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Li Zheng[1], Claude Baron[1], Philippe Esteban[1], Rui Xue[1], Qiang Zhang[2]

[1]LAAS-CNRS, Université de Toulouse, INSA, UPS, Toulouse, France
[2]Hefei University of Technology, 193 Tunxi Road, 230009, Hefei,China
{li.zheng, claude.baron, philippe.esteban, rui.xue}@laas.fr, qiang_zhang@hfut.edu.cn

Abstract: With a long history in project management practices, project performance measurement (PPM) offers a wide range of methods and good practices which help project managers to effectively monitor the project and evaluate project progress and results. However, several critical issues remain, such as an unbalanced development of KPIs types or a limited availability of leading Key Performance Indicators (KPIs). On the other hand, systems engineering measurement (SEM) is a more recent discipline, with practices and theories that appeared with the emergence of the systems engineering discipline. Moreover, SEM has been much more developed with some practical research results published in several standards and guides. In particular, SEM does not only use lagging indicators, used to track how things are going but defines methods to promote leading indicators, used as precursors to the direction where the engineering is going; indeed, 18 leading indicators (LIs) were recently proposed, validated, and finally engineered in a practical guidance. Our goal being to improve project performance and success rate, one mean is to improve the project performance measurement, on which decisions rely for project management. To achieve this goal, this paper proposes to extend the project performance measurement of indicators by considering how performance is measured in systems engineering.

***Keywords**:* performance measurement; leading indicators; lagging indicators; KPIs.

1. INTRODUCTION

Project performance measurement (PPM) is receiving wide focus from both academy and practitioners (Lauras et al., 2010; Zheng et al., 2016) and some remarking methodological results have been achieved, such as earned value project management (Anbari, 2003; Lipke et al., 2009), performance measurement of engineering projects (Guo and Yiu, 2015), or benchmarking project performance management (Barber, 2004; Kim and Huynh, 2008). Even though these results have great contributions to the economic development and enterprise competitions, it seems that most studies are based on the outcome project performance measurement with a wide variety of lagging indicators, used to track how things are going and can confirm that something is occurring or about to occur (Zidane et al., 2015; Kakar and Thompson, 2010). Relatively few studies focus on prediction-based PPM with leading indicators (Juglaret et al., 2011; Mearns, 2009). These types of indicators signal future events; they are input oriented, hard to measure and easy to influence.

What has become clear over years of research is that a combination of leading and lagging indicators results 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.

On the other hand, systems engineering measurement (SEM) is related to more recent practices and theories, which appeared with the emergence of the systems engineering discipline (Wilbur, 1995); however SEM offers very deep developments, published in several standards and guides (Wilbur, 1995; INCOSE Measurement Working Group, 2010; Roedler et al., 2010). In particular, it is also important to note that SEM does not only use lagging measurement but defines methods to promote leading measurement (Rhodes et al., 2009) recently; therefore, as a result, 18 leading indicators were recently proposed, validated, and finally engineered in a practical guidance (Roedler et al., 2010).

The purpose of this paper, therefore, is to broaden the path of PPM through applying the SE leading indicators based on a mapping and integrating approach. A case study demonstrates that it is possible to find appropriate positions in PPM for the SE leading indicators and SE leading indicators can also integrate well with existing performance measurement methods and processes in the context of the specific project.

Next two sections review literature in PPM and SEM. Section 4 presents a mapping approach transferring SELIs into PPM. Section 5 presents results from the case study. Section 6 concludes on the achievement of our research objectives and gives perspectives about further research.

2. RESEARCH BACKGROUND OF PPM

PPM plays a key role in project management by helping project managers to effectively evaluate project progress and results. Generally, in the PPM there are two kinds of indicators, which are lagging indicators and leading indicators. The lagging indicators measure performance data already produced during or after a project; they are described as the outcomes that result from previous actions (Mearns, 2009); a classical example in the occupational health and safety (OHS) management is “the frequency rate of accidents and illness” (Juglaret et al., 2011). Prediction-based PPM uses the leading indicators and is regarded as a precursor to the direction something is going. A leading indicator is defined as something that provides the users information to achieve desired outcomes or avoid unwanted outcomes (Mearns 2009), and a related example in the OHS management is ‘progress of completed audits’ that helps to identify the work that remains to be done (Juglaret et al., 2011).

The choices of indicators for PPM differ from project to project. But evidently, the lagging indicators have got a wider focus compared with the leading ones. Some models or methods, typically like the earned value project management (EVPM) and its extensions, have been identified as efficient tools for cost and schedule prediction (Anbari, 2003; Lipke et al., 2009; Pajares and López-Paredes, 2011; Chen et al., 2016). However, both the traditional EVPM research and studies on extensions and applications of EVPM concentrate on cost and time rather than other important performance measures like customer satisfactions, team performance and so on, which couldn’t be apt to the more complex projects in challenging environments. Some researchers have proposed a web-based project performance monitoring system which can provide project managers timely signalling of project problems (Cheung et al., 2004). Obviously, the prediction-based PPM with leading indicators have not been implemented to a substantial degree and its benefits like risk indication haven’t received wide attentions (Kueng et al., 2001).

Indeed, a set of balanced indicators are needed for measuring different aspects of project performance, and especially the balance of leading indicators and lagging indicators is important to ensure the right activities are in place to ensure the right outcomes. The dominance of outcome-based PPM based on the lagging indicators should be modified by the efforts of the academic and the practice. Systems engineering, as one of its related disciplines, is experiencing a remarking development with a shift from outcome measurement to predictive one, which has provided many available guides and standards for measurement, particularly its advance in leading indicators.

3. RESEARCH BACKGROUND IN SEM

In our literature review, only directly SE-related measurement guidebooks are chosen (see Fig.1). Metrics Guidebook for Integrated Systems and Product Development, published in 1995, includes thousands of metrics as candidates. In this guidebook: 1) it presented only lagging indicators; 2) no detailed guide about how to aggregate the collected data with models or functions. INCOSE SE Measurement Primer version 2.0 (INCOSE Measurement Working Group, 2010) helps: 1) to define the basic concepts behind measurement and measurement programs; 2) to provide requisite background knowledge. However no information is about how to realize a construct of a SE leading indicator (Rhodes et al., 2009). Technical measurement, version 1.0 (Roedler and Jones, 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 solutions. 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 got general recognition; however, all these are still for outcome measurement with lagging indicators, as to how to predict potential risks and issues has only been referred as a concept. For overcoming the limitations in the lagging indicators, the INCOSE organization collaborated with others, having published systems engineering leading indicators guidance, version 1.0 (Roedler and Rhodes, 2007) with defining thirteen indicators which have been extended to 18 indicators (Roedler et al., 2010). Such measurement practices have brought SE measurement stepping into a new milestone—shift from only outcome measurement to the combination of both outcome and predictive ones.

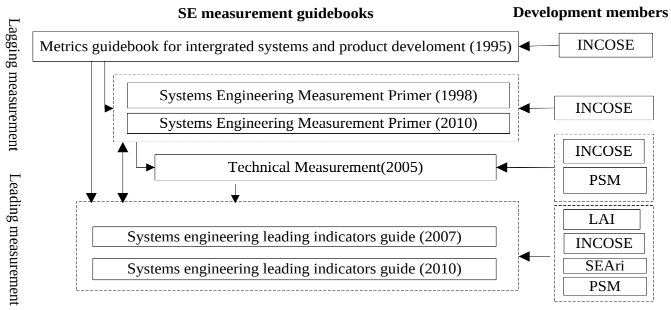

Fig. 1. The systems engineering measurement evolution

From the development and characteristics of SEM, some of its advantages could be summarized as following: 1) The history of systems engineering measurement has experienced the shift from lagging indicators to the “balance” of lagging and leading indicators; 2) The leading indicators align well with pre-existing measurement references, and the specification of leading indicators has been engineered.

The application of SE leading indicators has been conducted by NAVAIR (Naval Air Systems Command) on some aircraft development programs (Roedler et al., 2010. There are also some studies pointing that the benefits of applying the SE leading indicators for each technical review and audit defined in the United States Defence Acquisition Guidebook

(Orlowski et al., 2015). But no studies available for its value in general project management. A mapping of measurement methods of SE to the PPM has been proposed in Section 4 to analyze the processes of transferring and adapting the good practices of SE measurement to "balance" the PPM.

4. MAPPING AND INTEGRATING SE LEADING INDICATORS INTO THE PPM

With consideration of the history and evolutions of integration of project management and systems engineering, we propose to transfer the good practices from SE measurement such as the SE leading indicators to the PPM. This proposal is targeted at project managers who want to use SE measures & indicators to guide their project to success. For better integration and application of SE leading indicators to the project management processes described in the PMBoK 5 and thus to improve the PPM, a mapping and integrating approach is recommended here including two phases--phase 1 being the mapping process presented in Fig. 2, and phase 2 depicting the integrating process presented in Fig. 3.

(1) Phase 1--The preliminary mapping of SE leading indicators to Knowledge Areas in the PMBoK 5

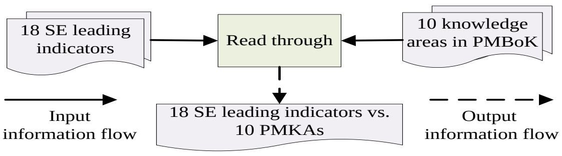

Fig. 2. The process to obtain the preliminary mapping result

Every SE leading indicator has its information category and leading insights. The information category specifies what categories are applicable for this leading indicator (for example, schedule and progress). And the leading insights specify what specific insights that the leading indicator may provide. Each Knowledge Area (KA) of PMBoK 5 has a set of processes and an overview of the processes by which main functions and application can be captured. The mapping procedures in this study are conducted in two tours. Firstly, we verify whether the information category of one SE leading indicator corresponds directly to the Knowledge Area. And then we need further to verify whether the "leading insights" provided by the LI can serve to one or several processes of other KAs. To explain the procedures, we take an example—the LI "System definition change backlog trend". An abstracted specification about the LI is provided in table 1. From Table 1, the LI has three information categories, which are *Schedule and progress, Process performance*, and *Product stability*. Obviously, the *Schedule and Progress* corresponds directly the Project Time Management, so the LI is mapped to the KA; and then the leading insights provides by the LI are around "changes", which shows that it can serve Process "Perform Integrated Change Control" of Project Integration Management, thus the LI is also mapped to the Project Integration Management. A preliminary mapping of 18 leading indicators to 10 Knowledge Areas of the PMBoK 5 has been made and shown in Table 2. From Table 2, there is not any mapping in the project procurement management column because there is neither direct information categories from SELIs for the KA nor leading sights of SELIs that can serve to one or several processes of the KA.

Table 1 The abstracted specification of "System definition change backlog trends"

System definition change backlog trends	
Information need description	
Information need	Evaluate backlog trends of system definition to understand whether changes are being made in a timely manner
Information category	1.Schedule and Progress; 2.Process Performance; 3.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.

Table 2 Leading indicators application per the Knowledge Areas in the PMBoK 5

	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 and skills trends				X		X				
Process compliance trends										
Technical measurement trends		X			X					
Facility and equipment availability trends			X	X						
Defect/ error trends					X					
System affordability trends			X	X				X		
Architecture trends					X					X
Schedule and cost pressure			X	X				X		

(2) Phase 2--Integrating each leading indicator into the processes of certain Knowledge Area and the inputs, tools and techniques, and outputs of these processes

The phase 1 makes a reference available for project teams. In Phase 2, it is suggested to conduct detailed analysis on how one SE leading indicator integrates with the inputs, tools and techniques, and outputs of processes in the Knowledge Area by 3 steps--"specify", "tailor", and "apply". The detailed description of each step in Fig. 3 as follows:

Specify: one KA has several processes, and it's necessary to specify the processes under specific project backgrounds and issues and look through the inputs, technique and tools, and outputs of each specified process. Generally, the project-specific issues can be generated in this step. And the result of this step becomes a reference for the next step — "tailor".

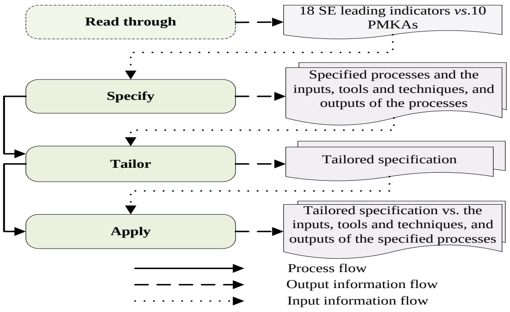

Fig. 3. The steps for integrating one SE leading indicator with the processes of one KA

Tailor: each leading indicator has its information measurement specification in the SE leading indicators guidebook.. Nevertheless, not every project needs all specification information. Once the project background is specified in the step "specify", it's necessary to conduct the useful filter to get appropriate specification to address the specified project issue.

Apply: after tailoring, integrating the appropriate specification generated in the step "tailor" to the inputs, tools and techniques, and outputs of the specified processes is necessary. This process is to see how the tailored specification will actually function with the project structure.

5. A CASE STUDY FOR MAPPING THE SE LEADING INDICATORS WITH PROCESSES GROUPS

As we know, each project has its characteristics when considering different industries, different expects, stakeholder participation and so on. When the mechanism proposed is applied in different industry background, it's possible to get different mapping results. In our research, manufacturing industry has been opted for. A medium-sized equipment manufacturing company has been chosen for the case study.

5.1 Introduction of the case and implementation steps

Hefei Keye Company was established in Jan. 2007. It 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. K** is one of the typical projects contracted by the company. It is a new reverse field pinch (RFP) device. Its design is undertaken jointly by Keye Company and some research institutions. The project is characterized by a long research period, a lot of requirements, and high precision etc.

5.2 Complementation process

Through interviewing with the project manager, the project team is often perplexed by some issues in quality management as follows:

• The existing quality management process is mainly about quality control (QC) records of operational processes and periodic evaluation of the project;

• No available leading indicators for predicting the potential risks caused probably by project quality documents such as Quality plan and Quality control documentation.

Through the above issues, it is thought that the project quality documents could be one of root causes of non-conformance product quality. With reference to the preliminary mapping in Table 2, it can be seen that, in project quality management column, many SE leading indicators are available. As the LI--defect and error trends (DET) provides information needs of defects being found at each stage of the development process of a product, which could be defects of documents or products, it has been selected as the starting point (See Table 2). Next, the LI has been integrated according to the steps proposed above—*specify*, *tailor*, and *apply*.

Table 3 Specified processes of project quality management

Processes completed by the project team according to PMBoK 5	
Plan quality management	*Inputs*-historical documents of similar projects, results from other management activities, requirements documentation; *Tools and techniques*-benchmarking; statistical sampling, meeting;*Outputs*- Quality Plan (QP), Quality control (QC) documentation
Perform quality assurance	*Inputs*-QP, QC documentation, project documents; *Tools and techniques*- quality audits, statistical sampling, meeting, process analysis; *Outputs*- change requests, project documents updates
Control quality	*Inputs*- QP, QC documentation, approved change requests, project document;*Tools and techniques*- inspection, experts reviews;*Outputs*-validated changes, change requests, project document updates

Table 4 The tailored specification of “Defect and error trend”

SE leading indicator: Defect and error trend	Base measures provided.	1. M1: number of defects found at each discovery stage
	Derived measure	1. 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: N(t)=E*(1-(exp(-b*(t^2))), Where: b=0.5/ (tp^2), t=x-axis value, and tp=location of the peak.
	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

(1) *Specify:* All the information described here are the results with reviewing the project documents and interviewing the project manager. We transform the collected project information into the three processes of the project quality management according to the structured “inputs, tools and techniques, and outputs” described in the PMBoK 5. Finally a specific description of creation and complementation of Quality Plan (QP) and Quality Control (QC) documentation has been generated in Table 3.

(2) Tailor: Focus returns to the information measurement specification of defect and error trends. According to the result of Table 3, one base measures, one derived measure and its related measurement function, indicator description, and thresholds and outliers have been selected for the case study. Table 4 presents the tailored specification.

(3) Apply: We have built the defect discovery profiles separately about defects and errors (e.g. ignored quality requirements, wrong procedure documents etc.) in QP and QC documentation per time interval. 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 4. The profiles can reflect whether defect discovery will meet expected results compared with the “Thresholds and outliers” described in Table 4. And a corrective action should be taken with experts when values exceed tolerance in the profiles. The analysis on how the tailored specification integrated into the “inputs, tools and techniques, and output s” (ITO) of the specified processes is as follows.

Firstly, the ITO of planning quality process has been analyzed for leading indicators preparation in Fig. 4. In the inputs, *the specification of defect and error trend in the SE leading indicators guidebook* has been added as a new reference in addition to the existent inputs of the project identified in Table 3. In the outputs, in addition to the QP, QC documentation, *the defects and errors discovery profiles of QP and QC documentation--thresholds and outliers* have been added.

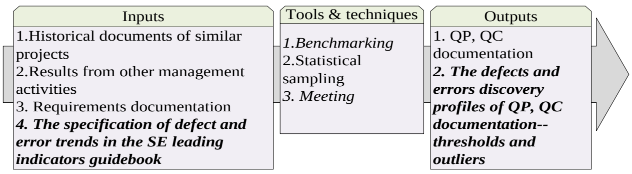

Fig. 4. Integrating the tailored specification of DET into the ITO of the “plan quality management” process

And then, the ITO of performing quality process has been analyzed for leading indicators execution in Fig. 5. The QP and QC documentation and *the defects and errors discovery profiles of QP and QC documentation -- thresholds and outliers* created in the process of “plan quality management” become the inputs of “performing quality assurance”. Piloting total defects will start. The defects and errors could include: spelling mistakes; information gaps between the author and the users; omitted 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 and techniques. M1 and M2 in Table 4 will be depicted in *the defects and errors discovery profiles of QP and QC documentation* that is a new output added into the existent ones.

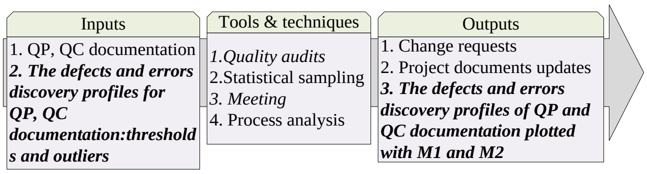

Fig. 5. Integrating the defect and error trends into the data flows of the “performing quality assurance” process

Lastly, the ITO of controlling quality has been completed for corrective action in Fig. 6. In the inputs, *the defects and errors discovery profiles of QP and QC documentation plotted with M1 and M2* help providing insights of deviation. Some analysis will be conducted once unexpected deviation occurs, and some mitigating actions will be taken with the change requests, for example re-inspecting the QP document by *expert reviews* in the tools and techniques. The *corrective actions documents for responding the defects and errors discovery profiles of QP and QC documentation* will be added in the extent outputs.

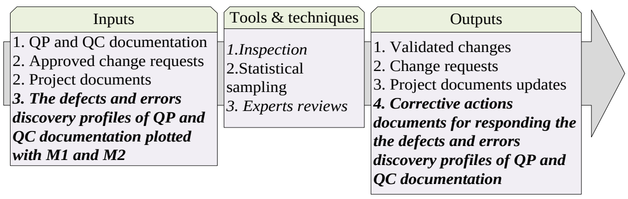

Fig. 6. Integrating the defect and error trends into the data flows of the “control quality” process

Through the case study, the preliminary mapping results and integrating processes in this study has been conducted and has pushed the project team to apply leading indicators to improve the PPM. It can be concluded that it’s feasible to apply some methods of Systems Engineering measurement in the general project management for Small and Medium Enterprises. Another conclusion is that leading indicator could find its appropriate position in PPM.

6. CONCLUSION

This study addresses the project performance measurement and its balanced utilization between lagging and leading indicators. The methodology of this study is to map the SE leading indicators with project management Knowledge Areas in the PMBoK 5 and to integrate each leading indicator into the specified processes of certain Knowledge Area. The approach has been verified in a case project in a manufacturing company, which showed that the application of leading indicators in SEM could integrate well with existing project measurement activities to control the performance of project quality management. The defects and errors discovery profiles will provide the foresight for proactive management and alarm the potential risks and issues in the processes.

The validation of the approach was based on qualitative interviews and documentation review, which were subjective in nature. And more, only one SE leading indicator and one Knowledge Area of PMBoK 5 have been chosen in the case study, which was limited to some degree. Thus, for further research, quantitative validation activity should be developed.

REFERENCES

Anantatmula, V. S. (2015). Strategies for Enhancing Project Performance.Journal of Management in Engineering, 31(6), 04015013.

Anbari, F. T. (2003). Earned value project management method and extensions. Project management journal, 34(4), 12-23.

Barber, E. (2004). Benchmarking the management of projects: a review of current thinking. International Journal of Project Management, 22(4), 301-307.

Chen, H. L., Chen, W. T., and Lin, Y. L. (2016). Earned value project management: Improving the predictive power of planned value. *International Journal of Project Management*, 34(1), 22-29.

Cheung, S. O., Suen, H. C., and Cheung, K. K. (2004). PPMS: a web-based construction project performance monitoring system. *Automation in construction*, 13(3), 361-376.

Guo, B. H., and Yiu, T. W. (2015). Developing Leading Indicators to Monitor the Safety Conditions of Construction Projects. *Journal of Management in Engineering*, 32(1), 04015016.

INCOSE Measurement Working Group (2010). Systems Engineering Measurement Primer: A basic introduction to measurement concepts and use for systems engineering, version 2.0.

Juglaret, F., Rallo, J. M., Textoris, R., Guarnieri, F., and Garbolino, E. (2011, May). Occupational Health and Safety Scorecards: New leading indicators improve risk management and regulatory compliance. *The 40th ESReDA Seminar-Risk Analysis and Management Across Industries* (pp. 16-pages).

Kim, S. Y., and Huynh, T. A. (2008). Improving project management performance of large contractors using benchmarking approach. *International Journal of Project Management*, 26(7), 758-769.

Kueng, P., Andres, M. and Wettstein, T. (2001). Performance measurement systems must be engineered. *Communications of the Association for Information Systems*, Vol. 7 No. 3, pp. 1-27.

Lynch, R.L. and Cross, K.F. (1991). Measure up-The Essential Guide to Measuring Business Performance, Mandarin, London.

Lauras, M., Marques, G., and Gourc, D. (2010). Towards a multi-dimensional project Performance Measurement System. *Decision Support Systems*, 48(2), 342-353.

Lipke, W., Zwikael, O., Henderson, K., and Anbari, F. (2009). Prediction of project outcome: The application of statistical methods to earned value management and earned schedule performance indexes. *International journal of project management*, 27(4), 400-407.

Morris, P., and Pinto, J. K. (2010). *The Wiley guide to project control* (Vol. 9). John Wiley and Sons.

Mearns, Kathryn. (2009). From Reactive to proactive–Can LPIs Deliver? *Safety Science* 47 (4): 491–92.

Neely, A., Gregory, M., and Platts, K. (2005). Performance measurement system design: A literature review and research agenda. *International Journal of Operations and Production Management*, 25(12), 1228-1263.

Orlowski, C., Blessner, P., Blackburn, T., and Olson, B. (2015). A Framework for Implementing Systems Engineering Leading Indicators for Technical Reviews and Audits. *Procedia Computer Science*, 61, 293-300.

Pajares, J., and Lopez-Paredes, A. (2011). An extension of the EVM analysis for project monitoring: The Cost Control Index and the Schedule Control Index. *International Journal of Project Management*, 29(5), 615-621.

Project Management Institute (PMI). (2013). *Project Management Body of Knowledge* (PMBOK® GUIDE)-Fifth Edition.

Rhodes, D. H., Valerdi, R., and Roedler, G. J. (2009). Systems engineering leading indicators for assessing program and technical effectiveness. *Systems Engineering*, 12(1), 21-35.

Roedler, G., and Jones, C. (2005). Technical measurement guide. International Council on Systems Engineering and Practical Software and Systems Measurement.

Roedler, G., and Rhodes, D. H. (2007). Systems engineering leading indicators guide. Version, 1.

Roedler, G., Rhodes, D. H., Schimmoller, H., and Jones, C. (2010). *Systems engineering leading indicators guide*. INCOSE-TP-2005-001-03. Version, 2.

Wilbur, A., (1995). "Metrics guidebook for integrated systems and product development, international council on systems engineering". INCOSE-TP-1995-002-01.

Zheng, L., Baron, C., Esteban, P., Xue, R., Zhang, Q., and Sotelo, K. I. G. (2016). Pointing out the gap between academic research and supporting software tools in the domain of the performance measurement management of engineering projects. *IFAC-PapersOnLine*, 49(12), 1561-1566.

Zidane, Y. J., Johansen, A., and Ekambaram, A. (2015). Project Evaluation Holistic Framework–Application on Megaproject Case. *Procedia Computer Science*, 64, 409-416.