less applicable for companies specialized in offering services whose products generally do not include complex technical requirements.

Research developed in this chapter follows a research methodology that consists in integrating the best measurement practices from different disciplines (here from systems engineering) to improve project performance measurement. The result presented in this study is a standard approach for project performance measurement, based on a better use of leading indicators, on a set of pre-defined base measures and on an information model that aggregates base measures into performance indicators. To complement this approach next chapter is to consider the 7 Practical Software and Systems Measurement categories that defines a set of measures and the ISO/IEC 15939 that standardized a measurement information model to design more indicators relevant to project-specific information needs and thus to get a more developed coherent framework.

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Chapter IV A new method for improving the performance measurement of projects

In Chapter II, we concluded that designing performance indicators plays an essential role in performance measurement systems, and literature provides some recommendations for designing project-specific performance indicators. In Chapter III, we concluded that a set of predefined and generic performance indicators are far more sufficient for complex projects characterized by ever changing scopes and technologies, multiple stakeholders participation and long time span. The current chapter now extends the previous approach in Chapter III to consider good performance measurement practices from the Practical Software and Systems Measurement (PSM), the ISO/IEC 15939 and the PMBoK in the goal to design more indicators relevant to project-specific information needs and thus to get a more flexible and integrated performance measurement framework.

1. Introduction

Measuring project performance has always been an important part of project management activity in business and industry today. It allows identifying problems early and provides the organization with a clear picture of the status of project health. To effectively measure project performance, referring to a system of measures adherence to performance criteria is essential (Barclay and Osei-Bryson 2010). Many studies have been conducted for designing and developing appropriate performance measures. For example, the term "key performance indicators" (KPIs) is recurrent in project management terminology, practices and research. However, these KPIs differ from one study to another, and how to design relevant performance indicators for specific projects has been always a big challenge for practitioners. Issues of project performance measurement have been continuously discussed in literature, such as how to specify performance measures and what is the influence of performance measurement on performance (Dickinson 2008). Chapter III raised the issue of the inconsistency of terms and concepts in the literature of project performance measurement, and a consistent terminology from some international guidance and standards (base measure, derived measure and indicator) have been adopted in this report. Chapter III also proposed a set of systems engineering leading indicators for project performance measurement, which helps to solve the issue of the unbalanced use of leading and lagging indicators (Zheng et al. 2017). The chapter concluded that owning a set of leading indicators and a method to obtain the most relevant leading indicators for project management helps improving project performance measurement.

However useful it is, providing a set of predefined generic indicators is not enough for effectively managing complex projects (Kerzner 2011) (William 1999). Project performance indicators should be designed to match to organizational context (Neely et al. 1997) (Wouters 2009). In this regard, it is necessary to go further in improving project performance measurement by designing and developing project-specific performance indicators to obtain a better project performance. In this chapter, three problems regarding designing relevant performance indicators have been identified based on continuous literature review of project performance measurement. These issues are summarized as follows.

1) There are different opinions among researchers about the sources from where performance indicators are derived and the stance of “measures are derived from project objectives” dominates practices (Cha and Kim 2011) (Kerzner 2011) (Alaloul et al. 2016) (Barclay and Osei-Bryson 2010).

2) Methods for defining a set of indicators have been focused on widely (Cha and Kim 2011) (Rui et al. 2017) (Yun et al., 2016) (Almahmoud et al. 2012), but the transformation from data to indicators has not been well addressed yet.

3) Mechanisms or procedures for collecting, analyzing and reporting performance data have been designed in literature but how to associate them with project management processes has not been well developed (Basili and Rombach 1994) (McGarry et al. 2002).

Thus, our objective in this chapter is to propose a comprehensive method that addresses all the three issues. To reach this objective, we try to learn from other disciplines where performance measurement has been well addressed, developed and documented in a standardized way, such as software and systems engineering, as we already proceeded in Chapter III. We thus consider practices from the Practical Software and Systems Measurement (PSM), the ISO/IEC 15939 norm and the Project Management Body of Knowledge (PMBoK) guide.

PSM is an information-driven measurement, which has used “information needs” to replace the dominant “project objectives” to derive performance indicators. This practice brings many benefits for managing complex projects. As projects become more and more complex, predefined project objectives and derived performance indicators for ensuring the achievement the objectives at the initiation of a project cannot be well adapted to the ever-changing environment of the projects (Kerzner 2011). However, this information-driven measurement practice has not been well addressed in general project performance measurement. The ISO/IEC 15939 allows defining an indicator which combines heterogeneous data and structures the elements (e.g. base measure, derived measure and indicator) for interpreting the results. The model has been developed in software and systems engineering and adopted by many other domains, such as total quality management (Buglione 2008) and evaluation of Human-Computer Interaction (Assila et al. 2016). However, this model has not been very well referred in project performance measurement. The PMBoK for its part has well-designed processes that relate to data collection, analysis and report, however, used alone, these processes cannot provide practical and relevant indicators for practitioners.

This chapter analyzes good practices from the PSM, the ISO/IEC 15939 norm and the PMBoK that proved to be able to address respectively the issues of deriving performance indicators dynamically, transforming data to indicators and collecting and analyzing performance data along with project management processes. This results in a method integrating these practices to address the three previously identified issues in project performance measurement. The method is illustrated on a real project context, which demonstrates its usability. Evaluation of the method has been conducted in a workshop of project managers, which confirmed the interest for the proposal.

The chapter is organized as follows (cf. Figure IV–1). Section 2 presents literature review on project performance measurement, particular about designing appropriate project performance indicators, and results in identifying issues; it analyses the information-driven measurement of the PSM, the ISO/IEC 15939 Measurement

Information Model, and the measurement-related processes in the PMBoK. Section 3 demonstrates a method to construct relevant performance indicators by integrating the good practices previously analyzed to solve the issues identified in literature review. Section 4 illustrates the method in a real project context and reports how it has been evaluated by project managers. Section 5 concludes on the proposal.

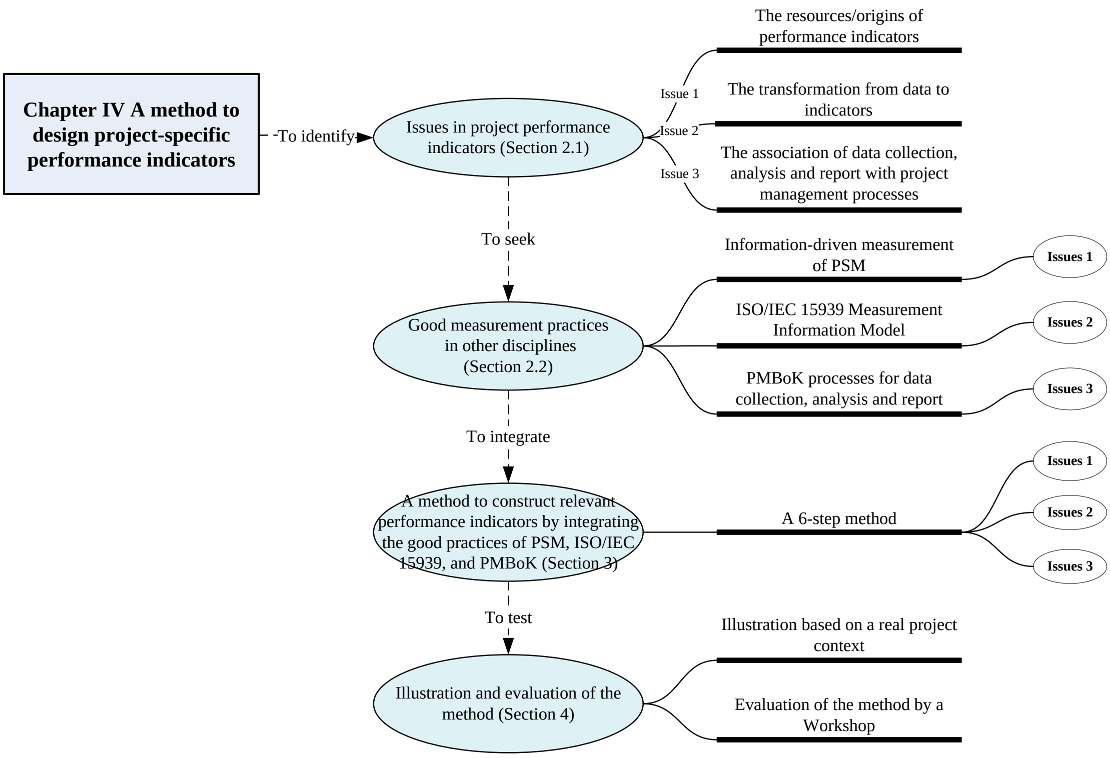

Figure IV–1 The mind mapping of Chapter IV

2. Research backgrounds

As already mentioned earlier, performance indicators are essential in a project performance measurement system, which is often used to benchmark the actual deviation against planned baseline (PMI 2013) and thus provides information for decision making. The importance of designing relevant performance indicators has been recognized in performance measurement systems research and various industrial practices (cf. Chapter II). Various KPIs methodologies have boomed in literature to respond different issues that have arisen in project performance measurement (PPM) research, which differ from one study to another. In Chapter III, literature review has been conducted around the issues of the inconsistency of terms and concepts raised in project performance measurement literature and of an unbalanced use of leading and lagging indicators. Literature review in this chapter still is within the topic "project performance measurement", but goes narrowly to exploring how to design relevant performance indicators for individual projects (Section 2.1). Literature review in software and systems engineering for measurement (Section 2.2) and project management international standards (Section 2.2) will be also conducted in this section.

2.1. Research in project performance measurement and related issues

Chapter II concluded that designing performance indicators in performance measurement systems generally consist of three steps: 1) deciding the source/origin from where the indicators will be derived, 2) defining and constructing indicators (that is defining a set of indicators and defining a method to build appropriate indicators), and 3) instilling the developed indicators into management thinking (a set of procedures of data collection, analysis and report for defined indicators) (cf. Chapter II). In this section, we check the development of each of the three steps in literature of project performance measurement, thus obtaining a global view of issues relative to designing project performance indicators.

A large amount of studies tackles the issues of designing an appropriate set of indicators; in this report, three main issues are identified compared to the three steps of designing a "good" indicator in PMSs. These issues are: 1) there are different opinions among researchers about the sources from where performance indicators are derived and the stance of "measures are derived from project objectives" dominates practices; 2) methods for defining a set of indicators have been largely addressed but the transformation from data to indicators has not been well addressed yet; 3) mechanisms or procedures for collecting, analyzing and reporting performance data have been proposed in some literature but how to associate them with project management processes has not been well developed. These issues should be addressed to further improve project performance measurement.

Issue 1: there are different opinions among researchers about the sources from where performance indicators are derived and the stance of "measures are derived from project objectives" dominates practices.

Firstly, it seems that there are different points of view about where the performance indicators should derive from. A dominant mode is "project objectives—performance criteria or areas—performance measures" that has been demonstrated in Chapter III. It can be proved by several studies that have begun from identifying project objectives, setting performance criteria or areas according to the project objectives and then deriving or identifying a set of measures under each performance criteria or area (Cha and Kim 2011). Traditionally project objectives have been set around the classical "triple constraints (time, cost and quality)" (Kerzner 2011) (Alaloul et al. 2016); thus the traditional system of measures is mainly adhered to time, cost and specification (Barclay and Osei-Bryson 2010). However some authors argued that projects becoming more and more complex, traditional constraints have been extended, and related performance measures are no longer effective for project performance measurement (Kerzner 2011). Some authors have also argued that a fundamental shift is needed to highlight the satisfaction of customers and other stakeholders (Cohen and Graham 2001). Barclay and Osei-Bryson (2010) have proposed a comprehensive project performance development framework where all the significant stakeholders' objectives have been stressed; this aligns to the performance PRISM model developed by Neely, Adams and Crowe (2001) where they argued that the stakeholders should be considered firstly in defining performance measures. Some researchers also argued that performance measures should be derived from critical success factors (CSFs) (Kerzner 2011) (Parmenter 2015). For example, Kerzner (2011) thought what constitutes success at the end of the project or during the project should be firstly defined between the customer and the contractor at project initiation, and then performance measures will be developed around the defined success factors. Parmenter (2015) thinks that the critical success factors have not been well addressed in the leading research of performance measurement of the past 30 years such as some classical PMSs models (e.g. the Balanced Scorecard), and he insisted in his study that organizational KPIs are easy to find if the critical success factors are defined right. However, project objectives, stakeholders, or critical success factors, are all decided at the initiation of a project, thus indicator development is around these predefined factors, which might be difficult to adapting themselves in more and more complex project environments. Moreover, the "project objectives" dominate the practice for deriving performance indicators.

Indeed, the importance of project objectives for designing and developing relevant performance indicators is beyond doubt. However, there are always different issues arising towards achieving fixed objectives in terms of budget, schedule, quality, and functionality during the course of a project (McGarry et al. 2002). McGarry et al. (2002) defined three types of issues: problems, risks and lack of information. In the software measurement domain, "Goal/Question/Metric" (GQM) is a well-known approach, where each goal is decomposed through a series of possible question to be answered by one or more measures (Basili and Weiss 1984). "Goal" in this model refers to several aspects, one of which is the concept "issues". Based on the original formulation of GQM, some variants of the approach have been proposed over the years. For example, McGarry et al. (1997) have developed the "Issue/Category/Measure" approach based on the GQM model. This is a directly issue-driven measurement. However, with the development of software measurement, people come to realize that both project objectives and issues are important to decide performance measures, and this thought has been brought to the Practical software and systems measurement (PSM) approach. The PSM approach refines and addresses the basic GQM idea and "Issue/Category/Measure" approach (McGarry et al. 1997) and then proposed the concept "information needs" that relate directly to both the established project objectives and issues. Indeed, the PSM approach begins with the recognition that a manager or engineer has a specific information need required to support project decision making. Once the information needs are identified, measures will be defined to address the identified information needs (McGarry et al. 2002) (PSM 2017). Information needs here are similar to goals in the "Goal/Question/Metric" (GQM) approach. However, they are more general (not limited to goals) and less open-ended (PSM provides potential solutions for the project manager) (Card 2003). Information-driven measurement has got wide application in both software and systems engineering. However, in project performance measurement, very little attention has been paid to them.

Issue 2: methods for defining a set of indicators have been focused largely but the transformation from data to indicators has not been well addressed.

Regardless of the disaccord of the derivation of performance measures, there are two different ways to define performance indicators. One way is to directly propose a set of well-defined and generic performance indicators to manage project (Cha and Kim 2011) (Rui et al. 2017) (Yun et al. 2016) (Almahmoud, Doloi and Panuwatwanich 2012); the other way is to follow an approach by which customized performance indicators can be generated (Neely et al. 1997) (Bourgault et al. 2002) (Barclay and Osei-Bryson 2010) (Henttonen et al. 2016). Based on the literature review, it seems that the first way dominates the practices; many studies focus on a post project evaluation of the success or failure of the completed projects (Cleland 1985) whereby various generic indicators have been developed around time, cost and quality. Considering the limits of this scope and type of indicators (limited number of indicators, limited to the post project phase), some researchers have considered a set of indicators for different project phases; for instance, Yun et al. (2016) criticized the limit of most project performance indicators designed for post evaluation of processes and practices after project completion, and a set of phase-wise and phase-specific indicators were created under the categories of Cost, Schedule, Efficiency, Staffing, Procurement, and Safety performance. In addition to the consideration of project phases for measuring performance, some other authors have built a set of performance indicators by considering both project scopes and project phases (Rui et al. 2017). Chen (2015) has identified the Communication, Team, Scope, Creativity, Technology, Risk, Quality, and Materials as performance measures to examine how changes in project-management performance in the execution phase affect project outcomes. This way to define performance indicators offers advantages: a list of performance indicators is available for practitioners to select and tailor according to the nature of the project. However, the indicators defined in studies above are what will be presented to measurement users, often not defined to a level of detail to show the transformation from data to indicators. The ignorance of the transformation from data to indicators in these studies causes difficulties for practitioners to come back to the raw data and the transformation process for the improvement or correction of project problems, thus preventing them from implementing the indicators in real project context.

In this regard, some authors criticize that there are no one-size-fit-all solutions (Henttonen et al. 2016). It is impossible to generate a universal checklist of project performance indicators, and thus they must be different depending on project characteristics, such as the size, uniqueness, complexity or the viewpoints (user, stakeholders, engineers, project sponsors, project managers, contractors, etc.) (Marques et al. 2011). Some authors thus have proposed some approaches for demonstrating how to design and develop a performance indicator in a step-by-step way (Neely et al. 1997) (Barclay and Osei-Bryson 2010). Barclay and Osei-Bryson (2010) have designed structured and easily implementable procedures to develop performance measures:

- Identify project stakeholders,
- Identify and structure project objectives,
- Prioritization of project objectives, and
- Elicit and define project measures.

In their model, the GQM approach has been adopted as a tool to derive performance measures, however GQM itself does not distinguish the data and indicators; it uses the concept "metric" that can mean a "base measure", for example "average cycle time" (the example is adopted directly from the article of Basili, Caldiera and Rombach (1994)). However, it can represent a "derived measure", for example "current average cycle time/baseline average cycle time" (the example is adopted directly from the article of Basili, Caldiera and Rombach (1994)). It can represent an "indicator" also, for example "subjective rating of manager's satisfaction" (the example is adopted directly from the article of Basili, Caldiera and Rombach (1994)). Thus, how the different "metrics" (base measures, derived measures and indicators) are structured and transformed from one to another has not been addressed.

Marques, Gourc and Lauras (2011) used an aggregation tool called MACBETH to analyze the performance measures according to project managers' own performance interest. Cha and Kim (2011) suggested a "performance total score" to quantify the established performance indicator system and a calculation process, but how the raw data converted into the indicator has not been presented clearly.

Although very valuable such methods ("design and develop an indicator in step-by-step process") for defining indicators, their focus on the transformation from "data to indicator" is still very limited, not very well developed. A better model that demonstrates how data can be converted into a useful indicator is necessary.

Issue 3: mechanisms or procedures for collecting, analyzing and reporting performance data have been designed in some literature but how to associate them with project management processes has not been well developed.

Both methods referred in the issue 2 for defining indicators ("a predefined set of indicators" and "design an indicator in step-by-step process") can provide a practitioner a set of indicators. Such approaches are undoubtedly valuable, however, one key issue is that they did not define in detail how to collect, analyze and report data related to the defined indicators. A few studies have proposed to develop a set of procedures or design some mechanisms to address this issue. For example, in software measurement, Basili, Caldiera and Rombach (1994) have claimed that "after the measures have been specified, we need to develop the data collection mechanisms, including validation and analysis mechanisms". Chirinos et al. (2005) developed a model for the definition of unambiguous collection, storage and interpretation of data related to the developed software products to aid the software measurement. They advocated to making full use of existing data sources in a project. However, they considered little associating the procedures or mechanisms for data collection and analysis with project management processes. For example, McGarry et al. (2002) proposed that the measurement approach should be integrated into project's technical and management processes. Their focused approach is to integrate data collection procedures into processes providing data, and to integrate analysis and reporting procedures into decision-making processes. However, the "processes" in their writing is a very general concept. Such questions are not addressed: Which processes produce data? Which processes are for analyzing data to produce indicators? And which processes report the performance for decision-making? How the different processes are connected? As we know, project management processes are essential part for project management, thus, how the "defined indicators" can be integrated into project management processes (e.g. 47 processes of the PMBoK) to collect, analyze and report data should be considered and addressed.

Against this background (cf. issues 1, 2 and 3), this study seeks a way to resolve the identified issues above to thus improve project performance measurement. As measurement has been widely applied in different disciplines, many good practices have been published in a standardized way by some communities, such as the project management institute (e.g. PMI), systems engineering community (e.g. INCOSE) and software engineering community (e.g. PSM). It is a good way ("Multi-crossed disciplines" recommended in Chapter II) to learn from the practices conducted by these communities and thus improving the project performance measurement activities. Indeed, our previous study (Zheng et al. 2017) has enabled us to obtain a deeper understanding of the knowledge in software and systems engineering for measurement and project management standards, thus we come to know: PSM has led its way to conduct a measurement program by addressing "information needs", which allow a more agile way to derive performance measures compared to traditional project performance measurement that looks to project objectives for deriving performance indicators. The idea "information needs" has been adopted by some ISO standards like ISO/IEC 15939. The ISO/IEC 15939, based on some principles of the PSM approach, has been developed to become a popular norm, especially its measurement information model that allows the project data to be converted into indicators by a structured way. PMI has developed the internationally recognized guide to Project Management of Body Knowledge (PMBoK), which includes a set of 10 knowledge areas and 47 supporting processes. Measurement is an integral in all the 10 knowledge areas across various processes. The measurement-related processes provide a framework where performance data is generated in a process and then flow into another process for analysis to get performance information and finally the performance information is interpreted and documented by decision-making processes. The following literature review of these methodologies in these communities shows that the sole use of any practices cannot get a comprehensive method for project performance measurement, while an integration of the three can address all the three previously identified issues. Detailed analysis for this will be introduced in Section 2.2.

2.2. Presentation and selection of the three good measurement practices from the PSM, the ISO/IEC 15939, and the PMBoK

This section begins from a systematic searching and reading of some performance measurement practices applied in systems and software engineering disciplines, particular focus on the PSM approach and the ISO/IEC 15939 norm. This allows us to find solutions for issue 1 and issue 2. Then several PM standards are demonstrated and compared and finally the PMBoK is select as one of the references of our method. The processes of the PMBoK relating to performance data collection, analysis and report have been well defined, which allows us to answer issue 3.

2.2.1. *Information-driven measurement in software and systems engineering*

The software and systems engineering communities have developed some measurement guidance and standards for objective project management. Chapter III has presented the development and evolution of systems engineering measurement (SEM), where the relationship of the SEM and PSM has been demonstrated (mainly consistency of terms and definition is shared). This section presents the relationship between PSM, ISO/IEC 15939 and SEM to demonstrate that there is a strong tie in the three approaches. The strong tie lies in the shared consistency of terms and concepts between them and especially the common adoption of information-driven measurement in them. Detailed presentation follows.

(1) The history and evolution of systems and software measurement and its standardization

By reviewing the guidance and standards for measurement in both systems and software engineering, particularly focusing on the PSM, the ISO/IEC 15939 and the SEM, their relationship has been demonstrated in Figure IV–2 below.

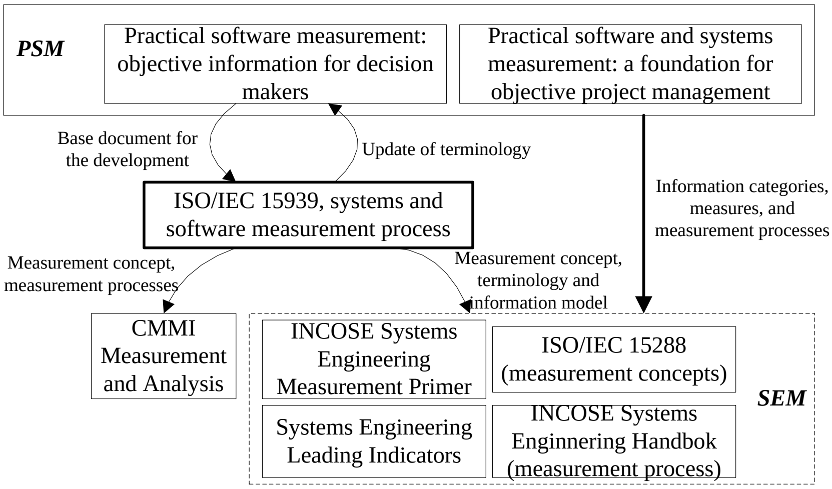

Figure IV–2 The evolution and relationship between PSM, ISO/IEC 15939 and SEM

PSM (Practical Software and System Measurement) is an organization that performs measurement-related activity, providing products such as measurement whitepapers, tools, trainings, and measurement guidance. All their products can be accessed by their official website (PSM 2017). On the other hand, PSM represents approaches proposed by the organization. The US DOD (Department of Defense) and US Army co-sponsored *Practical Systems and Software Measurement: a foundation for objective project management* that is a large handbook containing guidelines. Companies can use it to establish information-driven measurement programs. Version 4 of the handbook, released in 2001, added systems engineering and process improvement measurement to the contents of the former Practical Software Measurement standard. There are many measures (mainly including base measures and derived measures) available in this guidance, and there is a specification table for each measure. The measures and specification tables summarized in this guidance become an important input for other guidance or standards in SEM. Another important product is a published book *Practical Software Measurement: Objective Information for Decision Makers* (McGarry et al. 2002). This book is the definitive guide to the PSM approaches, and it is updated with ISO/IEC 15939 terminology, new case studies, and an information model and definitions. The PSM approaches are based on actual experience, compatible with other standards and guidance in systems and software engineering.

From Figure IV–2, it can be concluded that the PSM approaches have its characteristics such as:

- It is a base document for the development of ISO/IEC 15939 and some of systems engineering measurement guidance.
- Thus, the systems and software engineering communities are sharing a set consistent measurement concepts and terms.
- The consistent measurement concepts and terms are spreading across various software and systems related standards.

(2) Information-driven measurement approach

Indeed, the systems and software engineering communities are not only sharing a set of consistent measurement concepts and terms, but also have common theories and practices in designing and developing performance measures. These theories and practices are very different from those proposed in literature of general project performance measurement (PPM). As mentioned above (cf. Section 2.1) there are mainly three standpoints for deciding the derivation of performance measures: 1) project objectives, 2) stakeholders' objectives, and 3) critical success factors (CSFs). Different from the theories and practices in project performance measurement, the PSM, the ISO/IEC 15939 and the SEM have the standpoint that measures derive from information needs.

PSM thinks that "the information needs of the decision maker drive the selection of software measures and associated analysis techniques" (McGarry et al. 2002). This stance is indeed based on two widely accepted approaches to software measurement, which are respectively the "Goal/Question/Metric" (Basili and Weiss 1984) and the "issue/categories/measure" (McGarry et al. 1997). The concept "Information needs" in PSM is similar to the concept "goals" in the "Goal/Question/Metric" (GQM) approach. However, they are more general (not limited to goals) and less open-ended (PSM provides potential solutions for the project manager) (Card 2003). GQM is a well-known approach that is often used in software engineering measurement, where each goal is decomposed through a series of possible question to be answered by one or more measures (Basili, Caldiera and Rombach 1994). Based on the original formulation of GQM, some variants of the approach have been proposed over the years, such as V-GQM (Validating Goal/Question/Metric) (Olsson and Runeson 2001). PSM indeed refines and addresses the basic GQM idea, and stresses the central role of the issues that are defined at the initiation of a project and arise on the course of the project.

In the PSM approach, the practitioners have first identified 7 common information categories that cover most software project information needs from a number of possible sources (cf. Annex A). The multiple resources include the following (adopted directly from the research of McGarry et al. (2002)):

- *Risk assessments: the results of technical and management risk assessments should always be considered when identifying project information needs. Risk assessments may point to information needs related to requirements, technology, process, cost, or schedule.*
- *Project constraints and assumption: the project plan is usually based on many assumptions, such as the performance of the supplier or the availability of test facility. Lack of information that impacts effort, schedule, and quality estimates should be treated as an information need. Moreover, schedules and budgets may have inflexible or conflicting constraints. If derivations from these constraints can threaten project success, identify these areas as information needs.*
- *Leveraged technologies: project success may depend on leveraging certain technologies such as the use of non-developed components (commercial components; reused components; etc.), common domain architectures, or advanced programming languages. If project objectives depend on utilizing specific technologies, the effectiveness of these technologies is an information need.*
- *Product acceptance criteria: customers may impose stringent milestone or acceptance criteria on the deliverable software product. If there is significant doubt about the organization's ability to meet defined acceptance criteria, advertised objectives, or other external criteria, identify the degree of satisfaction of these criteria as an information need.*

- *External requirements: many project information needs are related to requirements and concerns external to the project. For example, the need to make decisions concerning readiness for test or product delivery may necessitate that certain external customer-derived information needs be identified and tracked within a project. The probability of fulfilling aggressive or unrealistic organizational goals may also be treated as a project information need.*
- *Experience: a project team with experience on similar projects may be able to identify potential problem areas as information needs.*

It can be seen that the vision for deciding the derivation of performance measures in the PSM approach has been broadened by considering multiple resources. This consideration of multiple resources can enrich the body of knowledge for the derivation of performance indicators where "project objectives" dominate the practice. Information needs as defined in the PSM is based on a much wider focus compare to the traditional project objectives (around time, cost and quality). This broadened horizon makes projects more aware of the issues likely to occur during project completion.

The PSM practice of designing performance indicators beginning from identifying information needs has got wide application in systems engineering measurement and software measurement. This study adopts the stance from the PSM approach for designing performance indicators relevant to project-specific information needs. This good practice can be indeed well connected with the Measurement Information Model of ISO/IEC 15939 where the model begins from identifying information needs in accordance with the PSM approach. The Measurement Information Model is demonstrated in the following section.

2.2.2. *The ISO/IEC 15939 Measurement Information Model*

ISO/IEC 15939/IEC Measurement Information Model (MIM) has been a standardized reference to redefining measurement concepts and terms in some standards such as CMMI (PSM 2017), ISO 9126 (Abran et al. 2006) and some models such as the Data Quality measurement information model (Abran et al. 2005), or used as a structure allowing for comparability due to a use of a standard (Feyh and Petersen 2013). Except as a reference of terms, it is also used a technique to help derive the control measures at the end of each "cause bone" of "Fishbone Program" in total quality management (Buglione 2008).

The Measurement Information Model of ISO/IEC 15939 is illustrated in Figure IV–3. The Measurement Information Model of ISO/IEC 15939 is a structure that links information needs to what can be measured. It describes how relevant measurable attributes are quantified and converted into base and derived measures. It also describes how the base and derived measures are converted into indicators that provide insight to decision-makers. The model also includes the specific rules for assigning values, defining the measurement methods, functions, and analysis models and it helps to guide how to quantify attributes into base measures, combine base measures into one derived measure, and form derived measures into an indicator.

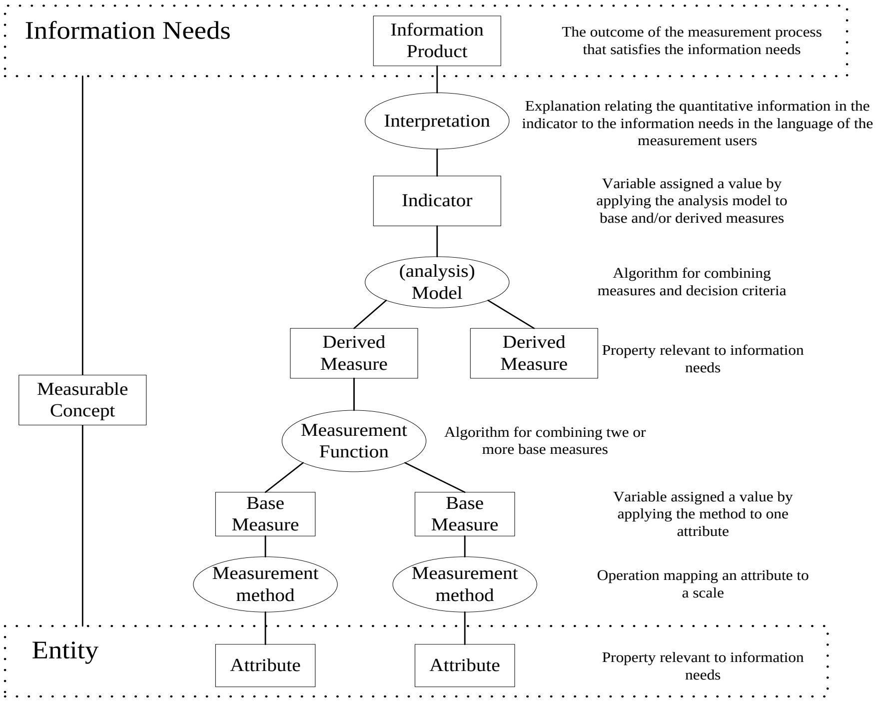

Figure IV–3 the Measurement Information Model of ISO/IEC 15939:2007

There are 12 terms in the model: information needs, measurable concept, entity, attribute, measurement method, base measure, measurement function, derived measure, analysis model, indicator, interpretation, and information product. Descriptions of the terms in this model are adopted directly from the norm:

- *Information need: insight necessary to manage objectives, goals, risks and problems.*
- *Measurable concept: A measurable concept is an abstract relationship between attributes of entities and information needs.*
- *Entity: An entity is an object (for example, a process, product, project, or resource) that is to be characterized by measuring its attributes. Typical engineering objects can be classified as products (e.g., design document, network, source code, and test case), processes (e.g., design process, testing process, and requirements analysis process), projects, and resources (e.g., the systems engineers, the software engineers, the programmers and the testers). An entity may have one or more properties that are of interest to meet the information needs.*
- *Attribute: An attribute is a property or characteristic of an entity that can be distinguished quantitatively or qualitatively by human or automated means.*
- *Base measure: A measure defined in terms of an attribute and the method for quantifying it. A base measure is functionally independent of other measures. A base measure captures information about a single attribute.*
- *Measurement method: A measurement method is a logical sequence of operations, described generically, used in quantifying an attribute with respect to a specified scale. The operations may involve activities such as counting occurrences or observing the passage of time.*

- *Derived measure: A derived measure is a measure that is defined as a function of two or more values of base measures. Derived measures capture information about more than one attribute or the same attribute from multiple entities.*
- *Measurement function: A function is an algorithm or calculation performed to combine two or more base measures.*
- *Indicator: An indicator is a measure that provides an estimate or evaluation of specified attributes derived from a model with respect to defined information needs. Indicators are the basis for analysis and decision-making. These are what should be presented to measurement users.*
- *Model: An algorithm or calculation combining one or more base and/or derived measures with associated decision criteria. It is based on an understanding of, or assumptions about, the expected relationship between the component measures and/or their behaviour over time. Models produce estimates or evaluations relevant to defined information needs.*
- *Information product: one or more indicators and their associated interpretations that address an information need.*

ISO/IEC 15939 Measurement Information Model has got wide recognition and application across various disciplines or industries such as Data Quality measurement information model (Abran et al. 2005), or lean software development (Feyh and Petersen 2013), total quality management (Buglione 2008), evaluation in the field of Human-Computer Interaction (Assila et al. 2016); and navigation performance measurement (Assila et al. 2017). There are several main reasons behind this success:

- Allowing for comparability due to a use of a standard (Feyh and Petersen 2013);
- Providing a comprehensive measurement construction process ranging from the specification of its attributes to the establishment of indicators that meet the specific requirements of stakeholders and their information needs (Assila et al. 2017);
- Allowing effective integration of heterogeneous results by retaining its raw values (Assila et al. 2017);
- This model links information needs with the entities being evaluated by the definition of measures and indicators (Assila et al. 2016).

In this research, the ISO/IEC 15939 Measurement Information Model has been adopted by considering its benefits such as:

- Building the link of the real project-specific information needs and entities and its attributes in a project;
- Adopting the standard terminologies of metrology for the improvement of communication;
- Demonstrating the transformation process from data to indicators.

2.2.3. *The measurement-related processes in the context of international project management standards*

Performance measurement practices have been also integrated in some project management guidelines such as the PMBoK (PMI 2013), ISO 21500 (ISO 2012) and PRINCE 2 (PRojects IN Controlled Environments) (OGC 2009). Although the topic “project performance measurement” has not been addressed directly in the standards, how to control projects (by measurement) is an integral part in these standards. In this section, a general introduction and comparison of the standards is proposed, including a description of the measurement-related processes.

(1) General introduction of the PMBoK, the ISO 21500 and PRINCE 2

There exist some representative standards for project management at international level: the PMBoK, the ISO 21500, and the PRINCE 2. A standard is a formal document that describes established norms, methods, processes, and practices. In these standards, the term "project performance measurement" is not addressed directly, but performance measurement is an integral part penetrated in the project management processes, for example the "Monitoring and Controlling Process Group" (one of the five Process Groups) of the PMBoK *not only monitors and controls the work being done within a Process Group, but also monitors and controls the entire project effort* (PMI 2013). As stated by PMI (Project Management Institute), "if you cannot measure it, you cannot control it; if you cannot control it, you cannot manage it." It is common in all those three standards that "controlling" (through measurement) is performed through the whole project lifecycle. But how to conduct the controlling process and how the project performance information links and interacts is structured in a different way, and the difference provides us a reference to choosing one from the three PM guides.

PMBoK contains the globally recognized guide for the project management profession. The knowledge contained in this standard has been developed partly based on the recognized good practices of project management practitioners. In the last version, it includes 10 knowledges areas and 5 process groups. The 10 knowledge areas are: Project Integration Management, Project Scope Management, Project Time Management, Project Cost Management, Project Quality Management, Project Human Resources Management, Project Communication Management, Project Risk Management, Project Procurement Management and Project Stakeholder Management. The 5 Process Groups are: Initiating Process Group, Planning Process Group, Executing Process Group, Monitoring and Controlling Process Group, and Closing Process Group. The standard lays out the processes (each Process Group includes several processes) across Knowledge Areas, and describes how the processes link together through in-and-out information flows and the tools and techniques that can be invoked.

ISO 21500:2012 provides guidance on concepts and processes of project management that are important for, and have impact on, the performance of projects. It provides high-level description of concepts and processes that are considered to form good practice in project management. Projects are placed in the context of programs and project portfolios. It includes 10 subjects groups similar with 10 Knowledge Areas in the PMBoK: Integration; Stakeholder; Scope; Resource; Time; Cost; Risk; Quality; Procurement; and Communication. It has 5 process groups including: Initiating Process Group; Planning Process Group; Implementing Process Group; Controlling Process Group; and Closing Process Group. Data and information related to performance measurement is the progress data produced in Implementing Process Group and progress reports produced in Controlling Process Group.

PRINCE2 provides a set of best practices around project management, which covers the control, administration, and organization of projects. It is a structured, process-based project management method with a life-cycle-based presentation. The processes define the management activities to be carried out during the project. In addition, it describes a number of components that are around the processes. The processes include: Directing a project; Starting up a project; Initiating a project; Controlling a stage; Managing stage boundaries; Managing product delivery; and Closing a project. Process "Controlling a stage" describes the monitoring and control activities of the Project Manager involved in allocating work, ensuring that a stage stays on course and reacts to unexpected events. Performance measurement activities occur in the process and it produces and analyzes data and information related to performance measurement, such as the checkpoint reports, quality log, work package status, stage plan, and stage status information.

Reading through the three standards above has helped a better understanding of the advantages of existing measurement practices in these standards. Measurement constitutes an important part in the processes of the standards. However, it may be very difficult to get more practical guidance when a project team tries to use them to conduct a measurement program.

(2) Comparison

Based on the description of the current PM references above, the differences between the ISO 21500 (ISO 2012) and the PMBoK (PMI 2013) are minimal concerning the Process Groups and Subjects/Knowledge Areas. The main difference lies to two aspects: one is in the description of tools and techniques, where ISO 21500 does not provide it. In the PMBoK, there are 47 processes across 5 Process Groups and 10 Knowledge Areas. Each process is characterized by its inputs, the tools and techniques that can be applied, and the resulting outputs. However, each process of the ISO 21500 is characterized only by its inputs and the resulting outputs, the term "tools and techniques" is not considered. The other one is the details of description of inputs and outputs, where ISO 21500 presents them less detailed than the PMBoK. Then, we compare the PMBoK with PRINCE 2. Some studies have compared the PMBoK and PRINCE 2 from methodologies at high level (Singh and Lano 2014), themes vs. Knowledge Areas and detailed processes (Karaman and Kurt 2015). People agreed that PMBoK provides more comprehensive approach with detailed techniques compared with PRINCE 2 (Karaman and Kurt 2015). Considering that they have their individual advantages and application environments, we will not give a detailed comparison between them.

In our study here, the PMBoK will be focused on to build the framework in Section 3 mainly based on two considerations: 1) it provides detailed description of each process characterized by inputs, tools and techniques, and outputs in which we can integrate the different elements in the Measurement Information Model of the ISO/IEC 15939 (cf. Section 2.2.2); however neither the ISO 21500 nor PRINCE 2 include the term "tools and techniques"; 2) it has a more comprehensive 'Monitoring and Controlling Process Group' across nearly 10 knowledge areas which are used on most projects most of the time (PMI 2013), compared to PRINCE 2. Thus, we can build a framework for designing relevant performance indicators by considering more comprehensive information.

(3) Measurement-related processes in the PMBoK

The PMBoK is the globally recognized guide for the project management profession. There are 47 processes grouped into 5 Process Groups and the processes are also laid out across 10 Knowledge Areas. In this section, all the processes relating to performance data collection, analysis and report are identified and named as the measurement-related processes.

PMBoK has distinguished the term "data" from the term "information". There are three concepts related to the data and information defined in the standard, and these concepts are respectively *work performance data*, *work performance information* and *work performance reports*.

Work performance data is the raw observations and measurements (e.g. "number of defects"), continuously measured, collected and analyzed during the dynamic context of the project execution, mainly produced in Process 4.3 "Direct and manage project work" in the PMBoK (PMI 2103). *Work performance data* flows into the various monitoring and controlling processes where data is transformed, analyzed, and aggregated to *work performance information* (e.g. "status of defects"). And then the *work performance information* will be compiled in project documents and becomes the *work performance reports*, and then flows into Process "4.4 monitor and control project work" where project managers could generate decisions, or raise issues, actions or awareness. Once different *work performance reports* are formed, they will be sent to other processes concerning to the information needs of different stakeholders.

The three types of data and information, flowing through different Knowledge Areas and processes in the PMBoK, are mainly used to measure project performance. According to the flows, we have identified the processes relating directly to performance measurement, named as the measurement-related processes in this study. Figure IV–4 is the measurement-related processes identified from all the 47 processes of the PMBoK structured and connected by *work performance data*, *work performance information*, and *work performance reports*. It can be found that the performance measurement activities in the PMBoK are mainly conducted in the "Monitoring and Controlling Process Group". The key benefit of this Process Group is that *project performance is measured and analyzed at regular intervals, appropriate events, or exception conditions to identify variances from the project management plan* (PMI 2013). The concerns of each Knowledge Area have been summarized on the right of Figure IV–4 after surveying the information statements of each Knowledge Area.

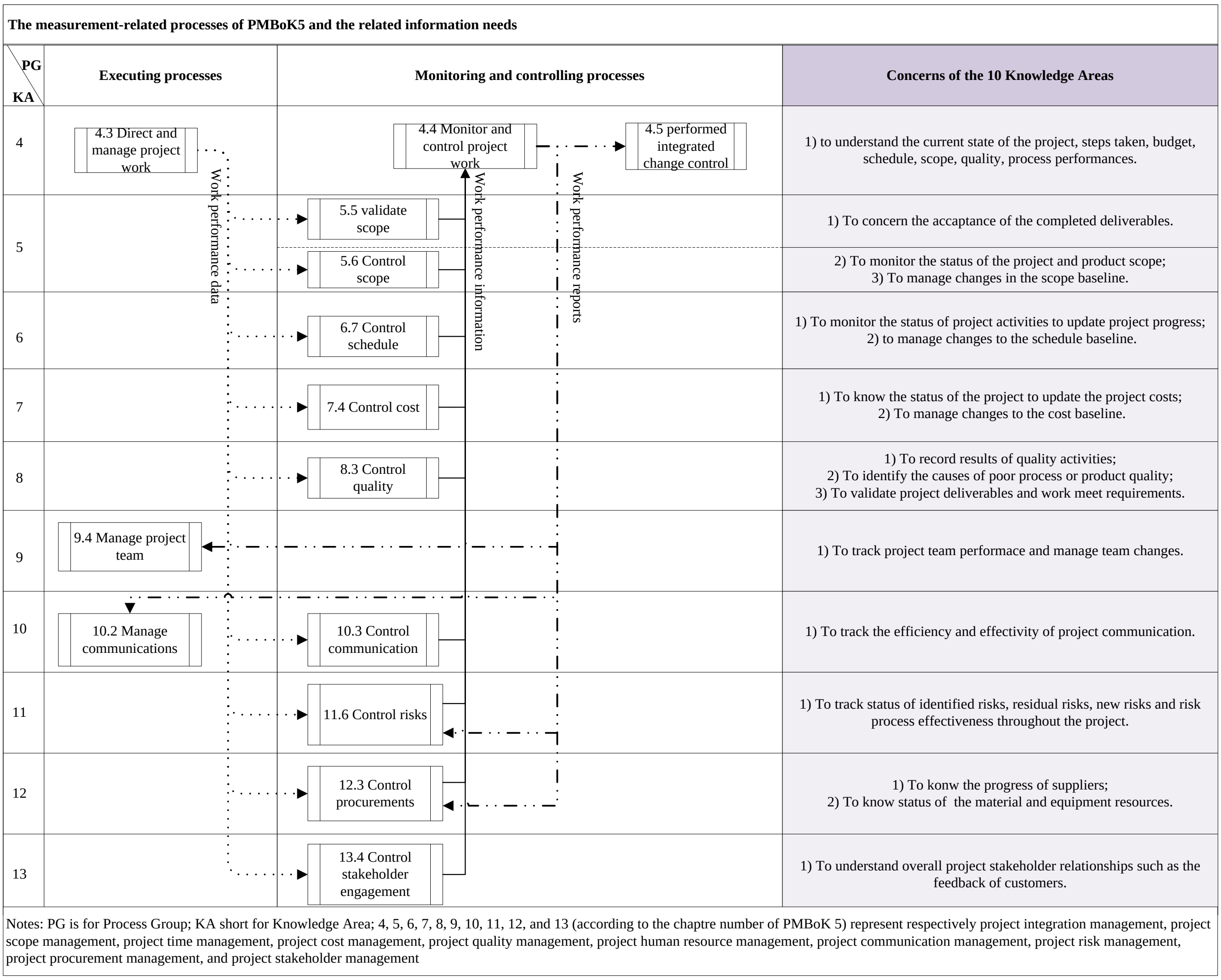

Figure IV–4 The identification of measurement-related processes from the PMBoK

The measurement-related processes are laid out across the 10 KAs of the PMBoK, providing a clear picture of performance data collection, analysis and report. However, a deeper analysis on the practical use shows that using these processes alone cannot provide a good project performance measurement. The reasons are:

- It lacks a consistent terminology for basic measurement ideas and concepts, which is critical to communicate project performance to project stakeholders. For example, the concepts like measures, metrics, and indicators have been used in a mixed and confused way.
- It lacks a systematic approach and mechanism to transform the 'data' into useful 'indicators'. For example, according to Figure IV–4, it is clear that the work performance data is produced in Process "Direct and Manage Project Work", and then flows into other processes; however, it is not clear how the work performance data in the PMBok can be converted to work performance information and work performance reports.

Here an example is illustrated to demonstrate some weak points inherent in the identified measurement-related processes from the PMBoK. We suppose to measure the quality of a software product, which obviously related to

Project Quality Management Knowledge Area. According to Figure IV–4, the *work performance data* and *work performance information* flow in and out of Process "Control Quality". After surveying the proposed *work performance data* and *work performance information* in the PMBoK, we find that using alone the recommendations in the standard is far more from sufficient to provide project managers useful insight on the quality of the software product. Survey result is listed in Table IV–1:

Table IV–1 The available work performance data and information from Process "Control Quality"

Control quality		
Work performance data		Work performance information
▪ Planned vs. actual technical performance ▪ Planned vs. actual schedule performance ▪ Planned vs. actual cost performance		▪ Cause for rejection ▪ Rework required ▪ The need for process adjustments

Result of Table IV–1 confirms the statements done in literature review. Most of these indicators have been designed based either on the traditional "iron triangle" (time, cost and quality) or on an extension of the "iron triangle". No customer requirements or product related indicators have been addressed in the standard. In addition, the transformation process from *work performance data* to *work performance information* is not obvious, even confusing. For example, the "planned vs. actual technical performance" in the left column of table IV–1 is one of the work performance data, but the process of how the data is transformed into items in the right column (the work performance information) is not mentioned. This example shows that using the PMBoK alone cannot provide project managers a comprehensive and practical way to conduct project performance measurement.

In spite of the limits of the measurement-related processes of the PMBoK demonstrated above, these processes can still be considered as a good measurement practice as it provides a good process framework where data can be collected and analyzed and performance indicators can be constructed. The processes here can be a complement to the body of knowledge about performance data collection and analysis in the literature (cf. Section 2.1).

2.2.4. *The relationship between data and information of the PMBoK and elements of the ISO/IEC 15939 Measurement Information Model*

Section 2.2.2 has presented the Measurement Information Model of the ISO/IEC 15939 and its 12 items that structure the model. It shows also that the model can be very useful for transforming data to indicators. However, the model has not addressed how the transformation process is associated to project management processes. Then section 2.2.3 concluded that some measurement-related processes in the PMBoK can serve to performance data collection, analysis and reporting. This section will demonstrate how the 12 items of the ISO/IEC 15939 Measurement Information Model can be integrated into the measurement-related processes identified in Section 2.2.3.

Integrating the elements of the ISO/IEC 15939 Measurement Information Model into the inputs, tools & techniques and outputs of the project management processes of the PMBoK

The measurement-related processes identified in Figure IV–4 can be regrouped by their functions into three parts as depicted at the top of Figure IV–5. Part 1 is called “Collect performance data” where work performance data is produced. Part 2 is named as “Analyze performance information”. In this part, work performance information is generated from work performance data. Part 3 is termed “Report project performance” where work performance information is interpreted by project managers to generate work performance reports.

Actually, each process of the PMBoK is characterized by the inputs, tools & techniques and outputs. From Figure IV–5, we can also see that most items (e.g. entity, attribute, base measure etc.) of the ISO/IEC 15939 Measurement Information Model, indeed, can be integrated respectively into the inputs, tools and techniques and outputs of the identified measurement-related processes. In the following paragraphs, it is analyzed how the integration can be made in detail.

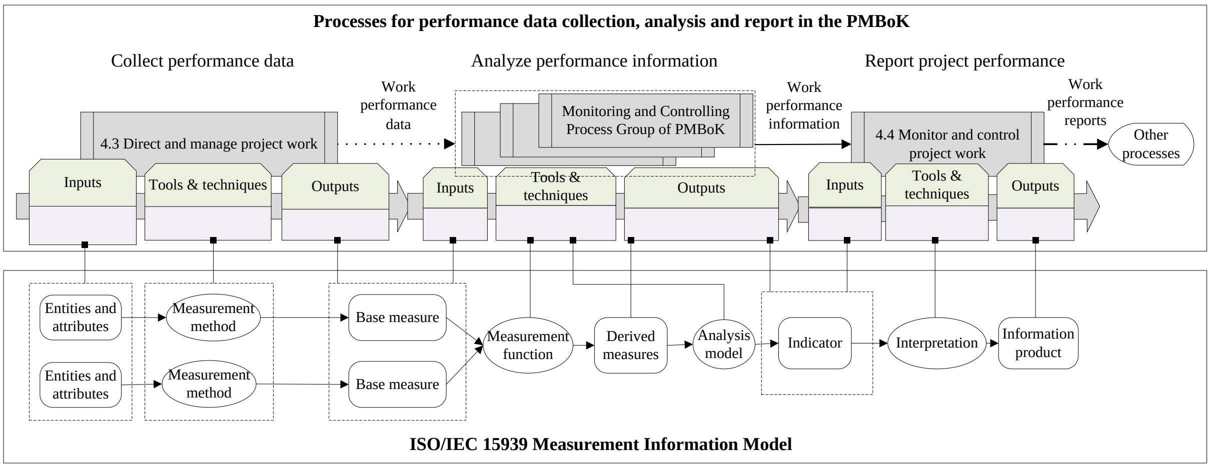

Figure IV–5 The Measurement Information Model of ISO/IEC correspond to processes for performance data collection, analysis and report in the PMBoK

(1) Collect performance data

According to the definition of ISO/IEC 15939, an **attribute** is *a property or characteristic of an entity that can be distinguished quantitatively or qualitatively by human or automated means*. An **entity** could be objects like *a process, product, project, or resource*. In this study, the entity includes activities being performed to carry out the project work, which occurs mainly in the Process “Direct and Manage Work” of the PMBoK (PMI 2013). Attributes will be abstracted from the identified entities by judging whether they are relevant to the measurement user’s information needs, and then documented into the inputs of Process “Direct and Manage Work” where there are project management plan, approved change requests, organizational process assets.

A **measurement method** is *a logical sequence of operations, described generically, used in quantifying an attribute with respect to a specified scale*. In the PSM specification tables, there are many available measurement methods. With the given organizational context, some methods could be selected and then documented into the tools and techniques of Process “Direct and Manage Work”. Each unique combination of an attribute and a measurement method produces a different **base measure** that is a *measure of a single attribute defined by a specified measurement method*. Data collection involves assigning values to base measures, and the base measure here corresponds one main output--Work Performance Data of Process "Direct and Manage Work" of the PMBoK. Work Performance Data is the raw observations and measurements identified during activities performed to carry out the project work and is passed to the controlling processes for future analysis.

(2) Analyze performance information

Once performance data is collected, it proceeds to "analyze performance information". To analyze performance data is where much of the project's measurement effort will be made. It transforms values of base measures into values for indicators. Indicators and its interpretations are used to make planning decisions. In the PMBoK, to analyze performance data is conducted in the controlling processes of each knowledge area. The base measures from the outputs of Process "4.3 Direct and manage work" in the PMBoK, becoming the inputs of the monitoring & controlling processes.

The **measurement function** proposed in the *measurement information model, is an algorithm or calculation performed to combine two or more base measures*. In PSM specification tables, there are many available measurement functions based on larges of engineering experiences. According to specific project context, measurements functions could be adopted from the PSM and then be documented into the tools and techniques of the controlling process of one knowledge area in the PMBoK (PMI 2013). By the measurement functions, we get the **derived measure** that *is defined as a function of two or more values of base measures. Derived measures capture information about more than one attribute or the same attribute from multiple entities.* Derived measures will be documented into the outputs of the monitoring & controlling processes. But they could not yet provide very useful information of project status for stakeholders. We need further to analyze them by a **model** *that is an algorithm or calculation combining one or more base and/or derived measures with associated decision*. And then we get an **indicator** that *is a measure that provides an estimate or evaluation of specified attributes derived from a model with respect to defined information needs criteria*. Indicators are the basis for analysis and decision-making. The model to obtain an indicator will be documented into the tools and techniques, and the obtained indicator becomes the output of the monitoring & controlling processes, and also as the inputs of some processes where performance reports are documented.

(3) Report project performance

The ultimate purpose of performance measurement is to help project managers, customers, and organizational managers make more informed and objective decisions. Measurement results should be discussed and communicated to various parties. A report is a periodic snapshot of information fed back by indicators. The indicators generated in the monitoring & controlling processes are informed to project manager who charges of Process "Monitor and Control project work", and the **interpretation** of ISO 15939 Measurement Information Model could be referred and then documented into tools & techniques of Process "Monitor and Control project work", and then **information products** (performance reports) will be generated and documented into the output of the process. Project managers will decide which indicators should be delivered to the stakeholders according to real situations, and then the documented information products flow into different inputs of other processes, for example Process "Manage project team" (cf. Figure IV–4).

Against the backgrounds in the PSM, the ISO/IEC 15939 and the PMBoK, The current PPM research highlights the development of a system of performance indicators; however several issues have been underlined. The issues in the PPM indeed can be addressed respectively by learning from the PSM, the ISO/IEC 15939 and the PMBoK. A method must be developed to integrate the three measurement practices to obtain a comprehensive project performance measurement framework. A further elaboration on it will be showed in the following section.

3. A new method to design project-specific performance indicators

This study follows the standpoint from the PSM and ISO/IEC 15939 that a project performance measurement program begins from the project-specific information needs. To integrate the three good measurement practices from the PSM, the ISO/IEC 15939 and the PMBoK, a method consisting of 6 steps has been proposed in this section, which are respectively “identify”, “associate”, “specify”, “select”, “construct” and “integrate” as demonstrated in Figure IV–6 below.

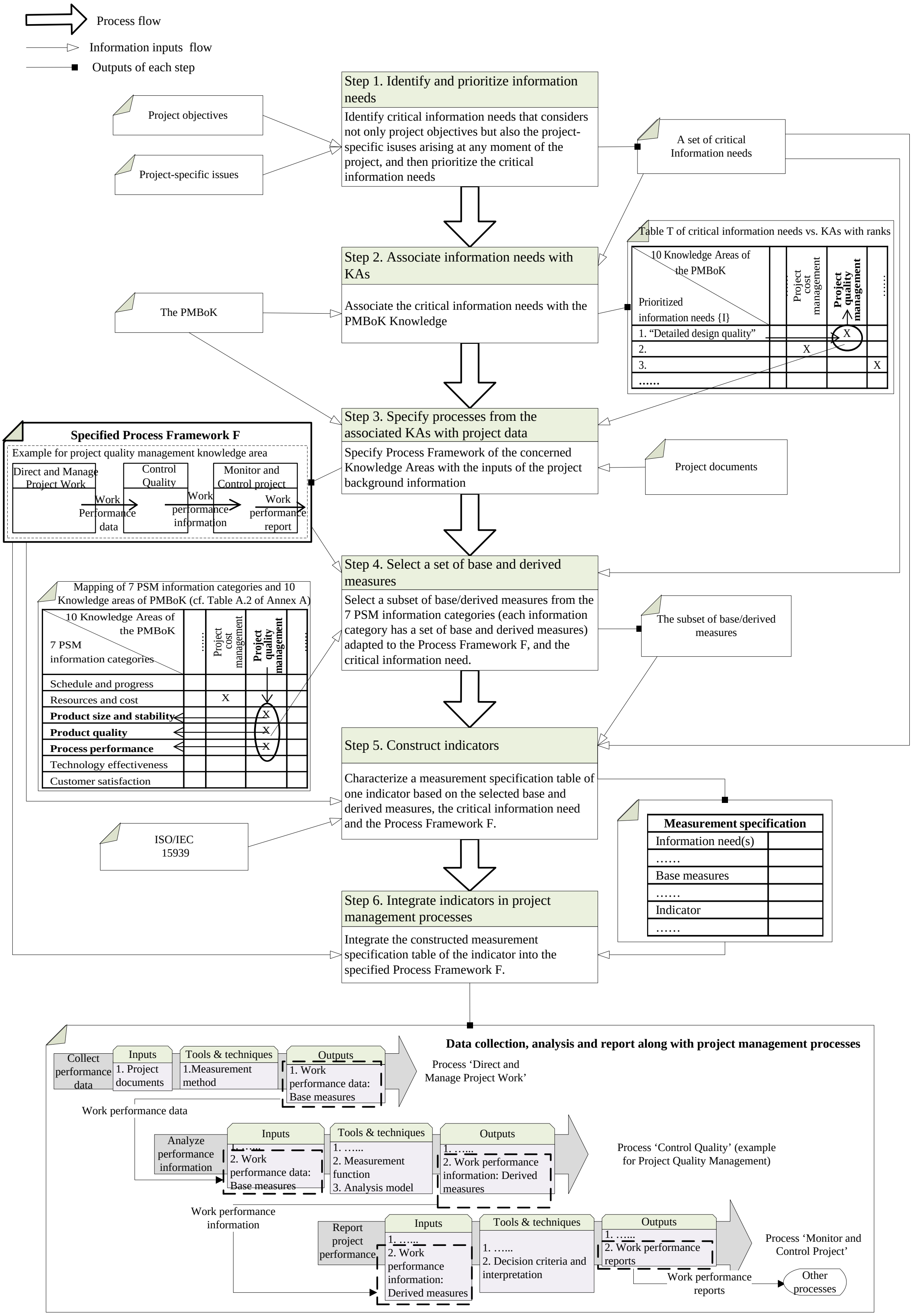

Figure IV–6 A 6-step method to construct and apply one or more performance indicator relevant to project-specific information needs

The detailed descriptions for each step are given here after.

Step 1 Identify and prioritize information needs:

Identify: The practitioners from both PSM and ISO/IEC 15939 have the standpoint that a measurement program begins from identifying a set of information needs in a project (PSM 2017) (ISO/IEC 2007). Project information needs directly relate to both project objectives and issues that impact the achievement of these objectives (McGarry et al. 2002). More specifically, they provide insights necessary to manage objectives, goals, risks and problems (ISO/IEC 2007). In PSM, research has been extended to the scope of information needs to other project-specific issues, for example, which are related to risk assessment, project constraints and assumptions, leveraged technology, product accept criteria, external requirements, and experiences from other projects. This consideration of multiple resources can enrich the body of knowledge for the derivation of performance indicators where "project objectives" dominate the practice. Information needs as defined in the PSM is based on a much wider focus compare to the traditional project objectives (around time, cost and quality). This broadened horizon makes projects more aware of the issues likely to occur during project completion. Last, as indicators defined for project objectives are comparatively static as the project moves on, information needs tend to be updated.

Prioritize: According to PSM there could be many information needs for project managers and they must be prioritized to "ensure the measurement program address the information needs that have the greatest potential impact on defined project objectives" (McGarry et al. 2002). Thus this step also consists in prioritizing the information needs. As measurement takes many resources (time, human, and equipment etc.), indicators should be constructed for addressing the information needs that are of top concern. It is necessary to select one or more critical ones from them as a set {I}. As the output of Step 1, the selected critical information needs set {I} become a starting point of measurement program, while the newly evolving information needs should be clearly identified and added into the set {I} if they become of top concern.

Step 2 Associate the information needs with knowledge areas:

We now need to associate each critical information need from the set {I} to KAs of the PMBoK in order to be able later to refer to PMBoK processes to collect, analyze and report data. The 10 KAs of the PMBoK cover integration management, time management, cost management, quality management, and risk management etc., which are used on most projects most of the time (PMI 2013). Thus, generally each project information need can be associated to one KA. To get this association, we need analyzing each information need and its main concern and then judge to which KA it relates most. For example, for an information need of "detailed design quality", it obviously relates to Project Quality Management Knowledge Area. This association that links one information need to one Knowledge Area helps building the relationship between a project and the standardized framework of the PMBoK. In conclusion, this step considers the set {I}, associate them to KAs, and then produces a table of critical information needs {I} vs. KAs with ranks, named T.

Step 3 Specify processes from knowledge areas with project data:

The goal of this step is to adapt the inputs, tools and techniques and outputs of processes of one associated KA for one information need with project-specific data (e.g. project documents). We need to specify each of the associated KAs that appear in the table T to obtain a framework for each information need in each KA where project-specific information (e.g.; the project documents) can be integrated. First choose one information need and its concerned KA and specify the KA. To specify, referred to Figure IV–4 in Section 2.2.3, a general Process Framework of the associated Knowledge Area (KA) will be abstracted according to the flows of work performance data, work performance information and work performance reports. The general Process Framework of the associated Knowledge Area (KA) generally includes 3 processes that serve to data collection, analysis and report. For example, we suppose that the concerned KA is Project Quality Management, according to Figure IV–4, the process framework of Project Quality Management includes Process "Direct and Manage Project Work" that produce work performance data (where to collect), Process "Control Quality" that produces work performance information (where to analyze), and Process "Monitor and Control Project" that generates work performance reports (where to report). The final objective of this step is to integrate the project-specific information (e.g. the project documents) into the inputs, technique and tools and outputs of the general Process Framework and finally to obtain a specified Process Framework F. In conclusion, this step considers the table T resulted from step 2 and the measurement-related processes of the PMBoK for abstracting the general process framework of each concerned KA (cf. Figure IV–4), and then integrates the project-specific information (the project documents) into the general Process Framework to obtain a specified Process Framework F of each concerned KA..

Step 4 Select a set of base and derived measures:

The critical information needs {I} and the specified Process Framework F for each information need have been obtained from the previous steps. This step bases the specified Process Framework F and seeks some base measures to construct one or more indicators for each of the critical information needs. Indeed a preliminary work, independently of any project situation, has been done to generically map some base and derived measures regrouped in 7 information categories in PSM, to each KA of the PMBoK (cf. Table A.2 of Annex A). For each of the critical information needs {I}, we have associated it to one KA of the PMBoK (cf. Step 2). Referring to the preliminary mapping result of Table A.2 which indicates which set {S} of PSM information categories can be useful for this concerned Knowledge Area. For example, for the Project Quality Management Knowledge Area, 3 of the 7 PSM information categories (product size and stability, product quality and process performance) are mapped to it (cf. A.1 of Annex A). Under each of the three information categories, there are 7-10 base and derived measures. We need to select a subset of base and derived measures from them to construct relevant performance indicator. The candidate measures should be aligned to the information needs obviously, as well as the project phases and the specified Process Framework F. For example, if a complex machine development project has an information need for "quality of mechanical part", the appropriate measures will be selected based on the project phases: if it is in the design phase, the "requirements" measure or "functional changes" measure may be selected; however, if it is in the manufacturing phase, "defects" or "rework components" may be selected as a base measure. It depends also the specified Process Framework F where project-specific information has been integrated and the existing data resource of the project for constructing a performance indicator becomes obvious. For example, a project may only record "rework components" not "defects" of the products, thus available data resource is the "rework record documents". In conclusion, this step considers the critical information needs {I}, project phases, and the specified Process Framework F for selecting an appropriate subset of base and derived measures {SB}.

Step 5 Construct indicators:

Once a subset of base measures {SB} is selected for each critical information need (obtained from Step 4), we need to construct one or more performance indicators based on this {SB}. Referring to the ISO/IEC 15939 Measurement Information Model (cf. Figure IV–3), the base measures, derived measures and indicators must be defined and aligned to each information need and the specified Process Framework F for this information need (obtained in Step 3). Each indicator is described with a "measurement specification" table naming the indicator and demonstrating its entities and attributes, measurement methods, base measures, measurement function, derived measures, analysis model, the interpretation of the indicator, and information product. In conclusion, this step considers the set {I}, the specified process framework F for each critical information need, and the subset {SB} as inputs for constructing relevant performance indicators. Thus, a set of measurement specification tables (one table for one indicator) is obtained.

Step 6 Integrate indicators in project management processes:

Based on the previous steps, the specified Process Framework F for each of the set {I} has been obtained (cf. Step 3), and measurement specification table for each indicator has been elaborated (cf. Step 5). We need further integrating each indicator into the specified Process Framework F to which the indicator is associated. To do it, each of the elements in the measurement specification table must be associated to the inputs, tools and techniques, and outputs of the specified Process Framework F. For example, for an information need of product quality of manufacturing phase, base measure is "number of rework components", this corresponds to the work performance data, that is one output of Process "Manage and Direct Project Work". Thus, this base measure will be integrated into the output of the process. It shows how the raw data will be collected, analyzed and transformed to useful performance indicators, and reported to stakeholders along with the specified Process Framework F.

4. Illustration and evaluation: research results

To illustrate the application of the proposed model in this study, this method has been conducted in a project of an equipment development and manufacturing company for a real information need identified from a project team. Section 4.1 presents the company and the project information. The detailed illustration of the method will be given in section 4.2. Section 4.3 evaluates the method by a workshop.

4.1. A presentation of the use case

Ariez is a company that manufactures heavy batteries test devices and associated software tools and offers operational consulting service in various sectors such transports and energies. The software tools developed in this company are complex because many customers have high quality requirements for products (mostly for safety and ergonomics). The project R&D time varies from a few months to many years.

There are several parallel projects currently in the company, and one of the projects involves the development of multiple-batteries management via traceability. Considering the project time span (about 3 years), technology requirements, and the ever-changing customer's needs, the project is considered to have certain complexity. To realize the complex project, they are developing software that redesigns and repackages some existing functions and integrates them well for a bigger and general battery management. At the time of the research, the project was at the implementation phase. They had already finished 70% of the planned code packages, and work focus began to transfer to the integration and test of the software to deliver the product on schedule with certain quality requirements. For now, the project is on schedule, thus product quality becomes the first concern for Project manager. This situation presented the researchers with the opportunity to apply the new method proposed in this study to construct one or more performance indicators relevant to project-specific information need.

4.2. Conducting the 6 steps to construct an indicator in the use case

(1) ***Step 1 Identify and prioritize***—the critical information need(s) {I} can be identified.

In this case of illustration, the critical information need was identified after several times of interviewing the project manager. The project is in product complementation phase, product quality is the core competition of the company and the top of concern in this phase, and thus the critical information need is "to evaluate development quality of software products during the implementation phase of the project".

In this case, the measurement for the project was not planned at the beginning of the project. Thus there was no procedure for identifying and prioritizing a set of information needs as described in the Step 1 of our method (cf. Section 3); but it shows well that the defined method in this study is flexible as a measurement activity can happen at any time when a project team wants to start managing performance by measurement.

(2) ***Step 2 Associate***—the critical information need is associated to the concerned Knowledge Areas of PMBoK.

It is in this step that the concerned KA has been judged and selected. It is obvious that the critical information need here is related most to Project Quality Management Knowledge Area, thus a matrix of the critical information need {I} vs. the concerned Knowledge Areas has been obtained (cf. Table IV–2).

Table IV–2 The critical information need and its concerned Knowledge Area

10 KAs of PMBoK / {I}	Project integration management	Project scope management	Project time management	Project cost management	**Project quality management**	Project resource management	Project communication management	Project risk management	Project procurement management	Project stakeholder management
Detailed design quality					X					

(3) ***Step 3 Specify***—the Process Framework of the concerned Knowledge Area (KA) is specified under the project-specific context.

In the precedent step, the Project Quality Management Knowledge Area has been decided as the concerned one in this case. According to Figure IV–4 in Section 2.2.3, a general Process Framework of the Project Quality Management Knowledge Area will be abstracted according to the flows of work performance data, work performance information and work performance reports. We will further characterize the Process Framework of the KA with available data of the project to thus specify it.

According to the project flows (work performance data, work performance information and work performance report) through the Project Quality Management Knowledge Area described in the PMBoK, the Process Framework of Project Quality Management is depicted in Figure IV–7.

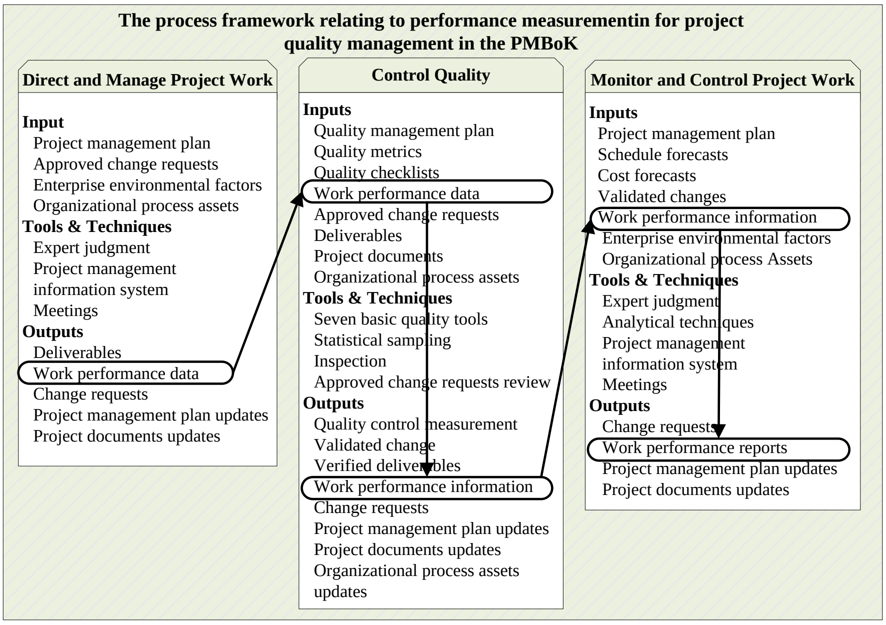

Figure IV–7 The Process Framework of Project Quality Management Knowledge Area

Firstly, a documental survey from the PMBoK provides us the original work performance data, work performance information and work performance reports flowing through the Process Framework of Project Quality Management Knowledge Area. Figure IV–7 shows that the work performance data is produced and flows out from Process "Direct and Manage Project Work", then flow into Process "Control Project Quality" where data should be analyzed and transformed into "performance information" and then flows into Process "Monitor and Control Project Work" where the current status of the project, the steps taken, and budget, schedule, and scope forecast should be generated into work performance reports and communicated with the stakeholders. The original work performance data from the PMBoK flowing from Process "Direct and Manage Project Work" to Process "Control Project Quality" is documented in Table IV–3.

Table IV–3 Work performance data flowing into Process "Control Quality"

Work performance data into Process "control quality"
▪ Planned vs. actual technical performance
▪ Planned vs. actual schedule performance
▪ Planned vs. actual cost performance

Then the original work performance information produced in Process "Control Project Quality" is documented in Table IV–4.

Table IV–4 Work performance information generated in Process "Control Quality"

Work performance information generated in Process "control quality"
▪ Cause for rejection ▪ Rework required ▪ The need for process adjustments

According to the PMBoK, work performance reports are the physical or electronic representation generated from work performance information, it will be generated in Process "Monitor and Control Project Work" which is concerned with providing appropriate reporting on project progress and status to program management as the project is part of an overall program. And documented reporting is sent to several processes of other Knowledge Areas for communication and decisions.

From Table IV–3 and IV–4 above, it is obvious: 1) the PMBoK has no relevant indicators that can provide insights for the identified information need in step 1; 2) there is no model that converts the work performance data to the work performance information (this point has been discussed also in Section 2.2.3 of this chapter).

However, the Process Framework of Project Quality Management Knowledge Area (cf. Figure IV–7) consists of three processes for performance data collection, analysis and reporting. They can be used as a basis whereby the project context information (e.g. the project documents) can be integrated to obtain a specified Process Framework. Next, we demonstrate how to specify the Process Framework of Project Quality Management Knowledge Area with the project context information.

The formal and main documents related to the project include the "Company environmental factors" (the company policy and some industrial standards), the "Defects documents" and "Code packages". All of the documents are integrated into the Input of Process "Direct and Manage Project Work".

The work performance data, work performance information and work performance reports have been kept for the project (demonstrated in italic in Figure IV–8). Some tools and techniques used by the company have been documented in the column of Tools & Techniques. Thus a Specified Process Framework of Project Quality Management Knowledge Area can be obtained and depicted in Figure IV–8. The measurement specification of the performance indicator that will be constructed next step will be integrated into them. The rationale of the integration has been demonstrated in Section 2.2.4.

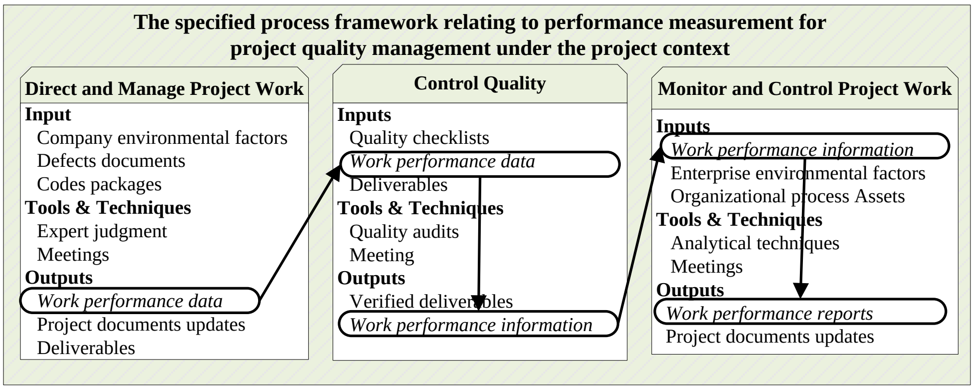

Figure IV–8 The specified Process Framework of Project Quality Management Knowledge Area

(4) Step 4 Select—The appropriate "base or derived measures" will be selected to construct one relevant performance indicator.

As mentioned in *Step 3 Specify*, the PMBoK provides no indicator for the identified information need in *Step 1 Identify*, but it has the good process framework as depicted in *Step 3 Specify*. Thus we will select some appropriate base and derived measures for constructing one relevant indicator for the information need of the project.

The available measurement-related data, especially the entities and attributes of concern in this project can be obtained from the Specified Process Framework of Project Quality Management Knowledge Area obtained at the precedent step.

Under this situation we refer to the mapping result (cf. Annex A) to get a subset of the 7 PSM information categories that have been mapped to the Project Quality Management Knowledge Area. As discussed in Annex A, the mapping results displayed in Table A.2 permit project members to quickly find their way to subjects of interest. To quickly find appropriate measures for responding the project-specific information need, to refer to Table A.2, three PSM information categories "product size and stability", "product quality" and "process performance", are mapped with the concerned Knowledge Area (cf Table IV–5).

Table IV–5 PSM information categories associated with Project Quality Management Knowledge Area

10 Knowledge Areas of the PMBoK / 7 PSM information categories	Project quality management
Schedule and progress	
Resources and cost	
Product size and stability	X
Product quality	X
Process performance	X
Technology effectiveness	
Customer satisfaction	

As for each PSM information category is followed by its base or derived measures, thus many base or derived measures are available for the concerned Knowledge Area, depicted in Table IV–6.

Table IV–6 The selected PSM information categories and associated measures

PSM information categories	Measurable concepts	Base or derived measures
Product size and stability (C3)	Physical size and stability	Database size Components Interfaces Lines of code
	Functional size and stability	Requirement Functional changes Function points
Product quality (C4)	Functional correctness	Defects Age of defects Technical performance level Time to restore
	Maintainability	Cyclomatic complexity
	Efficiency	Utilization Throughput Response time
	Protability	Standards compliance
	Usability	Operator Errors
	Reliability	Mean-Time-to-Failure
Process performance (C5)	Process compliance	Reference maturity ratings Process audit findings
	Process efficiency	Productivity Cycle time
	Process effectiveness	Defects contained Defects escaping Rework effort Rework components

Now, it is necessary to select candidate base or derived measures from Table IV–6 for constructing one indicator to address the information need of the project. The candidate measures should be aligned to the information needs obviously, as well as the project phases and the specified Process Framework F (discussed in Section 3). According to *Step 1 Specify*, the critical information need of the project is "to evaluate development quality of software products during the implementation phase of the project". For our knowledge, the software product quality is related to the amount of defects found and the size of product. Obviously, the project is in the implementation phase, the project manager wants to evaluate the quality of the software components developed in design process, not the design process itself. Thus the "Defects" associated with the "Product Quality (C4)" information category (cf. Table IV–6) is chosen, not the "defects contained" or "defects escaping" of "Process performance (C5)” information category. Then based on the specified Process Framework of Project Quality Management Knowledge Area (cf. Figure IV–8), for this project, the available project information is the “Code packages” (integrated in the specified Process Framework of Project Quality Management Knowledge Area). Thus the “Lines of code (size)” is selected to construct the indicator that the project needs. The two chosen base measures are presented in Table IV–7.

Table IV–7 Selected information categories-measurable concepts-measures

Information category	Measurable concept	Selected measures
Product size and stability	Physical size and stability	Lines of code
Product quality	Functional correctness	Defects

(5) Step 5 Construct—Based on the base measures selected in the precedent step, one indicator is constructed relevant to the project-specific information need by using the ISO/IEC 15939 Measurement Information Model.

The precedent steps have identified the critical information need, mapped the information need to the KA that concerns, and then specified the Process Framework of the KA with the project information. In this step one indicator to address the identified information need has been constructed by using the ISO/IEC 15939 information model and depicted in Table IV–8.

Table IV–8 The measurement specification of the constructed indicator

Information need: to evaluate development quality of software products during the implementation phase of the project	
Relevant entities (product-related documents generated in the project)	1. defect documents 2. code packages (package A, B, C, D and E)
Attributes	1. lists of defects recorded in the defect documents 2. the size of code packages
Measurement method	1. count the number of the defects documented in defect documents 2. count the number of code lines for each code package
Base measures	M1: total defects of each code package M2: total size (code lines) of each code package
Measurement function	Divide total defects by size for each package
Derived measure	DM1: Defect rate per code package
Analysis model	Compute control limits using historical data generated in similar projects
Indicator	Defect rate control chart
Decision criteria and interpretation	Results outside the control limits require further investigations
Information product	Performance reports

(6) Step 6 Integrate—the constructed measurement specification of the performance indicator will be integrated in the specified Process Framework of Project Quality Management Knowledge Area.

This step includes three sub-steps which are respectively “Collect performance data”, “Analyze performance information” and “Report project performance” that has been demonstrated in the previous section (cf. Section 2.2.4).

First, the overall view of how all of the elements of the measurement specification of the constructed indicator (cf. Table IV–8) integrate with the specified Process Framework of Project Quality Management Knowledge Area (cf. Figure IV–9) will be demonstrated in 3 sub-steps: Collect performance data, Analyze performance information, and Report project performance.

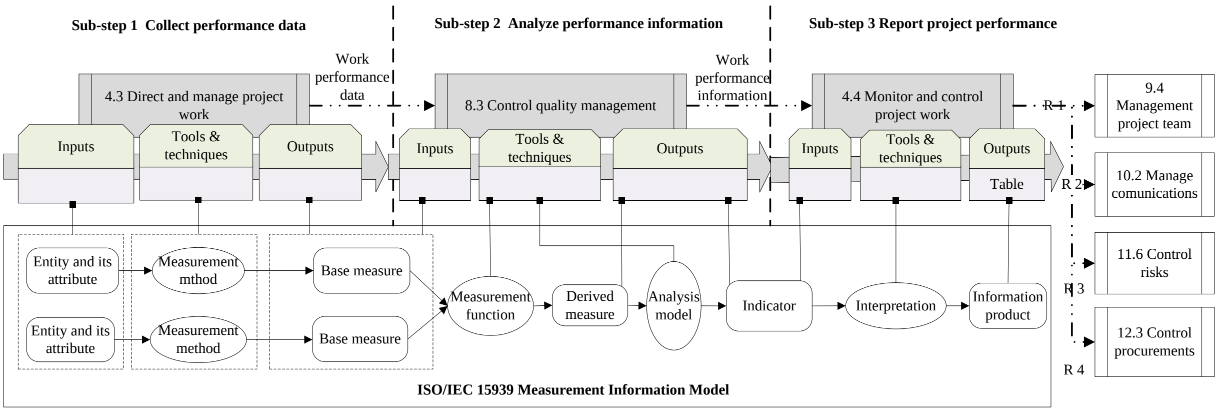

Figure IV–9 The measurement specification is integrated with the specified Process Framework

Then detailed analysis on the integration will be presented from 3 sub-steps as follows:

Sub-Step 1 Collect performance data

This sub-step presents how some items of Table IV–8 can be integrated into the inputs, tools & techniques and outputs of Process “Direct and Manage Project Work”. The result of collecting performance data is depicted in Figure IV–10.

- Appropriate entities and attributes related with the information need identified in this project have been specified in the inputs of Process “Direct and manage project work” (cf. Figure IV–8 “the specified Process Framework of Project Quality Management Knowledge”). In this case, one available attribute is “lists of defects recorded in the defect documents” from the entity “defect documents”, and the other available attribute is “the size of code packages” from the entity “code packages”. All the specified entities and its attributes have been documented into the “inputs” of Process “Direct and manage project work”.
- Then the measurement methods in table IV–8 have been documented into tools & techniques of Process “Direct and manage project work”, in this project, the measurement methods are to count total defects and to count the number of code lines for each code package during product design and development.
- Record the base measures “Total defects of each code package” obtained from the measurement method of “count the number of the defects documented in defect documents” and “Total size of each

code package" obtained from the method of "count the number of code lines for each code package" into the outputs of Process "Direct and Manage Project Work".

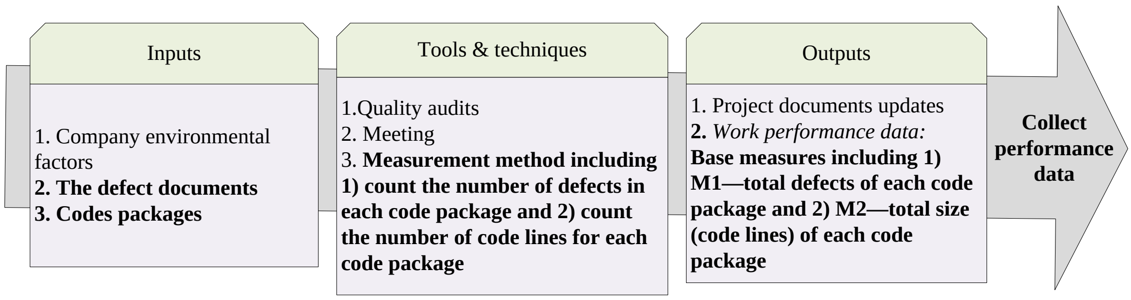

Figure IV–10 Collecting performance data

Sub-Step 2 Analyze performance information

This sub-step presents how some items of Table IV–8 can be integrated into the inputs, tools & techniques and outputs of Process "Control Quality". The result of analyzing performance data is depicted in Figure IV–11.

- As descripted in sub-step 1 "Collecting performance data", the base measures have been recorded in the outputs of Process "Direct and Manage Project Work". In this step, these base measures flow out from Process "Direct and Manage Project Work" and flow into the inputs of Process "Control Quality".
- The measurement function that is used to generate derived measure is "Divide total defects by size for each package" and analysis model that generates the indicator is "Compute process center and control limits using historical data generated in similar projects". Both the measurement function and analysis model are documented into the tools and techniques of Process "Control Quality" (cf. Figure IV–11). The existing tools in the project such as "Quality audits" and "Meeting" can provide additional usage for analyzing the base measures in the inputs.
- The derived measure "Defect rate per code package" and Indicator—"Defect rate control chart" have been documented into the outputs of Process "Control Quality".

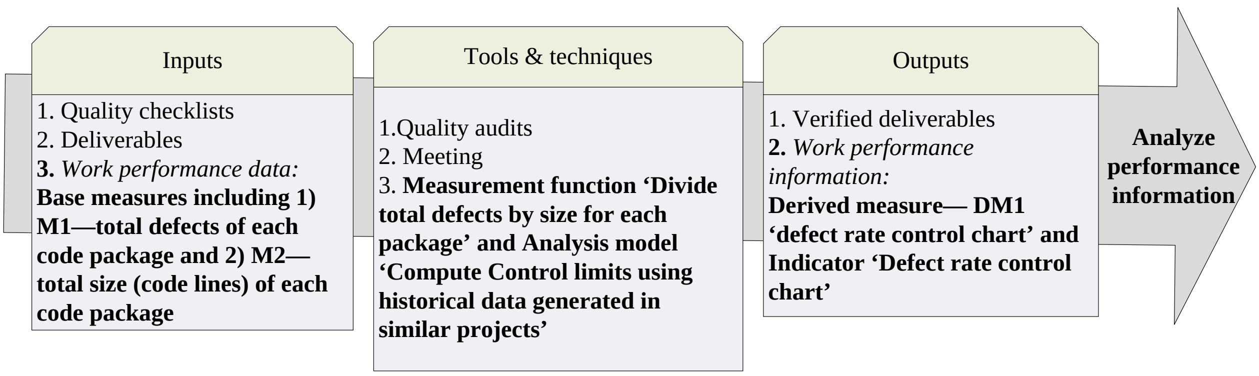

Figure IV–11 Analyzing performance information

In this example, a graphical representation can be generated along with the code inspection process (Figure IV–12): the derived measure is marked in the graph with target range limits (historical norms), all the information constitutes the indicator—Defect rate control chart. The lines of code are measured in components of 1000, expressed as KSLOC (thousands of source lines of code). The defect density for Code Package B was above this organization's target range and should be investigated.

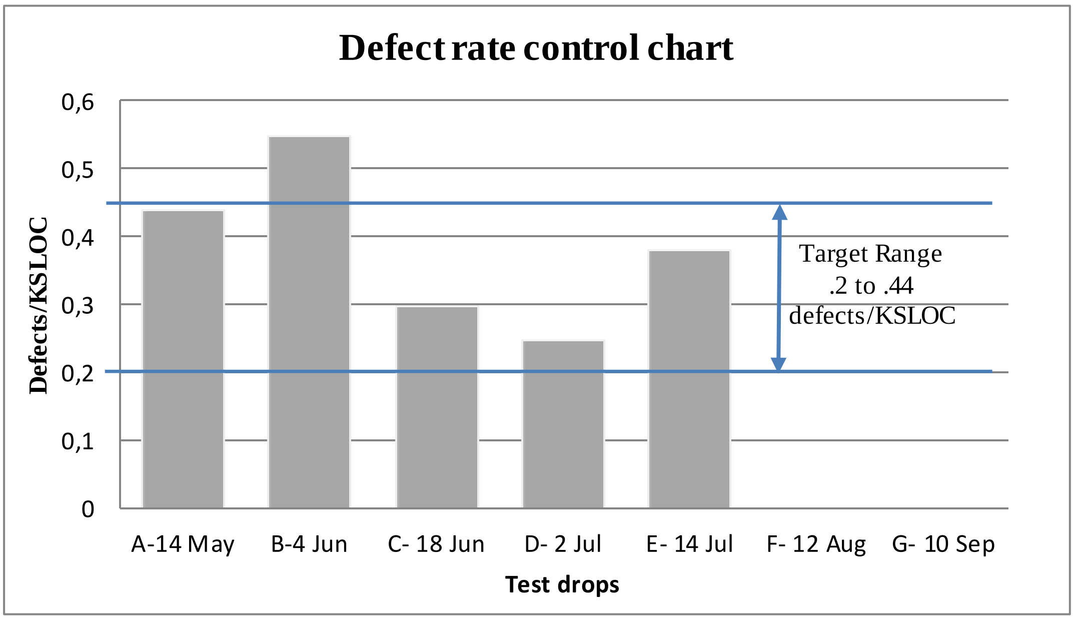

Figure IV–12 Product design quality tracking and controlling

Sub-Step 3 Report project performance

This sub-step presents how some items of Table IV–8 can be integrated into the inputs, tools & techniques and outputs of Process "Monitor and Control Project Work". The result of reporting project performance is depicted in Figure IV–13.

- As descripted in sub-step 2 "Analyzing performance information", the derived measure and the indicator have been recorded in the outputs of Process "Control Quality". In this step, the derived measure and the indicator flow out from Process "Control Quality" and flow into the inputs of Process "Monitor and Control Project Work".
- Both the decision criteria and interpretation are documented into the tools and techniques of Process "Monitor and Control Project Work" (cf. Figure IV–13). The existing tools in the project such as "Analytical techniques" and "Meeting" can provide additional usage for analyzing the derived measure and the indicator.
- The information products "performance reports" of Table IV–8 is the interpretation of the indicator, and it can be added into the outputs of Process "Monitor and Control Project Work", and then communicated to the users who need to know the project status.

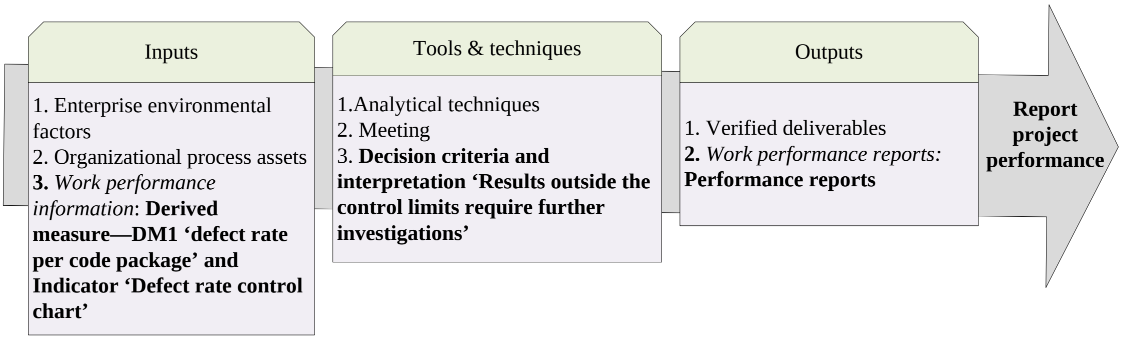

Figure IV–13 Reporting project performance

According to the PMBoK, the performance reports documented in the outputs of Process 4.4 will flow into 5 other different processes (cf. Figure IV–4). As the presentation in Figure IV–4, the generated performance reports flow into the following processes: Process "Perform Integrated Change Control", Process "Manage Project Team", Process "Manage Communications", Process "Control Risks", and Process "Control Procurements". The project manager plays a key role in generating and selecting useful information for other stakeholders based on the processes.

In this example, the indicator "Defect rate control chart" has been constructed, tracked and finally graphed in Figure IV–12 above. The project manager will investigate and analyze why the defect rate of Code package B was above the target limits, and then some reports aimed for different stakeholders will be written. For reports flowing into different project management processes, specific report contents should be considered combined with the characteristics of the processes. Detailed analysis is followed as below for this case:

- Report 1, flows into Process "Manage Project Team" where high defect rate should be informed, and thus an analysis on whether the defects are caused by personnel turnover, staffing, and so on.
- Report 2, flows into the Process "Manage Communications" which has the main information needs like communication efficiency and effectiveness. In this example, when defect rate over the target limits, project manager should report it timely during some meetings to facilitate discussion and to create communication.
- Report 3, flows into Process "Control Risks" that has the main information needs about monitoring residual risks and identifying new risks. It makes use of performance variance and trends information to forecast the potential deviation of the project at completion from cost and schedule targets. In this case, when defect rate of code package B does not fall into the planned thresholds, it means a potential threat of not fitting the quality requirements of customers, and indicates also a possible cost overrun and schedule slip.
- Report 4, flows into Process "Control Procurements" which has the main information needs about contract performance. In the description of the PMBoK, the work performance reports include technical documentation developed by sellers and work performance information from the seller's performance reports. In this case, if the development design is subcontracted by some suppliers, the unusual defect rates could indicate the schedule slips, which will affect other activities for the project in the organization.

Work performance reports of particular interest to Process “Perform Integrated Change Control” includes resource availability, schedule and cost data, and earned value management reports, burnup or burndown charts according to the PMBoK. In this case, the defect rate report provides little interest for the process, so it is not considered.

4.3. Evaluation of the new framework through a workshop

4.3.1. *Workshop presentation*

To test the new framework proposed in this study, a workshop has been held at Heriot Watt University on July 2017. This workshop engaged a panel of 30 project managers from different industrial contexts. Firstly, this researcher did a 30-minute presentation about the framework to explain the panel of experts what the framework is, how it works in project context and why it brings benefits to practitioners. Then the panel of project managers was divided into 5 groups. Each group discussed one hour around our designed questions as follows:

- Could you describe Usefulness of the PMBoK to your context?
- Have you developed any improvements/supplements (similar to what is presented by the presenter) in your organization?
- How would you use this framework in managing your projects?

After this one hour discussion, each group presented their opinions and suggestions about the framework, which are documented as follows.

4.3.2. *Feedbacks and findings from the workshop and analysis*

(1) Feedbacks from the 5 groups of the workshop

Group 1 gave the feedback:

- Concept is good
- It can work for some projects but not for all types of projects
- It is good when projects have their detailed specifications.
- It would be a good idea to use some of the framework elements in the scope of the project.
- The framework would help watermelon reporting.

Group 2 gave the feedback:

- It is useful in terms of developing a product.
- It would not work with change or service industry.
- Project manager’s report only includes cost and time, this framework can extend that.
- It can help to change management process and procedures.

Group 3 gave the feedback:

- The framework will improve the project management office process and procedures to control the projects.
- It can help to make some project processes simple to understand.

- It can help customers and/or stakeholders understand the control and monitoring of the project much better.
- The framework could be utilized in agile project management.

Group 4 gave the feedback:

- Most of the projects base the method on cost and benefits.
- The application of the framework is good for discipline such as products and software, but not service industry.
- PMI (PMBoK) has new version every 5 years, so the new framework that base on the PMBoK should be revised as well.

Group 5 gave the feedback:

- The framework will be useful as a check-list.
- It is applicable to products rather than services.
- It is applicable to projects with specific outputs and detailed specification but not emergency changes.
- It is maybe complex to use in real work due to lack of resources and overlap with internal auditors.
- It can be coupled with internal auditors' existing framework for better process and procedures improvement.
- It can be used in a troubled project.

(2) Findings are summarized from the feedbacks

To synthesize the feedbacks from the 5 groups, we reassemble some statements formulated in a different way but meaning the same. Thus the main findings from the workshop feedbacks are summarized in Table IV–9, showing which of the findings are made in each of 5 groups.

Table IV–9 The findings with regard to the 5 groups' feedbacks

Findings	Source
The new framework for improving project performance measurement will be more applicable to product or software industries than some industries such as service (Finding 1).	Group 1,2,4 and 5
The new framework can help to improve the project process and procedures (Finding 2).	Group 1,2,3 and 5
Project managers focus on only time and cost (Finding 3).	Group 2 and 4
The framework helps to find real causes behind a bad project performance as it provide a perspective on how the raw data has been transformed into performance indicators (Finding 4).	Group 1, 3 and 5
The framework helps in agile project management (Finding 5).	Group 3
The cost/benefits consideration is important when considering applying the framework (Finding 6).	Group 4

(3) Analysis based on the summarized findings

Finding 1 confirms that our study is useful for complex engineering projects.

Finding 2 confirms the benefits of Step 3 Specifying of the method. As we presented in the illustration of the method above, the project context is integrated into the process framework of the PMBoK, which helps to tidy the project information under interconnected Process Framework for data collection, analysis and reporting.

Finding 3 has further proved that project performance measures basically developed around time and cost are not enough and that developing an extended set of performance indicators would be a help.

Finding 4 proves that using the Measurement Information Model of the ISO/IEC 15939 helps project transparency by dividing an abstract measurement concept into some elements, and then structuring the elements together to answer project-specific information needs. The model can help to solve some issues such as performance “watermelon phenomenon”. “Watermelon phenomenon” is when something is green on the outside, but bright red on the inside. In performance measurement, sometimes your indicators are telling you everything is fantastic, but your users/customers/employees are telling you it is actually problematic.

Finding 5 proves that information-driven measurement could be more flexible for the ever-changing project environments and thus leads us to think about how the framework can be applied in agile project management.

Finding 6 indeed confirms the value of our method: we mapped the 7 PSM information categories and associated measures to the 10 Knowledge Areas of the PMBoK in our method, and the well-defined measures set in the PSM provides references for project team in deciding what measures are appropriate. Indeed, the use of predefined set of metrics lowered the cost considerably. Common set of measures were used across different projects which have similar goals and thereby enabled reuse of same measures that cut down the cost and effort for data collection. It is suggested using pre-defined standard set of attributes/measures for reusability, aggregation and optimization.

5. Conclusion and perspective

With the goal to find solutions to improve the project performance measurement, this study has reviewed good measurement practices from the PSM, the ISO/IEC 15939 and the PMBoK. These practices offer individual advantages in providing decision-making support to conduct an objective project management. The PSM is an information-driven approach for performance measurement; it has defined a set of 7 information categories and associated predefined measures, which is proven very practical and cost effective by larges of its application in both systems and software industries. The ISO/IES 15939 is a standard for measurement in systems and software engineering, which has a standardized way in defining concepts and terms and good information model that structures the concepts and terms and aggregates basic data into useful performance indicators. The PMBoK demonstrates the well-defined process framework relating to performance measurement where work performance data, work performance information and work performance reports flow through. However, using alone any of the three measurement practice cannot address comprehensively the identified issues in project performance measurement. The PSM has initiated the information-driven measurement that decides the derivation in a wider horizon and in a more flexible way. The ISO/IEC 15939:2007 has a standardized measurement information model which can convert base measures into indicators, especially the model beginning from the identification of the information needs. The measurement-related processes in the PMBoK provide a process basis for performance data collection, analysis and reporting, but it lacks project-specific indicators and a model that transforms the data into indicators.

The research opportunity in this study has thus been to integrate the three good measurement practices to get a new framework for improving project performance measurement by constructing more performance indicators in a dynamic and flexible way.

The method proceeds in 6 steps. An illustration of the method under a real project context has been implemented. The use case shows in a step-by-step way how critical project information need has been identified in a real project and then mapped to one concerned Knowledge Area of the PMBoK. Thus the process framework of the concerned Knowledge Area in the PMBoK was obtained to specify the project. Referring to the framework we specified, some appropriate measures was selected to construct a measurement specification of the performance indicator, and then a step consisting of three sub-steps was used to integrate the constructed measurement specification into the Specified Process Framework to answer the project-specific information need.

Then the framework was presented in a workshop gathering project managers. The feedbacks are positive, and some feedbacks provide deeper thinking for our further study, for example thinking of its application in agile project management. The findings prove that the framework can help to improve project management process and procedures.

This study provides innovative methods to improve measurement practices of project management; in the future, a verification of its application and effect should be conducted in different industry and project contexts.

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Annex A: Mapping of 10 Knowledge Areas in PMBoK and 7 PSM information categories

It is practical to have a set of pre-defined measures (base and derived measures) from which projects can choose and tailor measures based on their information needs. PSM provides a set of 7 information categories with prospective measures so that a project could have a starting point when planning a measurement program. In this section, we describe firstly the 7 PSM information categories and the prospective measures. Then, we conduct a mapping analysis of the 10 Knowledge Areas of the PMBoK and 7 PSM information categories.

(1) PSM and its 7 information categories and associated measures

According to the PSM (McGarry et al. 2002), the most information can be grouped into general areas, called *information categories*, that are basic to almost all projects. PSM proposed that once the real project information needs have been identified, they can always be mapped into the 7 defined categories as follow. The 7 PSM information categories have got wide recognition and application in both academic and practices. For example, a catalogue of indicators in process performance measurement improvement has been built in (Monteiro and de Oliveira 2010), in which the 7 PSM information categories were used as one of its references for constructing the measures classification and thus proposing a set of 6 different categories including time, effort, cost, scope, productivity and quality. PSM has standardized on base measures by holding the opinion that a same set of base measures can be combined in many ways to produce different indicators that address different information needs (McGarry et al. 2002). The 7 information categories and associated measures have also provided an important reference to the development and construction of 18 SE leading indicators (Roedler et al. 2010); nearly 80 % the set leading indicators have used the associated measures.

- *Schedule and progress: This information category addresses the achievement of project milestones and the completion of individual work units. A project that falls behind schedule can usually meet its delivery objectives only by eliminating functionality or sacrificing product quality.*
- *Resources and cost: This information category relates to the balance between the work to be performed and personnel resources assigned to the project. A project that exceeds the budgeted effort usually can recover only by reducing software functionality or by sacrificing product quality.*
- *Product size and stability: This information category addresses the stability of the functionality or capability required of the software. It also relates to the volume of software delivered to provide the required capability. Stability includes changes in functional scope or quantity. An increase in software size usually requires increasing the applied resources or extending the project schedule.*
- *Product quality: This information category addresses the ability of the delivered software product to support the user's needs without failure. If a poor-quality product is delivered, the burden of making it work usually falls on the assigned maintenance organization.*

- *Process performance: This information category relates to the capability of the supplier relative to project needs. A supplier with a poor software development process or low productivity may have difficulty meeting aggressive project schedule and cost objectives.*
- *Technology effectiveness: This information category addresses the viability of the proposed technical approach. It addresses engineering approaches such as software reuse, use of commercial software components, reliance on advanced software development processes, and implementation of common software architectures. Cost increases and schedule delays may result if key elements of the proposed technical approach are not achieved.*
- *Customer satisfaction: This information category addresses the degree to which products and services delivered by the project meet the customer's expectations. Indications of satisfaction may be obtained from customer feedback and the levels of customer support required.*

Table A.1 can help in selecting appropriate *measurable concepts* and *prospective measures (base and derived measures)*, and thus the link can be constructed between the information needs and prospective measures. The measurable concept is an idea about entities that should be measured to satisfy an information need, and prospective measures including applicable measures (generally base and derived measures) that can compute the measurable concepts (McGarry, 2002). In our study, we map the 7 PSM information categories into 10 KAs of the PMBoK 5. It provides a base for constructing one or more performance indicators relevant to project-specific information needs.

Table A.1 7 PSM information categories and measures

Information categories	Measurable concepts	Prospective measures (base and derived measures)
Schedule and Progress (C1)	Milestone Completion	Milestone dates
	Critical Path Performance	Slack time
	Work Unit Progress	Requirements traced
		Requirements tested
		Problem reports opened
		Problem reports closed
		Reviews completed
		Change requests opened
		Change requests resolved
		Units designed
		Units coded
		Units integrated
		Test cases attempted
		Test cases passed
		Action items opened
		Action items completed
	Incremental capability	Components integrated
		Functionality integrated
Resources and cost (C2)	Personnel effort	Staff level
		Development effort
		Experience level
		Staff turnover

	Financial performance	BCWS, BCWP, ACWP Budget Cost
	Environmental and support resources	Quantity needed Quantity available Time available Time used
Product size and stability (C3)	Physical size and stability	Database size Components Interfaces Lines of code
	Functional size and stability	Requirement Functional changes Function points
Product quality (C4)	Functional correctness	Defects Age of defects Technical performance level
	Maintainability	Time to restore Cyclomatic complexity
	Efficiency	Utilization Throughput Response time
	Protability	Standards compliance
	Usability	Operator Errors
	Reliability	Mean-Time-to-Failure
Process performance (C5)	Process compliance	Reference maturity ratings Process audit findings
	Process efficiency	Productivity Cycle time
	Process effectiveness	Defects contained Defects escaping Rework effort Rework components
Technology effectiveness (C6)	Technology suitability	Requirements coverage
	Technology volatility	Baseline changes
Customer satisfaction (C7)	Customer feedback	Satisfaction Ratings Award Fee
	Customer support	Requests for Support Support Time

Adopted from (McGarry et al. 2002)

(2) A preliminary mapping of 7 PSM information categories and 10 Knowledge Areas of the PMBoK

To provide a system of rich and practical measures (base or derived measures) for each Knowledge Area of PMBoK, helping to construct the relevant performance indicators, we can map one or several of 7 PSM information categories with the Knowledge Area. The mapping mechanism is shown in Figure A.1. Each KA of the PMBoK has its general concerns. Mapping procedures in this study are to verify whether the identified "concerns" in one KA can be responded by one of 7 PSM information categories. If the correspondence exists, then the PSM information category can be mapped to the KA. Next there is a detailed mapping analysis.

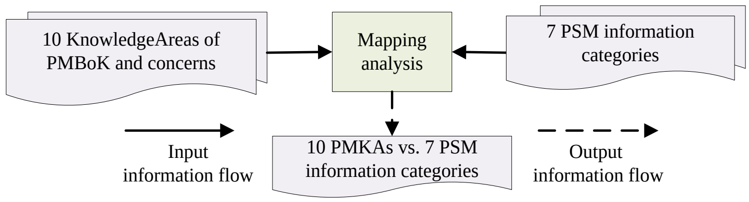

Figure A.1 Mapping analysis of 10 Knowledge Areas in PMBoK and 7 PSM information categories

(1) A detailed mapping analysis

As demonstrated above, there are 7 PSM information categories, which are respectively schedule and progress (C1), resources and cost (C2), product size and stability (C3), product quality (C4), process performance (C5), technology effectiveness (C6), and customer satisfaction (C7).

Process 4.3, 4.4 and 4.5 (cf. Figure IV-4) are measurement-related processes from Project Integration Management, with the main concerns "*To understand the current state of the project, steps taken, budget, schedule, scope, quality, process performances*". All 7 PSM information categories could be used to address it.

Process 5.5 (cf. Figure IV-4) in Project Scope Management is "*to concern the acceptance of the completed deliverables*"; C3-procudct size and stability, and C4-product quality can respond partially the concerns.

Process 5.6 (cf. Figure IV-4) in Project Scope Management is *to monitor the status of the project and product scope and manage changes in the scope baseline*, so C1, C3, and C4 can help to provide insights.

Process 6.7 (cf. Figure IV-4) in Project Time Management is *to monitor the status of project activities to update project progress and to manage changes to the schedule baseline*; the C1 in the PSM addresses all the concerns in the process.

Process 7.4 (cf. Figure IV-4) in Project Cost Management is *to know the status of the project to update the project costs and to manage changes to the cost baseline*; the C2 in the PSM address well these information needs.

Process 8.3 (cf. Figure IV-4) in Project Quality Management is *to record results of quality activities, to identify the causes of poor process or product quality, and to validate project deliverables and work meet requirements*; C3, C4, and C5 can partially respond the concerns.

Process 9.4 (cf. Figure IV-4) In Project Human Resource Management plays the roles *to track project team performance and to manage team changes*; the C2 in PSM can partially provide the insights of the human resource requirements.

7 PSM information categories cover no information for Process 10.2 "manage communications" and 10.3 "controlling communications" (cf. Figure IV-4).

Process 11.6 (cf. Figure IV-4) "control risks" has been covered completely because all PSM information categories are identified and constructed to help managing risks.

The main concerns for Process 12.3 (cf. Figure IV-4) are *to know the progress of suppliers, and to know status of the material and equipment resources*; C1 and C2 can help to satisfy the information needs.

The main information needs of Process 13.4 (cf. Figure IV-4) is *to understand overall project stakeholder relationships*; as customers are important stakeholders for a project, the measurable concepts and measures of C 7 in PSM can help know the status of expectation of customers.

(2) Results of mapping analysis and its practical meanings

With the mapping analysis above, a preliminary mapping result has been concluded in Table A.2.

Table A.2 The mapping of 10 Knowledge Areas of PMBoK and 7 PSM information categories

10 Knowledge Areas of the PMBoK / 7 PSM information categories	**Project integration management**	**Project scope management**	**Project time management**	**Project cost management**	**Project quality management**	**Project human resource management**	**Project communication management**	**Project risk management**	**Project procurement management**	**Project stakeholder management**
Schedule and progress	X	X	X					X	X	
Resources and cost	X			X		X		X	X	
Product size and stability	X	X			X			X		
Product quality	X	X			X			X		
Process performance	X				X			X		
Technology effectiveness	X	X						X		
Customer satisfaction	X							X		X

Table A.2 becomes a reference for the following method to construct and apply one or more performance indicators relevant to project-specific information needs. In a real project context, the mapping result displayed in Table A.2 enables project members to quickly find their way to subjects of interest. Upon needing certain information, quickly relating them to the subjects, project members can get access to any elements of each PSM information category (measures, indicators, specification tables). The mapping result helps to build the connection between 7 PSM information categories and 10 Knowledge Areas of PMBoK. According to the mapping result, a set of well-defined measures (base measures) are available once a project want to conduct a measurement program. But to respond project information needs, a set of base and derived measures cannot provide useful project performance information if they are not linked in with project context and not been aggregated into indicators with interpretations. In the third part of our methodology, we propose to apply a standardized measurement information model of the standard ISO/IEC 15939 to aggregate base measures into information product through measurement method, measurement function and analysis model.

Chapter V Conclusion

This chapter revisits the three stages of this dissertation report and addresses the contributions for research and the implications for practice. It also outlines the limitations. Based on the current findings and limitations, the avenues for future research are identified and discussed.

1. Contributions for research

This PhD report contributes to analyze good performance measurement practices from different disciplines to improve project performance measurement. Firstly, it contributes to the exploration of performance measurement systems (PMSs) research and good practices, thus providing theoretical and methodological implications and insights for project performance measurement. Then it contributes to investigating good practices in systems engineering measurement, where it identifies the recent definition of a set of 18 systems engineering leading indicators and thus defines a method to apply this set of indicators to project performance measurement. It also contributes to integrating the best practices from the Practical Software and System Measurement, the ISO/IEC 15939 norm and the PMBoK guide to obtain a well-designed and robust method for constructing project-specific indicators. These contributions are detailed here below:

(1) Stage 1 - Studying performance measurement systems

To recall, the main contribution of this stage is:

Contribution 1: highlighting the issues of performance measurement systems relative to project performance measures.

The objective of this PhD report is to improve project performance measurement. The existing literature on project performance measurement offers some indicators measuring time, cost and quality, but do not generally answer the issues rising in the management of complex engineering projects, relative to the scope and types of measures. Even though a few studies have addressed these issues, the models and approaches proposed have their limits. Thus we seek to find useful avenues from studying the performance measurement systems to fill in this gap.

Stage 1 (Chapter II) reviewed the literature on performance measurement systems and showed its development and evolution from classical performance measurement systems to the diversification of performance measurement systems. Then it concluded on the key learnings from the performance measurement systems such as the characteristics of PMSs and the essence of performance measures. The contributions of this stage are multiple. Firstly, the analysis of the different definitions of performance and performance measurement enable us to better understand the nature of this discipline and deepen our knowledge of project performance measurement. Then synthetizing the characteristics of the performance measurement systems provide theoretical and methodological recommendations for project performance measurement: 1) **A performance measurement system must be “balanced”, “integrated”, “strategy-oriented”, “multiple-perspective” and “dynamic”**; and 2) **current project performance measurement can be improved by integrating good practices from other disciplines**. Keeping the two recommendations in mind, we identified and highlighted several issues in **performance measurement**

systems, relative to the limitations of current project performance measurement systems, such as **the need to balance lagging indicators (to control) with leading indicators (to monitor)** and **the need to design context-matched performance indicators**.

(2) Stage 2 - Developing a set of generic indicators (extended scope and type)

The contribution of this stage is:

Contribution 2: a methodological proposal to using leading indicators for project performance measurement.

This stage focused on the extension of the scope and type of project performance indicators. Many other studies addressed this question; however, few have led to the development of leading indicators. According to one conclusion of Stage 1, a balanced use of leading and lagging indicators can improve overall performance. The importance and value of leading indicators have been well highlighted in performance measurement systems. This initiated our literature survey in project performance measurement concerning to the use of leading indicators. Results showed that the concept of leading indicator is not well addressed in project context, with a lack of definition and development for it.

In this regard, Stage 2 (Chapter III) proceeded to review the literature on project performance measurement, to identify the issues relative to the use of leading indicators and thus to propose a methodology for developing this type of indicators for engineering projects. The contribution of this stage consists of two aspects. The first one consists in analyzing the 18 leading indicators that have been defined in systems engineering to determine if any could be useful to measure project performance. This analysis results in a general mapping identifying subsets of leading indicators that could be relevant to measure the performance of the project processes. The second one is a methodological proposal to tailor these subsets of leading indicators for a specific project according to the context of the project, its goals and issues, and the importance given to processes.

(3) Stage 3 - Designing project-specific performance indicators

The contribution of this stage is:

Contribution 3: a methodological proposal to designing project-specific performance indicators dynamically.

Although useful, the set of leading indicators developed in stage 2 are generic and limited. Thus the need to design project-specific performance indicators that address information needs in a dynamic way still remains. An extensive literature review enables us to evaluate the difficulty to design performance measures in a specific project context; we identified several critical problems such as: the different opinions among researchers about the sources from where performance indicators are derived, the transformation from data to indicators, and the association of data collection, analysis and report along with project management processes.

With the goal to find solutions to improve the design of project performance measures, Stage 3 (Chapter IV) has contributed to review, analyze and integrate the good measurement practices from the Practical Software and

System Measurement (PSM), the ISO/IEC 15939 norm and the PMBoK guide. These practices offer individual advantages in providing decision-making support to conduct an objective project management. The PSM is an information-driven measurement, which has used “information needs” to replace the dominant “project objectives” to derive performance indicators. The ISO/IEC 15939 allows to define an indicator which combines heterogeneous data and structures the elements (e.g. base measure, derived measure and indicator) for interpreting the results. The PMBoK for its part has well-designed processes that relate to data collection, analysis and report. First part of the methodological proposal in this stage is to integrate the three good measurement practices, resulting in a 6-step method. Second part of the proposal is to illustrate the method in a step-by-step way in a real industrial context, and have it evaluated by a panel of project managers.

2. Implications for practices

This report made some valuable contributions to practice, providing meaningful insights, for project managers who seek to improve project performance in particular.

Firstly, the first stage of this report did an extensive literature review on performance measurement systems and a survey on supporting software tools. We made a gap analysis between academic research and the supporting software tools. It showed that the software vendors might not be delivering the complete value of academic researches of performance measurement into industries due to their segmentary and limited understanding about the theoretical results. This might be misleading users towards inappropriate directions. For project managers, choosing a tool to measure project performance is a critical point to consider.

Secondly, traditional lagging indicators, that look backward and evaluate performance results, are not able to avoid project failures. A set of leading indicators, looking forward, in a proactive way to manage project performance, provide practitioners useful tools for monitoring projects. Moreover, according to the evaluation result of our proposals and methods in a workshop, the positive feedback from experts shows that the leading indicators can help to redefine project management process, especially in addressing troubled projects.

In addition, the structured steps involved in the method in Stage 3 to design project-specific performance indicators enable the practitioners to dynamically construct an indicator. This method addresses information needs that might be generated in any moment of a project from different stakeholders. It has integrated the Measurement Information Model of the ISO/IEC 15939. Benefits of this Measurement Information Model are to help project transparency by dividing an abstract measurement concept into some elements, and then structuring the elements together to answer project-specific information needs. The model might help to solve some widely talked but non-resolvable issues of project evaluation in practice such as performance “watermelon phenomenon”. “Watermelon phenomenon” is when something is green on the outside, but bright red on the inside. In performance measurement, sometimes your indicators are telling you everything is fantastic, but your users/customers/employees are telling you that it is actually problematic.

3. Discussions

To address the issues relative to project performance measures, we proposed to develop leading indicators for projects, as well to design project-specific performance measures. However, some points about this research report need to be discussed here.

Firstly, however the methods proposed in this study have been illustrated in real industrial context and the usability and usefulness of the proposed methods have been tested in a workshop. yet, more experiments should be done in more and different industrial contexts to consolidate research results.

In addition, the current situation about the use of leading and lagging indicators has been interpreted from literature review. Directly interviewing managers from different industrial backgrounds about how these concepts are being addressed in industries and to what extent they have been developed should be interesting to do to confirm the facts.

Our research focuses on the development and design of project performance indicators. However, to elaborate a complete performance measurement system, three phases should be considered: 1) the design of the performance indicators, the implementation of the performance indicators, and the use of the performance indicators. Thus designing a set of indicators is an essential step, but not the only one. The validation of its implementation, and the validation of its use and impact on the whole performance measurement system are worthy to proceeding further, and need to be added to this work.

4. Some avenues for future study

This report has focused on questions about how to develop and design project performance indicators and has proposed several methods to address these issues. In spite of its contributions to knowledge, for improving project performance measurement, there are still some other avenues that can be considered. Three perspectives are mentioned here.

(1) Conducting a deeper research about how the development and evolution of organizational performance measurement system impact that of project performance measurement

To improve project performance measurement, some researchers are transferring some classical performance measurement system models or frameworks, which are developed for managing organizational performance. For example, Balanced Scorecard has been widely studied in research and used in industry for organizational performance measurement. A few researchers have directly extended this classical model to the project context, and some software vendors also propose it for projects. Indeed, well-developed performance measurement systems can contribute to improve project performance measurement, as demonstrated in Chapter II of this report. However, research on performance measurement systems covers a large domain: frameworks, indicators, implementations, etc. This report focused on the indicators. For the future, a wider exploration of the domain may be useful. For example, a survey on how performance measurement systems are impacting the project performance measurement theories and practices will be very useful to complete the theoretical knowledge system of project performance measurement.

(2) Considering how the project-based performance indicators can be integrated with organizational performance measurement systems

Studies have addressed the value of projects to business. Project performance indicators, as a tool to support project performance measurement and project management, are different from those developed for managing organizational performance. However, organizational performance is not independent from that of projects. Issue such as how the "connection" between indicators developed for projects and indicators for organizations can be built, may be a valuable exploration. For example, some base measures developed and collected for constructing project performance indicators might be useful for organizational performance indicator construction.

(3) Exploring the impact of project performance measurement on performance

In the organizational performance research, some researchers are convinced that the focus now should shift from performance measurement to performance management. According to Smith and Bititci (2017), performance measurement is "the process of setting goals, developing measures, collecting, analyzing, reporting, interpreting, reviewing and acting on performance data". This is called "technical-controls". Performance management is defined as "the cultural and behavioral routines that define how we use the performance measurement system to manage the performance of the organization". This is called "social-controls". Smith and Bititci's research (2017) has been conducted to show the interplay between the technical-controls and social-controls, and how this may influence the employee engagement and performance. Indeed, this issue has been raised because of conflicting results produced in literature of studying the effect of performance measurement on performance (Pavlov and Bourne 2011). Project performance measurement is proceeding quickly in terms of academic research in response to the ever-increasing industrial needs to managing complex engineering projects; it is thus very concerning to us to know what the effect of project performance measurement is on performance. To address this issue, some research questions could be:

- What is the impact of project performance measurement on the performance of a project?
- Is there the social-controls addressed in project performance research?
- Is there a problem about employee engagement in real project performance measurement?

After a preliminary literature review, we find that many studies focus on the investigation of critical success factors as predictors of performance. Some researchers have examined how project organizational structure interrelated with project performance outcomes. It seems that researchers have been interested in finding out the factors that drive the performance of a project, or project outcomes. For example, Dai and Wells (2014) identified and assessed an array of project management office's functions and services and their influence on reported project performance. Belout (1998) has proposed a conceptual framework to explore the effects of human resource management on project effectiveness and success. Yun et al. (2016) have focused on how the project management functions such as planning, organizing, leading, and controlling etc. influence project performance. Some researchers studies how the PMBoK Guide affects construction practices from the practitioner perspective (Chou and Yang 2012). It has been also argued that major project failures are usually sociological (Hubbard 1990). However, in literature, there are neither concerns on the effect of project performance measurement initiatives to the performance, nor subjects on how the social-controls (performance management) impacts the implementation of project performance measurement system. Thus this topic can be a future exploration.

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