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Mapping Systems engineering leading indicators with leading indicators in construction industry projects

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Résumé - La mesure de la performance de projet contribue à la surveillance et au contrôle des processus du projet, améliorant ainsi le résultat du projet en se basant sur un ensemble d'indicateurs, typiquement des indicateurs d'état et des indicateurs avancés. Les indicateurs d'état fournissent une vue d'ensemble des résultats sur la santé du projet. Les indicateurs avancés sont complémentaires; ils peuvent être utilisés de manière proactive pour permettre aux entreprises de prendre des mesures correctives avant que les performances diminuent. Mais les indicateurs avancés dans la gestion de projet est peu développée car ces indicateurs sont difficiles à interpréter. Cependant, [Roedler et al., 2010] ont fourni une contribution avec un ensemble de 18 indicateurs avancés, dans le domaine de l'Ingénierie Système. Une analyse approfondie de la littérature a également montré que certains champs d'application spécifiques, tels que le Génie Civil, ont développé leur propre ensemble d'indicateurs avancés. Ainsi, cet article analyse et compare les deux ensembles d'indicateurs avancés en Ingénierie Système et en Génie Civil, pour évaluer si les indicateurs avancés définis dans un domaine pourraient être adaptés à l'autre, dans le but d'améliorer la mesure de la performance en étendant la portée et la structure actuelles des indicateurs.

Abstract - Project performance measurement helps monitoring and controlling project processes, and thus improves project outcomes based on a set of indicators, typically lagging and leading indicators. Lagging indicators provide a comprehensive view on project health outcomes. Leading indicators are complementary; they can be used in a proactive way to enable companies to take corrective actions before performance decreases. But applying leading indicators on project management is not well developed because these indicators are difficult to be elaborated and interpreted. However, [Roedler et al., 2010] provided a great contribution to the state of art with a set of 18 leading indicators in the large domain of Systems Engineering. A deep analysis of literature also showed that some specific field of application, such as Civil Engineering, independently developed their own set of leading indicators. This paper thus analyzes and compares both sets of leading indicators in Systems Engineering and in Civil Engineering to point out similarities and differences, and to evaluate whether leading indicators defined in a field could be adapted to the other, with the goal to improve performance measurement by extending the current scope and structure of indicators.

Mots clés - indicateurs avancés, Ingénierie Système, industrie du bâtiment, mesure de la performance de projet.

Keywords - leading indicators, systems engineering, construction industry, project performance measurement.

1 INTRODUCTION

In project management activities, project performance measurement plays a significant role in providing information about project health status. In past decade, research efforts have produced several effective measures to monitor the project progress [Jaafari, 2007] and to evaluate project performance outcomes based on the criteria of success or failure [Cao and Hoffman, 2011; Atkinson, 1999]. However, most of the measurement is based on an approach that provides the ex-post performance information through the lagging indicators focusing on the iron triangle—cost, time and quality. Some researchers that extends the traditional “iron triangle” by including some indicators likes customer satisfaction [Atkinson, 1999] or safety [Swuste et al., 2016] are available, but the reality of adopting lagging indicators has not changed. Since lagging indicators are backward-focused or “trailing”—they measure performance data already captured. They help assessing whether goals are achieved, but they do not provide project team earlier warning signs of project risks to thus improve the performance or results

of projects through taking corrective actions. In addition, these indicators, used to evaluate results and based on outputs and outcomes, are easy to measure and accurate, but hard to improve or influence; they contribute to an after-the-event measurement, essential for charting progress but useless when attempting to influence the future. Typically, the “injury rates” is traditional metric classified into lagging indicators in the occupational health and safety. The metric provides data about incidents after the fact, but do not provides enough information to effectively avoid future accidents [Hinze et al., 2013].

Unsatisfied with the limits of the lagging indicators, some studies have focused on the identification and development of leading indicators (LIs). These leading indicators could provide early warning and identify potential risks, enabling project team gain additional insight into their project health status, and thus take action before project performance heavily slips down [Grabowski et al., 2007; Guo and Yiu, 2015; Mearns, 2009]. For example, in the systems engineering program management, “requirement trends” has been recognized as a leading indicator

for indicating schedule and cost risks and for indicating whether the system definition is maturing as expected. Applying leading indicators has been an approach in many domains, such as the prediction of turnovers and recessions in economic domain [Frankel and Saravelos, 2012], risk factors analysis in the occupational safety and health (OSH) [Juglaret et al., 2011; Lingard et al., 2011], evaluation of goodness of systems engineering (SE) on a program [Roedler et al., 2010], assessing design stability and minimizing costly changes late in development in NASA project life cycle [Blythe et al., 2014], and the capital projects within construction industry [Choi, 2007].

Some remarkable practices for capital projects are developed especially by the Construction Industry Institute (CII), which has developed leading indicators to drive construction safety performance [Hinze et al., 2013] and to drive general project performance [Yun et al., 2016]. On the other hand, the International Council On Systems Engineering (INCOSE) identified Systems Engineering Leading Indicators (SELIs) from some best practices and extended them from technical and product performance [Roedler and Jones, 2005; Wilbur, 1995] to global program performance [Rhodes et al., 2009]. In spite of these good practices improving project management, some challenges face the two domains above. CII has several programs to address the use of leading indicators, but some issues influence its advances. For example, there has been very little development of academic research that focuses on the measurement of leading indicators [Lingard et al., 2011]. Concurrent discussions about leading indicators can be found in professional/practitioner publications which aimed to focus on more specific indicators. In the SE domain, problems like the validation, interpretation, aggregation and evolution of leading indicators are perplexing its practitioners. Continuous improvement practices are conducted in both domains for resolving their facing challenges, but the efforts are made separately from the respective experts. By literature review, we observed that leading indicators have been developed separately in both domains with their respective advantages and drawbacks, and no academic efforts have been made in the cross-domains mapping and integration of leading indicators to overcome the shortcomings inherent to their specific domains. The question thus is: Can we benefit from research made on SELIs in civil engineering and conversely? For instance, can the set of SELIs be extended considering the set of LIs in CII? Can we transfer or adapt the way SELI are measured to the LIs developed by CII?

This study firstly reviews the literature on leading indicators in the domain of construction industry and systems engineering in Section 2. Then in Section 3, three processes are conducted: to identify the common characteristics inherent to the LIs of both domains; to compare the differences found in the ways in which the LIs have been organized, presented, and measured; to propose a preliminary mapping between CII and SE leading indicators and to conduct a detailed integration process. Section 4 concludes that both the preliminary mapping and the detailed integration process provide a useful reference for inspiring both domains.

In this study we are interested in the emergence of indicators and compare the leading indicators applied in specific domains like civil engineering and systems engineering. We do not address the questions of indicators construct from product or project

variable, nor the indicator valuation, nor the interpretation of the indicator values for decision aids.

2 LITERATURE REVIEW

Section 2.1 reviews several CII programs in developing leading indicators, including one program defining a set of 43 LIs which will later be selected as reference for a mapping with SELIs (cf. Section 3.2.1); Section 2.2 presents the evolution and development of SE leading indicators, and also points out the challenges in the systems engineering measurement.

2.1 CII leading indicators

CII is an organization of owner, engineering-contractor, and supplier firms from the public and private sector. The main purpose of this group is to improve the delivery of capital projects through measurement; CII is based at the University of Texas at Austin. More than 130 leading owners and contractors from both the public and private sectors have joined together to enhance the business effectiveness and sustainability of the capital facility. Through many years of efforts, some best practices and implementation tools have been proposed and practiced in some key areas like front end planning, project risk management, or project safety performance. As an example of the broad interest and activity in CII research, several programs on the development of leading indicators for capital delivery projects like construction have been launched: Project Definition Rating Index (PDRI) [CII, 1995], CII's 10-10 Performance Assessment Campaign [CII, 2014], RT 284 Research Team Safety Leading Indicators [CII, 2012] and Forecasting Potential Risks through Leading Indicators to Project Outcome [Choi, 2007].

Project Definition Rating Index (PDRI) was conducted by CII research on pre-project planning [Gibson and Dumont, 1996]. First PDRI tool developed by CII was the PDRI for Industrial Projects. The subsequent success of that tool and high demand led to the development of the PDRI for Building Projects [Cho et al., 1999] and infrastructure projects [Bingham, 2010].

CII's 10-10 Performance Assessment Campaign [CII, 2014] owns several main features: 1) Industry-Specific Questionnaire where there will be three different sets of questionnaires for Industrial, Infrastructure, and Building projects; 2) Phase-Level Questionnaire--Each set of questionnaires consists of five phase level questionnaires--Front End Planning, Procurement, Engineering, Construction, and Startup; 3) simple and easy to participate [CII, 2014]. 10 leading indicators (i.e., input measures) are obtained throughout a project's development, which can identify projects' impending problems. On the other hand, 10 output measures (i.e., lagging indicators) is to provide certainty that the project is proceeding on target through various metrics related to cost, schedule, capacity, quantity, and safety [CII, 2014].

RT 284 Research Team Safety Leading Indicators [CII, 2012] divides leading indicators into two groups, named passive and active. It has identified the characteristics of passive and active leading indicators that most effectively predict safety performance on construction projects, and has created a leading indicator measurement tool that facilitates the integration of leading indicators in a comprehensive safety program [CII, 2012].

Forecasting Potential Risks through Leading Indicators to Project Outcome [Choi, 2007] was inspired from the approach in the PDRI tool. The work behind this research was funded through a research grant from the CII. Nineteen industry professionals from CII member companies were formed as a research team for this project, and the results from [Choi, 2007] is available in the CII official website. In his study [Choi, 2007] has initially identified 181 potential leading indicators through brainstorming, and then refined and finally confirmed 43 leading indicators that had statistical relationships to project outcomes. The leading indicators were categorized as CII practices groups; they include alignment, change management, constructability, contracting, quality management, safety practices, project controls, and team building. In this paper, we will focus on these 43 leading indicators to experiment the mapping with the SE leading indicators (cf. Section 3.2) and will refer to them as ‘CII leading indicators’.

2.2 Systems engineering (SE) leading indicators

For effectively evaluating the health status of systems engineering during a program, many researchers and practitioners have provided some ideas for measuring and monitoring SE processes [Kasser, 1994]. As a result, a series of formal guidebooks have been developed and published since 1995: Metrics Guidebook for Integrated Systems and Product Development [Wilbur, 1995], Systems Engineering Measurement Primer [Antony et al., 2010], Technical Measurement [Roedler and Jones, 2005]. These three guidebooks

have been applied in SE practical activities and got general recognition. However, these are outcome measurement based on lagging indicators, as to how to predict potential risks and issues has only been referred as a concept.

In the early 21st century, for overcoming the limits of lagging indicators, the INCOSE organization collaborated with LAI (Lean Advancement Initiative), SEArI (Systems Engineering Advancement Research Initiative), and PSM (Practical Systems and Software Measurement); and they published the Systems Engineering Leading Indicators Guide, version 1.0 [Roedler and Rhodes, 2007] that defined thirteen indicators. They have lately extended the guide to 18 indicators (see table 1) [Roedler et al., 2010]. In this guide leading indicators are defined as “*measures for evaluating the effectiveness of the systems engineering activities on a program in a manner that provides information about impacts that are likely to affect the system or program performance objectives*”. Leading indicators at first glance may appear similar to existing measures and often use the same base information, the difference lies in how the information is gathered, evaluated, interpreted and used to provide a forward looking perspective [Rhodes et al., 2009]. The guidebooks are inspired from other different standards and guidebooks from other domains, typically like software engineering. 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.

Table 1. 18 SE leading indicators and their acronyms

Leading indicators	Acronyms	Information category
Requirements Trends	RT	Product size and stability; product quality and process performance
System Definition Change Backlog Trend	SDCBT	Schedule and progress—work unit progress; process performance; product stability
Interface Trends	IT	Product size and stability; Product quality; Process performance
Requirements Validation Trends	RVAT	Product size and stability; Product quality; Process performance
Requirements Verification Trends	RVET	Product size and stability; Product quality; Process performance
Work Product Approval Trends	WPAT	Schedule and progress; Product quality; Process performance
Review Action Closure Trends	RACT	Schedule and progress; Product quality; Process performance; Customer satisfaction
Technology Maturity Trends	TMAT	Technical effectiveness
Risk Exposure Trends	RET	Product quality; Schedule and progress; Resources and Cost
Risk treatment trends	RTT	Product quality; Schedule and progress
Systems engineering staffing and skills trends	SESST	Resources and Cost
Process compliance trends	PCT	Process performance
Technical Measurement Trends	TMET	Technical effectiveness; Product quality
Facility and equipment availability trends	FEAT	Resources and Cost
Defect/ error trends	DET	Product quality; Process performance; Product size and stability
System affordability trends	SAT	Product quality; Schedule and progress; Risk or Confidence
Architecture trends	AT	Product quality; Process performance; Technical effectiveness; Customer satisfaction
Schedule and cost pressure	SCP	Schedule and progress; Resources and Cost; Risk or Confidence

The application of SE leading indicators has been conducted by NAVAIR (Naval Air Systems Command) on some aircraft development programs [Roedler et al., 2010]; and research effort was also made to evaluate the potential use of LIs on some high speed sled testing programs within one organization [Knorr, 2012]. Some more studies point out the benefits of applying the SE leading indicators for each technical review and audit defined in the United States Defense Acquisition Guidebook [Orlowski et al., 2015]. But evidently the application still remains in the domain of systems engineering, and even though the validation of these leading indicators is essential, it’s difficult to share this in a variety of companies, and there is no available study to evaluate the value of this guidebook for general project management. There are still some challenges, including the

validation, interpretation, aggregation and evolution of leading indicators.

3 COMPARING AND MAPPING THE LEADING INDICATORS FROM BOTH DOMAINS

Section 3.1 makes the comparison between CII and SE leading indicators; the comparison is conducted considering the common characteristics and differences of leading indicators. Section 3.2 proposes an approach to get a preliminary mapping result and introduces how to integrate two indicators mapped together according to the preliminary mapping result. Section 3.3 discusses the discovery and value of the cross-disciplinary mapping.

3.1 The comparison between CII leading indicators and SE leading indicators

This section compares CII LIs and SE LIs and outlines their common characteristics and differences. Common characteristics reflect the nature that all LIs represent; different characteristics presented have been explored from 5 aspects based on the ways in which the LIs have been organized, presented, and measured.

(1) Common characteristics of leading indicators

Firstly, according to Table 2, through the analysis of definitions, we find that they have the same goals in providing early warning to help project team to proceed to some changes impacting the performance results, even though they have their own special application domains. They also have similar definitions. Secondly, the identifications of leading indicators in both domains were based on the expertise in industry. Thirdly, measuring the leading indicators aims to provide project health status represented by project outcomes like cost, schedule, quality, safety and customer satisfaction. The two studies have nearly the same project outcomes, except that SE leading indicators can also provide warning signs for another or sub-

process. Finally, in both domains, leading indicators are specified with same level of detail. For example the SE study explained one leading indicator through a form of specification mainly including information need description, measurable concept and leading insight, base and derived measure specification, and indicator specification; while the CII study presented each leading indicator through a format with definition, measurement consideration, and source documents. The detailed description for each leading indicator in both domains is helpful to make the comparison and mapping.

Thus, considering the common characteristics of leading indicators, we conclude that doing a mapping has sense.

(2) Different characteristics of leading indicators

Through reading through [Choi, 2007] and [Roedler et al., 2010], several differences can be found in the ways the LIs have been organized, presented, and measured. These differences are as follows: *the measurement of LIs, the scopes covered by LIs, the importance of LIs, relationship among LIs, and the classification of LIs*. The comparison results are presented in the Table 3.

Table 2. The common characteristics of leading indicators in both CII and SE

	CII leading indicators	SE leading indicators
Definition	"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"	"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 provide information about impacts that are likely to affect the system performance objectives"
Identification	Expertise of industry professionals	Experts and industrial experiences
Project outcomes	A common set of outcomes: cost, schedule, quality, safety and customer satisfaction	Nearly a common set of outcomes: cost, schedule, quality, customer satisfaction, but also impact on another or sub-process.
Explanation of leading indicator	Very detailed: through a specification for each leading indicator with description, insights and so on	Very detailed: through a format describing each leading indicator with definition, measurement consideration

Table 3. The different ways of organization, presentation, and measurement in both domains

	Measurement of LIs	Scopes covered by LIs	Importance of LIs	Relationship among LIs	Classification of LIs
43 CII leading indicators	Quantify the qualitative issues	Internal and External	Weighted	Aggregation	Classification in groups
18 SE leading indicators	Qualify the quantitative issues	Internal	Not weighted	No aggregation	No classification

The detailed analysis of the 5 differences is as follows:

For the measurement of LIs, one feature of the CII leading indicators is that it enables project teams to quantify qualitative issues, in which one leading indicator uses the qualitative description, such as *Leading Indicator 1* (see Table 5) "*The project team is lacking in the necessary expertise, experience, breadth, and depth to successfully execute the project*" [Choi, 2007], but the degree of negative impact of each leading indicator on project outcome is assessed by users through the five-point scale termed measurement considerations listed in the format of each leading indicator and thus there are performance health notes for each outcomes. Conversely, the SE leading indicators qualitatively interpret quantitative and derived measures through using trends graphs or temporal association. For example, the interpretation of a greater degree of variation in the actual versus planned requirements indicating a growing problem [Roedler et al., 2010]. Indeed, [Choi, 2007] has established a statistical relationship between leading indicators and project outcomes. However [Roedler et al., 2007] have not yet created the statistical relationship, and the methods used to present the relationship was mainly limited to finding a general trend or a temporal association between leading indicators and impacts on project performance objectives or other process. Both

approaches to establish the link between leading indicators and project performance have their advantages and disadvantages, and the use of multiple approaches in combination is likely to be much more effective and comprehensive than the exclusive use of a single type.

For the scopes covered by LIs, the CII study conducted by [Choi, 2007] have identified leading indicators from both internal and external environments, which provides benefits about the comprehension of leading indicators. In the contrast, the SE leading indicators focus on only the internal environment. We can see that CII refers to organization culture, relationship management, safety, quality management; however all those focuses have not been in the scope of interest of SE leading indicators. It's hard to judge which one is better, SE leading indicators have concentrated on the internal process with the benefits of deepening the processes while the CII ones cover widely and largely but not profoundly, and also more indicators may lead to wasted resources, time and effort.

For the importance of LIs, 43 CII leading indicators have been weighted by experts by considering that each leading indicator has different negative impact on project outcomes; the weights for SE leading indicators haven't been considered, and no explication about whether it is available in the guidebook. But

it's obvious that each leading indicator has different importance from others when considering the impact on project performance objective. If the weight hasn't been considered, the aggregation of leading indicators wouldn't be considered. Sometimes we cannot judge whether one project performance has been impacted only through one single leading indicator or the combination of multiple ones.

For the relationship among LIs, CII adopted the aggregation for all 43 indicators, while the SE leading indicators have not been aggregated (see the figure 1 and figure 2). Figure 1 shows the aggregation process used. The 43 CII leading indicators have

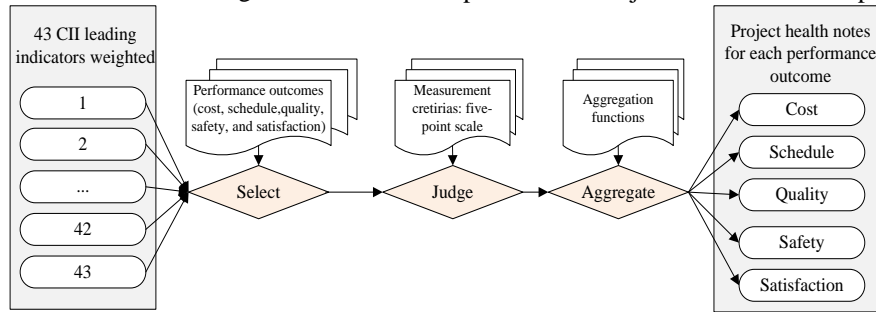


Figure 1. The aggregation process of CII leading indicators

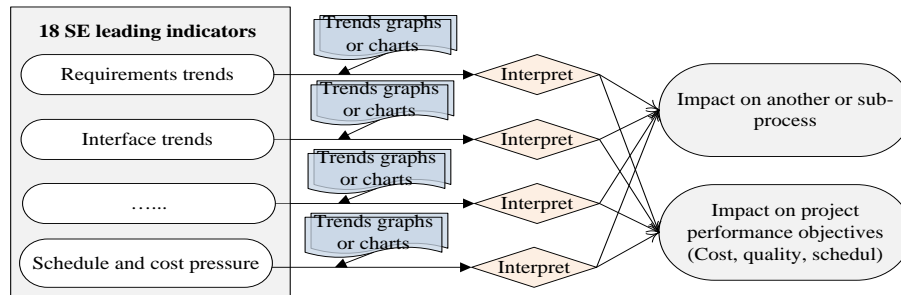


Figure 2. The interpretation of SE leading indicators without the aggregation

For the classification of LIs, the 43 CII leading indicators have been classified into 8 practice groups including: alignment, change management, constructability, contracting, quality management, safety practice, project control, and team building (see the left of the Table 5). The categories can help identifying where opportunities for improvement exist and to identify potential risk sources of project outcomes. Especially it is a way to provide benefits through presenting project health state in a comprehensive and aggregated way, which is also helpful for decision making. Otherwise the 18 SE leading indicators were summarized and listed in a no categorized way, essentially a checklist. While a checklist may be quick and simple, it is impossible to get a comprehensive view on project management functions [Yun et al., 2016].

Beyond the 5 differences between CII leading indicators and SE leading indicators, according to CII and SE LIs, some other differences can be distinguished. For example, CII method covers large of leading indicators at the beginning (181 potential leading indicators), and it takes much time for collecting and screening out the initial leading indicators, but in the final, there is a wide set of leading indicators available. SE method began not largely with only 13 leading indicators, and then extended to 18 leading indicators, and for the potential future ones, serious consideration about application and completeness should be completed. Through the comparison and analysis above, the

leading indicators have been identified and developed in different ways in both studies, and each one has its advantages and its drawbacks, so it is worth doing the mapping and thus to improve the leading indicators of each other.

Figure 2 shows that 18 leading indicators completed in the course of SE projects provide indications of impact on another or sub-process, and impact on project performance objectives (cost, quality, and schedule etc.) by individual interpretation. Neither the interdependence between leading indicators nor several leading indicators impacting concurrently one project performance objectives have been explored.

leading indicators have been identified and developed in different ways in both studies, and each one has its advantages and its drawbacks, so it is worth doing the mapping and thus to improve the leading indicators of each other.

3.2 Mapping and integrating CII leading indicators with SE leading indicators

In the CII study [Choi, 2007], the final 43 leading indicators have been fragmented into 8 practice groups. These groups detailed with its leading indicators are listed in the left of the Table 5. The 18 SE leading indicators are displayed along with the horizontal direction in the same table. For more details and insights on each one of the 18 leading indicators, the "Systems Engineering Leading Indicators Guide" [Roedler et al., 2010] is recommended. The approach in this study consists of two parts: a preliminary mapping, and a detailed integration process.

3.2.1 The preliminary mapping

The mapping approach in this study is to select one leading indicator respectively from both studies and then read through the descriptions of the leading indicator in the CII study [Choi, 2007] and the specification of the SE leading indicator. Information about every CII leading indicator can be captured from its name. Every SE leading indicator has its information categories. The information category specifies what categories

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). And they can be mapped together when there is correspondence between both indicators. For an explication, we take the *leading indicator 2* in the table 5 “*The project team is experiencing a high turnover rate and instability in team membership*” [Choi, 2007] and the SE leading indicator - Systems engineering staffing and skills trends (SESST) in Table 1 as examples. The *leading indicator 2* is about the turnover rate of team members from information of its name. And the SESST has its information category “*resources and cost-personnel effort with respect to staff level, effort, experience level, and staff turnover*” (see Table 4). Obviously, they are correspondent. So after the analysis, the two LIs from both domains are mapped together.

Table 4. The abstracted specification of the SESST

Information need description	
Information category	1. Resource and Cost--Personnel Effort with respect to staff level, effort, experience level, and staff turnover

Following the principle and the way of mapping above, a preliminary result from mapping the CII leading indicators and SE leading indicators is presented in Table 5.

3.2.2 The detailed integration process

One further analysis is to explore how to integrate the two leading indicators already mapped together according to the preliminary result in Table 5. In the study, the way of integration includes two directions as depicted in Table 6 represented by the empty arrow and the full arrow.

In the direction indicated by the empty arrow where one CII leading indicator is proposed to be integrated into one SE leading indicator, it means that the detailed description provided by it could be considered by the SE leading indicator to extend its qualitative interpretation. Taking the same example in Section 3.2.1, viewing from the empty arrow (see Table 6), the *Leading Indicator 2* “*The project team is experiencing a high turnover rate and instability in team membership*” in the CII study owns a very detailed description about turnover impact, it explained respectively indication by low turnover and high turnover, and provided also possible factors causing high turnover, which can be considered to fulfill the SESST only stating simply that *high turnover of SE staff can indicate that there are organizational issues that may adversely change the project in its indicator interpretation*.

Reversely the full arrow indicates one integration from one SE leading indicator to one CII leading indicator. First, when one SE leading indicator is supposed to be mapped into one CII leading indicator, it means that there are some base measures, some derived measures and related measurement functions of this SE leading indicators could be applied into the CII leading indicator to help its users quantitatively judge which measurement consideration fits the current situation. And the analysis provides also one view about whether there are still some aspects not well considered in the CII leading indicator. For example, the SESST includes 9 base measures, 9 derived measures, and 9 related measurement functions from which we select one base measure, one derived measure, and one related measurement function associated with the *Leading Indicator 2* “*The project team is experiencing a high turnover rate and instability in team*

membership” in the CII study; then we list them in Table 6. After the analysis from the full arrow direction in table 6, we can get two levels of information: 1) *Leading Indicator 2* in the CII study can make full use of the measures and measurement functions in the SESST to present the turnover rate quantitatively and graphically; 2) in the SESST, the turnover was considered more comprehensively from two types--intra-organizational turnover and inter-organizational turnover, while the “project team turnover” in the *Leading Indicator 2* was indicated not clearly. And thus it is likely possible to suggest a modification about the *Leading Indicator 2* through considering to add some quantitative measures from SE leading indicators, and rephrase the description in the measurement considerations clearly.

3.2.3 Interpretation and some results

We would like to highlight here some results from the previous study (the preliminary result in Table 5 and the integration process in Table 6).

From Table 5, we can see that there are some practice groups of the CII study which have not been made any reference in the SE leading indicators. For example the group “safety practice” including 7 leading indicators proves its value and importance in construction project performance management; however in the SE leading indicators, safety has not been considered. It is thus suggested that SE leading indicators could be extended from some CII leading indicators and broaden its application scope.

A second result is about the management of risks: from Table 5, we can conclude that the CII study have not referred any leading indicators associated with risk management which is an important part in project management, while two leading indicators were proposed in the SE study. For example, the *risk exposure trends*, indicating whether the project is effectively managing the project risks, and *risk treatment trends*, indicating whether the project is proactively handling potential risks at the appropriate times. It is thus suggested that the CII study could add the two SE leading indicators into its project controlling group (see table 5).

Finally, from the detailed integration process described in the Section 3.2.2, we can note that both domains have used different ways to present and explain their leading indicators, and advantages and shortages exist. A detailed integration gives some improvements for both indicators which have been mapped together as Table 6 shows. For example, adding the quantitative measures as used in one SE leading indicator to the qualitative measurement considerations of one CII leading indicator will help users to judge the current situation and thus to select one appropriate measurement consideration.

Table 5. The mapping between CII leading indicators and SE leading indicators

CII leading indicators		SE Leading indicators*	R T	SD CBT	IT	RVT -1	RVT -2	WP AT	RA CT	TMT -1	RE T	RT T	SE SST	PC T	TMT -2	FE A	DET	SA T	A T	SC T
Alignment	1. The project team is lacking in the necessary expertise, experience, breadth, and depth to successfully execute the project												X							
	7. Business goals, project objectives and priorities, and critical success factors are not being consistently used by project team members and key stakeholders to guide decisions.																			
	23. The level of maintenance and reliability personnel involvement in detailed design is low and the personnel lack alignment with other project team personnel with respect to maintenance issues for the facility.												X							
	27. The project manager (or team leader) is lacking in the required level of experience and skills												X							
	30. Commitments are increasingly made with the intention of not being met and are almost always not met.		X																	
	32. The project is frequently asking vendors, suppliers, service providers, and contractors to perform functions outside their areas of expertise and experience.																			
	41. The project is experiencing difficulties due to the lack of understanding cultural differences																			
	43. The client and/or upper management is frequently making unreasonable requests (includes setting unrealistic goals)																			
Change management	3. The project team's response to Requests for Information, questions, and changing events that can significantly impact the project results is slow, inadequate, or incomplete.		X										X							
	8. Owner and/or contractor are requesting an excessive number of contract changes and/or scope changes during project execution		X																	
	25. The project team is failing to identify and/or address missing requirements during detail design reviews	X			X	X														
	28. Project changes are not being processed in a timely manner for decision making		X																	
Constructability	21. The project lacks sufficient skilled craft and is experiencing high craft turnover due to competition from other projects, low wages, and/or undesirable work schedules.												X							
	22. The project lacks sufficient staff, bulk materials, small tools, and construction equipment to adequately support planned construction activities.												X			X				
	24. The project is using new technology or construction practices that are unproven in commercial or industrial use.									X					X					
	42. Material and/or equipment prices are increasing rapidly for certain types of materials/equipment that represent a high percent of the project cost.															X				
Contracting	6. Construction is awarded before adequate completion of project design, including discipline design packages, resulting in an incomplete scope definition at time of award/start of construction.																			
	9. Significant project scope items are inadvertently omitted from bid packages.																			
	10. Some project participant companies become financially unstable																			



* The acronyms here can be found in Table 1.

Table 5. The mapping between CII leading indicators and SE leading indicators

		SE Leading indicators*																		
CII leading indicators		R T	SD CBT	IT	RVT -1	RVT -2	WP AT	RA CT	TMT -1	RE T	RT T	SE SST	PC T	TMT -2	FE A	DET	SA T	A T	SC T	
Quality management	11. The project is experiencing a high level of engineering, design, and specification errors and scope changes.		X													X				
	12. A project specific quality plan is not consistent with the contract documents												X							
	13. The project fails to follow the quality plan for construction in relation to the roles and requirements of those who are responsible for that plan												X							
	39. The project is experiencing an above normal level of construction rework hours and costs when compared to target levels of rework included in the total budget or schedule						X												X	
	40. Project quality control results are reflecting high rejection rates for equipment and materials under fabrication in the factory and/or materials in place through testing in the field						X								X					
Safety practice	14. The project is experiencing a high level of safety incidents																			
	15. Design reviews fail to include qualified personnel who can analyze safety ergonomics, and/or loss prevention features of plans and specifications.																			
	16. The project team personnel lack involvement in safety inspections, awareness of safety issues, and education in safety practices																			
	17. Potential safety related problems are not being resolved in a timely manner																			
	18. The project is experiencing an increasing level of worker noncompliance in safety practices																			
	19. The project is not following the requirements of a specific safety plan during construction.																			
	33. Process Hazard Analysis (PHA) is late and/or is experiencing an excessive number of operational/support items that are not complete during the design phase																			
Project control	4. The project team is losing confidence in the accuracy and validity of the schedule.																X			
	5. Project milestones are not being met and are jeopardizing future project milestones.						X													
	26. The level of detail and the scope covered in the funding authorization estimate are not per estimating guidelines																			
	31. The project is experiencing difficulties in integrating schedules between project participants.																			
	35. Actual installed bulk material quantities are greater than estimated or forecasted total bulk material quantities																		X	
	36. Float for project activities is being used up at an increasingly high rate																			
	37. Actual schedule activities are lagging behind planned scheduled activities over several periods																		X	
Team building	38. Forecasts-to-complete based on actual project experience, actual commitments, and actual expenditures are projecting overruns																			
	2. The project team is experiencing a high turnover rate and instability in team membership											X								
	20. Owner and contractor project personnel are not properly aligned.																			
	29. Key project stakeholder(s) is (are) exhibiting poor relationships and pursuing private agenda																			
	34. The project team is not being realistic and truthful when project circumstances are unfavorable																			

* The acronyms here can be found in Table 1.

Table 6. One example of detailed integration between SE leading indicators and CII leading indicators

One CII leading indicator: Leading Indicator 2	Arrows	One SE leading indicator: SESST
<p>Description:</p> <p>Low turnover of team membership can indicate owners and contractors have confidence in the Project process and are confident of a positive outcome. High turnover of team members on the other hand may indicate the team cannot align or develop to the point where the team is performing effectively. High turnover of team members also maybe an early indicator that the execution of the Project is at risk due to factors associated with human conflicts within the team, conflicting objectives, design issues, lack of commitment to project objectives, team members taking on too much work, contractor companies taking on too much work, team members assigned are under-qualified, or other factors.</p> <p>Evaluation of this leading indicator requires identification of key team members, ongoing monitoring of the team membership, and investigation into the root cause of changes in membership during execution of the Project</p>		<p>Indicator interpretation:</p> <p>High turnover of SE staff can indicate that there are organizational issues that may adversely change the project</p>
<p>Measurement Considerations:</p> <ol style="list-style-type: none"> 1. Greater than 15% of Project Team turnover since beginning of the Project, with no process in place to identify reasons for turnover. 2. Greater than 15% of Project Team turnover since beginning of the Project, but there is a process in place to identify reasons for turnover. 3. Less than 15% Project Team turnover since the beginning of the Project. Project has an inadequate process to assess reasons for turnover. 4. Less than 15% Project Team turnover. Project has an adequate process in place to monitor reasons for turnover and plan to integrate new team members. 5. Less than 15% Project Team turnover. Project has an adequate process in place to monitor reasons for turnover and takes action to address root causes of turnover and plan to integrate new team members. 		<p>Base measures selected:</p> <p>9. number of SE staff leaving the project or company</p> <p>Derived measures selected:</p> <p>8. intra-organizational turnover (people leaving to work on another project in the same company): % of critical systems engineering resources leaving (by type, skill, or experience)</p> <p>9. inter-organizational turnover (people leaving to work on another project in the same company): % of critical systems engineering resources leaving (by type, skill, or experience)</p> <p>Measurement functions:</p> <p>8. critical systems engineering resources leaving the project (grouped by type, skill, or experience) / total systems engineering resources leaving the project</p> <p>9. critical systems engineering resources leaving the company (grouped by type, skill, or experience) / total systems engineering resources leaving the company</p>

4 CONCLUSION

In this paper we explored the issue of leading indicators for project performance measurement from two different domains, systems engineering and the capital projects within construction industry. Leading indicators have been proposed and developed in both domains and some good practices have been available since a decade. Our study shows that leading indicators of both domains share common characteristics including the definitions of LIs, the way to identify LIs, project outcomes, and the way to describe the LIs. But we also found some differences about the measurement of LIs, the scopes covered by LIs, the importance of LIs, relationship among LIs, and the classification of LIs. After the comparison, a preliminary mapping result has been proposed and a detailed integration process of the mapped indicators has been explored. From that, we conclude that SE leading indicators can be extended from some CII leading indicators and thus broaden the indicator scopes, and conversely the CII study could add some SE leading indicators into its project groups. Moreover, for indicators that can be mapped together, a detailed integration process can help improving either the description or the measurement of one indicator taking account of what is done with the other.

It is worth noting that some shortcomings exist both in the SE leading indicators and CII leading indicators. Firstly, validation of leading indicators is difficult. Because the calibration or validation should be based on the use of historic data, however larges of companies haven't built the data bases for this analysis. Sometimes even though data is available, dealing with it becomes a big problem due to the large amount of required time and resources. The interpretation of leading indicators is also a hard work, which can vary and depend on the viewpoints of

experts. As in the study of [Choi, 2007], the difference of the interpretation of leading indicators is based on each participant response and the perceived negative impact of a LI on project outcomes. It seems that there is still a long way for applying the leading indicators in project performance measurement. The proposal in this study about combining the leading indicators from both domains can provide a new insight into the complex issue.

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