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Investigation of Leading Indicators for Systems Engineering Effectiveness in Model-Centric Programs

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Abstract

Acquisition programs increasingly use model-centric decision-making approaches, generating and using digital assets throughout the life cycle. This transformation is resulting in new digital artifacts, revised processes, and more frequent reviews using models rather than documents. Accordingly, how engineering effectiveness is assessed must evolve. Systems engineering leading indicators provide visibility into expected project performance and potential future states. Visibility into the future state has not traditionally been part of a measurement process, and the leading indicators provide a forward-looking perspective. Prior research transformed lagging engineering metrics to systems engineering leading indicators; however, these are predicated on traditional systems engineering practice that uses document-driven processes and major milestone reviews. The research investigates adaptation and extension of existing systems engineering leading indicators for model-centric programs and how program leaders can use these to proactively assess systems engineering effectiveness in model-centric programs. The potential impact of this ongoing research is twofold: to better provide visibility into projected future state through use of leading indicators in model-centric programs, and to enhance the insights provided by the leading indicators as new digital artifacts enrich systems practice. This paper shares the approach and interim findings of the investigation.

Introduction

Digital transformation changes how systems are acquired and developed (Zimmerman, Gilbert, & Salvatore, 2019). Digital engineering (model-based engineering) produces new digital artifacts through the use of model-based practices and toolsets. Models, rather than documents, are authoritative source of truth. Myriad program stakeholders now communicate through models, and program decisions are informed by models. Model-centric approaches and advancement in technology open up opportunities for use of augmented intelligence. These changes increase the complexity and amount of information, and accelerate the pace and frequency at which it is generated and made accessible. Many in the systems community expect that traditional milestone reviews will be supplemented or perhaps even replaced by more frequent model-enabled program reviews. The desire to be able to measure engineering effectiveness remains a constant.

Motivation

Defense acquisition systems are increasing complex and interconnected, and must address the needs of diverse stakeholders in a changing ecosystem. With lengthy acquisition life cycles, challenges and emergent needs continuously drive cost, schedule, and performance risks that may jeopardize value delivery to societal stakeholders. The nature of these engineered systems means that they involve significant uncertainties, and therefore employing proven systems engineering processes is recognized as a means to help mitigate negative impacts and emergence. This makes the effectiveness of systems engineering a determinant in the ultimate success of the end system itself.

Accordingly, use of systems engineering metrics is key to assessing the effectiveness of engineering practice. However, measurement information on programs often lags ability to take corrective action. More predictability of effectiveness of engineering practice and resulting system itself is highly desirable. Conventional systems engineering measures have provided status and historical information, while leading indicators use an approach that draws on trend information to allow for more predictive analysis. By analyzing trends in context of the program's environment and known factors (e.g., requirements volatility trend), predictions can be forecast on the outcomes of certain activities (for example, probability of successfully passing a milestone review). Trends are then analyzed for insight into both the entities/activities being measured, and potential impacts to other entities/activities. Resulting information is used to inform decisions and where necessary, take preventive or corrective action during the program.

Effectiveness of systems engineering has been shown to be have positive relationship to the performance outcomes of projects and programs (Elm & Goldenson, 2013; Elm, Goldenson, El Eman, Donatelli, & Neisa, 2008). A study by Orlowski (2017) shows the use of systems engineering measurement on a project as positively impacting the performance of the project. His findings are 59% of higher performance programs in his study had higher use of systems engineering leading indicators (Orlowski, 2017).

The use of systems engineering measures is a standard part of traditional practice, though its limitations are acknowledged. Systems engineering leading indicators overcome some of the limitations but until recently collecting the underlying data and performing analysis has been constrained by document-driven engineering practice. As the use of model-based systems engineering increases, the increased ease of generating systems engineering leading indicators will make these more tractable for systems programs.

Background

Measurement of engineering effectiveness has been investigated for many decades. While lagging measures (such as number of system defects) provide useful information over time for an enterprise, they are insufficient for real-time decision making on a program. Both lagging and leading indicators are found to be useful in many fields (e.g., economic, health, social science; Zheng et al., 2019). Relatively little evidence exists on the application of leading indicators in systems programs. One reason is results are often not shared in the public domain. Another factor is that the leading indicators use trend data, which is somewhat difficult to obtain in traditional document-based engineering.

The interest in having leading indicators for acquisition and development programs has been discussed within the systems community for some time. In this context, a leading indicator is a measure for evaluating the effectiveness of how a specific activity is applied on a program in a manner that provides information about the impacts of engineering effectiveness that are likely to affect the system performance objectives. Leading indicators are designed to assist program leadership in delivering value to stakeholders, informing interventions and corrective actions to avoid problems, rework and wasted effort. Conventional systems engineering measures provide status and historical information. Leading indicators use an approach that draws on trend information to allow for more predictive insight (Rhodes, Valerdi, & Roedler, 2009).

The foundational work on systems engineering leading indicators was performed during 2004 to 2007 and further evolved through collaboration from organizations and individuals across the systems community. The early efforts produced a systems engineering leading indicators guide (Roedler & Rhodes, 2007) with 13 leading indicators defined using measurement specifications. Further work involved over 20 organizations as contributors, resulting in a second version of the guide, with five new leading indicators and several appendices added (Roedler, Rhodes, Schimmoler, & Jones, 2010).

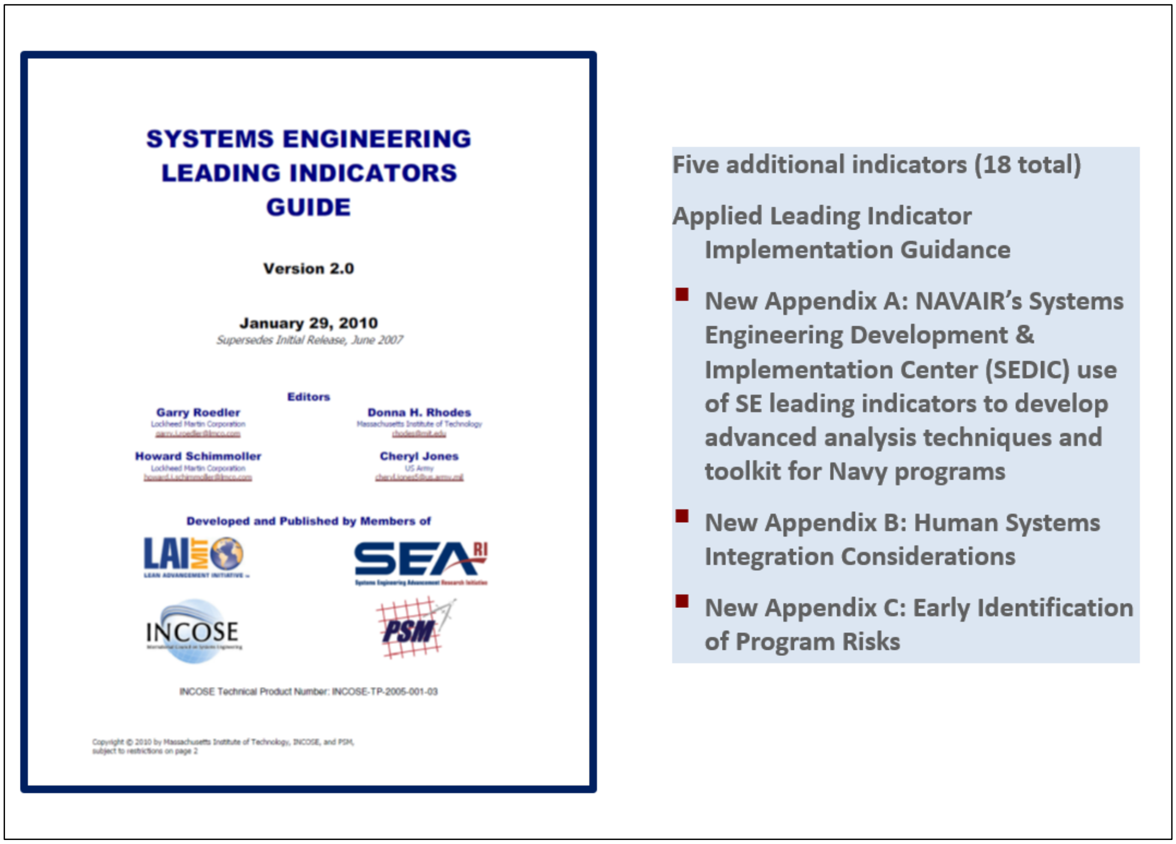

Figure 1 Systems Engineering Leading Indicators Guide Version 2.0

The initial thirteen leading indicators for systems engineering programmatic and technical performance are briefly described below. The additional five are found in (Roedler G. J., Rhodes, Schimmoler, & Jones, 2010).

Requirements Trends: Rate of maturity of the system definition against the plan. Additionally, characterizes the stability and completeness of the system requirements that could potentially impact design, production, operational utility, or support.

System Definition Change Backlog Trends: Change request backlog which, when excessive, could have adverse impact on the technical, cost, and schedule baselines.

Interface Trends: 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: 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, and schedule baselines and customer satisfaction.

Requirements Verification Trends: 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: 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: Responsiveness of the organization in closing post-review actions. Adverse trends could forecast potential technical, cost, and schedule baseline issues.

Technology Maturity Trends: 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: Effectiveness of risk management process in managing/mitigating technical, cost, and schedule risks. An effective risk handling process will lower risk exposure trends.

Risk Treatment Trends: Effectiveness of the systems engineering organization in implementing risk mitigation activities. If the systems engineering organization is not retiring risk in a timely manner, additional resources can be allocated before additional problems are created.

Systems Engineering Staffing & Skills Trends: Quantity and quality of systems engineering personnel assigned, the skill and seniority mix, and time phasing of their application throughout project life cycle.

Process Compliance Trends: Quality and consistency of the project defined systems engineering process as documented in SEP/SEMP. Poor/inconsistent systems engineering processes and/or failure to adhere to SEP/SEMP, increase project risk.

Technical Measurement Trends: 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 product design and/or team’s performance.

Each of the indicators is characterized using a measurement specification with detailed description, insights provided, interpretation guidance and usage guidance, as shown in Figure 2. Description of the contents is described in Roedler et al. (2010), and content is summarized in Table 2.

3.17.1 Architecture Trend Specification

Architecture	
Information Need Description	
Information Need	Evaluates the maturity of an organization with regards to implementation and deployment of an architecture process that is based on an accepted set of industry standards and guidelines
Information Category	• Product Quality • Process Performance • Technology Effectiveness • Customer Satisfaction
Measurable Concept and Leading Insight	
Measurable Concept	• Is the process definition based on industry accepted standards? • Is SE using a defined architecture process through the leadership of certified architects? • Do the architecture work products conform to an industry accepted set of standards?
Leading Insight Provided	• Indicates whether the organization has an architectural process that will assist in maturing the system design • Indicates whether the organization has the architectural skill set in order to execute an architectural process • May indicate future need for different level or type of resources / skills • Indicates whether the system definition is maturing • Indicates schedule and cost growth risk
Base Measure Specification	
Base Measures	1. Commitment 2. Capability 3. Plans and Products 4. Performance Metrics 5. Strategic Direction 6. Interfaces and Interoperability 7. Data 8. Security
Measurement Methods	Self-assessment or independent appraisal
Unit of Measurement	Each Base Measure has an associated unitless level.
Entities and Attributes	
Relevant Entities	• Assessment levels
Attributes	• Assessor contact information • Time Interval (e.g., date, time, monthly, quarterly, phase, etc.) • Objective evidence that support the assessment levels selected • Objective evidence meta-data • Associated attributes (e.g., status, maturity - identified and defined, interval, milestone, type, cause, severity, etc.)

Architecture	
Derived Measure Specification	
Derived Measure	1. Number of base measures failing to improve over time 2. Combined base measure scores 3. Certified architects
Measurement Function	1. Number 2. Weighted average 3. Number
Indicator Specification	
Indicator Description and Sample	Line chart depicting base measures at discrete review points in time.
Thresholds and Outliers	Organization-dependent experience is needed to identify the thresholds and outliers based on comparison to historic project and system performances.
Decision Criteria	Investigate and potentially take corrective action when the base measures do not all improve over time. All measures are expected to exceed level 3 by the time that design begins.
Indicator Interpretation	Lack of progress in any base measures over several periods indicates weakness in the architecting process.
Additional Information	
Related Processes	• Technical Risk • Requirements Analysis • Modeling • Design
Assumptions	Self-assessment is performed by experts with adequate breath of experience and proven judgment.
Additional Analysis Guidance	• System architects must work with leadership, subject matter experts, and stakeholders to build an integrated view of a system's structure, strategy, processes, and information assets to perform the assessment. • Assessment experience will aid in applying the measures in a consistent manner. • Singular assessors are to be avoided whenever possible.
Implementation Considerations	• Record the metadata and examples of objective evidence that supports the base measure level selected. (This might include architecture views, and products, security standards, interface standards, etc.) These data help in recreating or reevaluating the assessments during later project phases.
User of Information	1. Program/Project Manager 2. Chief Systems Engineer 3. Chief Architect 4. Process Lead 5. Architecture Review Board
Data Collection Procedure	See Appendix F
Data Analysis Procedure	See Appendix F

Each of the eighteen leading indicators has a specification, developed through empirical investigation, for the purpose of providing guidance for implementation and interpretation.

Figure 2 Measurement Specification for Architecture Trend (Roedler et al., 2010)

Within the measurement specification is a description of the leading insight provided by each indicator. Three examples are shown in Table 1. As can be seen in the three examples many current leading indicators are very requirements and document-focused. Model-based systems engineering, while still including requirements, involves many other digital artifacts in the engineering of systems (use case diagrams, activity diagrams, parametric diagrams, and others). Decisions are made on the collected digital artifacts, which drives the need to adapt and extend the existing leading indicators. With the advantages of model-based approaches, a leading indicator used to assess the progress of system definition that uses only requirements information would be a limited indicator. In this case, one would want to consider progress of systems definition using system diagrams of all types.

Table 1 Example Leading Insight for Requirements Trends, Interface Trends, and Validation Trends

Requirements Trends	Indicates rate of maturity of the system definition against the plan. Also characterizes stability and completeness of system requirements which could potentially impact design and production.
Interface Trends	Indicator of 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.
Validation Trends	Indicator of 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.

Adapting Measurement Specifications

Leading indicators for assessing the effectiveness of systems engineering on a program are expected to be more tractable and more useful in model-centric programs of the future. A necessary first step undertaken in this research to reexamine the existing set of systems engineering leading indicators to understand impacts of digital engineering on the defined measurement specifications. The intended outcome is to extend and adapt these as needed, and in the process to identify candidates for new leading indicators. Prior research informs this work, showing the value of continuing to mature systems engineering leading indicators.

Prior Research on Augmenting Measurement Specifications

As an initial step in adaptation and extension of the existing leading indicators involves investigating what is needed, and then updating and augmenting the existing measurement specifications. This approach was used in research that investigated enhancing the consideration of human systems integration (HSI) in systems engineering. HSI is the integrated, comprehensive analysis, design, and assessment of requirements, concepts, and resources for system Manpower; Personnel, Training, Environment, Safety, Occupational Heath, Habitability, Survivability and Human Factors Engineering. Accordingly, HSI is tightly coupled with the systems engineering process, particularly in large defense and government programs, making it challenging to determine whether HSI is sufficiently considered to ensure a successful program. It is also challenging to isolate and identify HSI issues, particularly in early stages of acquisition programs.

The objective of the research was to augment and extend the current systems engineering leading indicators, including interpretive guidance, to enhance the predictability of programmatic and technical performance on a program to include adequate HSI consideration. As a means to understand how the existing leading indicators may be augmented and the set of indicators extended to include additional useful indicators, an approach was employed to gather expert data through workshop discussions, surveys, and interviews. In this discovery process, the goal was to identify observations and “soft indicators” (that is, early insights and qualitative indicators) as a first step toward developing mature leading indicators drawing on quantitative information (Rhodes, Valerdi, et al., 2009). The investigation of adapting the leading indicators confirmed that basic augmenting of information in the measurement specification could be beneficial as a first step (Rhodes, Valerdi, Gerst, et al., 2009). In addition to adapting existing indicators, the findings led to a new proposed leading indicator focused on involving end-users in design (Gerst & Rhodes, 2010).

Adaptation and Extension of Existing Measurement Specifications

Prior research informs an approach for assessing the content of the existing eighteen systems engineering leading indicators and their measurement specifications. A general description of the fields in the systems engineering leading indicator specification is shown in Table 2.

Table 2. Systems Engineering Leading Indicator Specification Fields. (Roedler et al., 2010, adapted by Zheng et al., 2019).

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

For the purposes of this investigation, three categories are identified for the initial analysis to sort the existing indicators and determine what is needed to adapt or extend the indicators.

Category 1 is defined as a leading indicator that is minimally impacted by the transformation from traditional to digital engineering. Accordingly, the *Additional Information* sections of the measurement specification could be augmented with the approach descriptive information. This is similar to what was done in the HSI research. An example of a Category 1 leading indicator is *Staff and Skill Trends Leading Indicator,* where some additional discussion can be added to describe the any new aspects of staffing and skills that would be required on a program.

Category 2 is defined as the case where digital engineering results in more significant specific modifications or additions to the leading indicator measurement specification. Accordingly, there is a need to modify and add to all relevant sections in the measurement specification. An example of a Category 2 leading indicator is *Work Product Approval Trends*. It is expected that a model-centric program will involve new interim digital work products, and approvals may happen on a different time frame than in traditional engineering programs. As a result, there are multiple fields in the specification that are revised and augmented.

Category 3 is defined as novel leading indicators that do not currently exist that are made possible with model-centric tool sets and new practices. While not the central focus of this current phase of the research, many ideas are being uncovered in discussions with stakeholders. An example of a Category 3 leading indicator is *Model Volatility.* Just as requirements volatility can be used to judge readiness to proceed to a next phase of system development, for example, model volatility also enters into such a decision.

Category 1	Digital engineering has minimal impact on the leading indicator and its measurement specification	*Additional Information* section of measurement specification augmented with descriptive information
Category 2	Digital engineering results in significant changes and additions to the measurement specification	Modify and add information to all relevant areas of the measurement specification
Category 3	Digital engineering drives the need to identify and characterized novel leading indicators	Generate new measurement specification and illustrative graphics of displayed information

Figure 3 Three categories for approaching the adaptation and extension of leading indicators

Once the Category 1 and 2 leading indicators are identified, these need to be analyzed in context of model-centric programs. The approach of using a knowledge-based approach has been proposed by recent researchers (Orlowski, 2017; Zheng et al., 2019). The ongoing research is investigating whether a knowledge-based approach could be useful.

Orlowski (2017) maps systems engineering leading indicators to knowledge-based practice as shown in Table 3. A similar approach could be to adapt and defined knowledge-based practice areas for model-based practice and map leading indicators accordingly.

Table 3 Knowledge-based Leading Indicators (Orlowski, 2017, p. 58)

Knowledge-Based Practice	Example Leading Indicator
Demonstrate all critical technologies in a relevant environment	Technology Maturity Trends
Demonstrate all critical technologies in an operational environment	Technology Maturity Trends
Complete system functional review and systems requirements review before development start	Requirements Trends
Complete preliminary design review before development start	Technical Measurement Trends
Constrain development phase to 6 years or less	Schedule Pressure
Release at least 90 percent of drawings	Work Product Approval Trends
Test a system-level integrated prototype	Requirements Verification Trends
Establish a reliability growth curve	Technical Measurement Trends (ex. Reliability)
Identify key product characteristics	System Definition Change Backlog Trends
Identify critical manufacturing processes	Facility and Equipment Availability Trends
Conduct producibility assessments to identify manufacturing risks for key technologies	System Affordability Trends
Complete failure modes and effects analysis	Defect/Error Trends
Demonstrate manufacturing process capabilities are in control	Process Compliance Trends
Demonstrate critical processes on a pilot production line	Defect/Error Trends
Test a production-representative prototype in its intended environment	Requirements Validation Trends

The methodology proposed by Zheng et al. (2019) aims to integrate systems engineering leading indicators with processes of the PMBoK knowledge areas in order to adapt these for project performance measurement. They propose a five-step method to select, specify, identify, tailor, and apply as shown in Figure 4. This may be generally useful for analysis of tailoring measurement specifications for model-centric systems engineering.

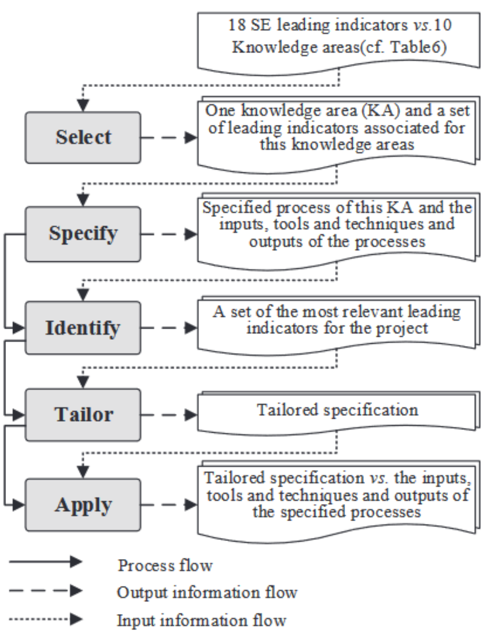

Figure 4 Methodology for integrating SE leading indicator with PMBoK knowledge area process (Zheng, et al., 2019)

Proactive Assessment in Model-Centric Programs using Leading Indicators

Program leaders have continuous responsibility to ensure that program activities are accomplished in accordance with plans, schedules, and budgets. With limited time and resources, program activities need to be accomplished as effectively as possible. In reality, it can be very difficult to judge effectiveness in real-time on a program so that course-corrections are possible. Leading indicators offer the possibility of more proactive assessment of effectiveness, particularly with support of emerging new frameworks, dashboards, and enabling technology.

Prior Research Related to Frameworks and Dashboards

A reexamination of the existing leading indicators in context of digital engineering includes understanding where enabling infrastructure, analytic approaches, frameworks, and constructed dashboards are needed. Some promising outcomes are emerging within the systems engineering community. Orlowski, Blessner, Blackburn, & Olson (2015) state that "premature transition through key decision gates is likely to lead to cost and schedule overruns," but that program risks can be monitored through systems engineering measurements. These authors propose a framework for implementing systems engineering leading indicators for technical reviews and audits. Dashboards for each technical review and audit, stating "an aggregate of the leading indicators will assist with assessing the risks with exiting decision milestone" and that "leveraging leading indicators to update the risk assessment will strengthen the end confidence around execution" (Orlowski, 2017; Orlowski et al., 2015).

While in the future leading indicators of engineering effectiveness may be available on-demand through interactive dashboards, at present the existing 18 systems engineering leading indicators will necessitate some manual effort to generate and track. In the near term, modeling toolsets can aid in generating the base information for generating leading indicators. This availability of measurement information that is more easily collected (and supported with automation) will help to mitigate the burden of collection that presently exists.

Enhancing Insights

Leading indicators provide the most value when they give a proactive assessment that informs programmatic decisions and/or corrective actions. The Requirements Trend indicator, for instance, is used to evaluate trends in the growth, change, completeness and correctness of the definition of system requirements. Traditionally, this indicator provides insight into the rate of maturity of the system definition against the plan. Additionally, it characterizes stability and completeness of the system requirements, which could potentially impact design, production, operational utility, or support.

In traditional documentation-based engineering practice, requirements are the central objects used for assessing maturity of system definition. In digital engineering, however, there are many other digital artifacts such as requirements diagrams, use case diagrams, activity diagrams, state machine diagrams, parametric diagrams, and others. In a model-centric program, a leading indicator used to assess the progress of system definition that used only requirements information would be a limited indicator. To provide enriched information on progress of systems definition, there are many other types of model constructs (e.g., activity diagrams) that would be available.

One of the trend indicators, requirements volatility, has been used to drive milestone technical reviews as show in the figure below. The graph illustrates the rate of change of requirements over time. It also provides a profile of the types of change (new, deleted, or revised), which allows root-cause analysis of the change drivers. By monitoring the requirements volatility trend, the project team was able to predict the readiness for the System Requirements Review (SRR) milestone. In this example, the project team initially selected a calendar date to conduct the SRR, but in subsequent planning made the decision to have the

SRR be event-driven, resulting in a new date for the review wherein there could be a successful review outcome.

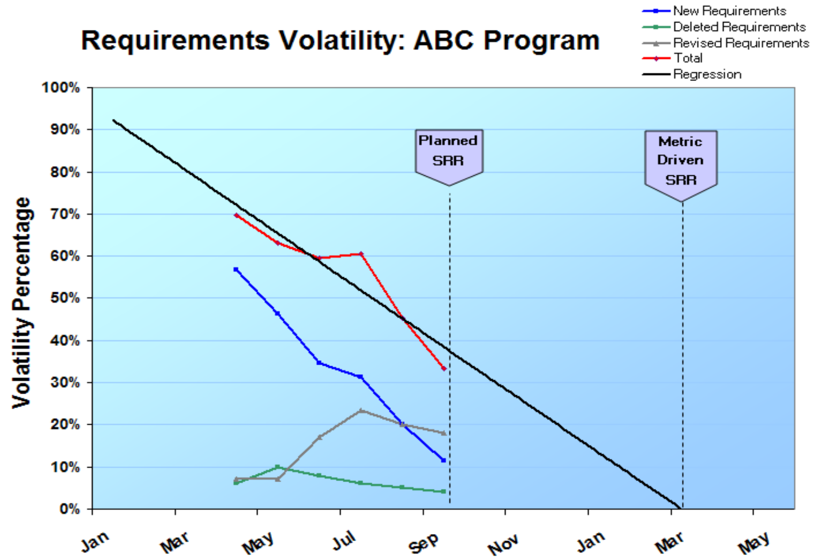

Figure 5 Illustrative Application of Leading Indicators on a Program (Rhodes, Valerdi, et al., 2009)

One of the expected outcomes of digital engineering is to move away from milestone design reviews to more continuous reviews given access to the maturing system model. Leading indicators are demonstrated to be supportive of this goal (Orlowski, 2017; Orlowski et al., 2015). An open question is how the trend information regarding the full set of digital artifacts (e.g., SysML diagrams) could be used in a similar manner to predict when the model is in a state where a review activity is most useful.

Ongoing work by other researchers and practitioners is beginning to identify model-based systems engineering artifacts used throughout the life cycle. An excellent example of this is work by Parrot and Weiland at NASA regarding using MBSE to provide artifacts for NASA project life-cycle and technical reviews (Parrot & Weiland, 2017). According to these authors, “the use of MBSE can reduce the schedule impact usually experienced for review preparation, as in many cases the review products can be auto-generated directly from the system model.” Parrot and Weiland believe leading indicators that might exist within a model (e.g., number of requirement changes, verification burndown status, etc.) could be populated within the model using parametric or by simple scripting techniques, while other indicators (e.g., drawing percent released) may need scripting or manual entry of the information (Parrot & Weiland, 2017).

While the understanding of using multiple digital artifacts will emerge as experience in digital engineering grows, the interim step will be to provide current knowledge on this situation in the measurement specification. In the future, for instance, it would be expected that requirements volatility will encompass additional base measures and that model volatility may be a companion indicator in decisions.

Future Directions

Continuing efforts on this research include collaboration with model-centric related research sponsored by the DoD Systems Engineering Research Center (SERC), a DoD University Affiliated Research Center (UARC). Various interim and completed SERC research projects provide insight into emerging needs and practices of model-centric programs, competency and knowledge-based practices, and digital engineering metrics (Systems

Engineering Research Center [SERC], 2020). As additional understanding of model-centric programs emerges, this will be used to further evolve the measurement specification of the leading indicators. Gathering knowledge from stakeholder in the systems community will be continued, with evaluating usability of the leading indicators. Future research will use publicly available model-based engineering cases to test and illustrate how adapted leading indicators could provide insights in practice.

Interim research was shared in a recent presentation and workshop at the Practical Software and Systems Measurement (PSM) annual users group (PSM, 2020). The workshop along with discussions with individual participants supported the categorization of the leading indicators. Discussions on novel leading indicators for investigation (for example, model volatility, similar to requirements volatility) will be continued with interested PSM stakeholders.

An anticipated next phase of this research will explore two areas of inquiry. The first area relates to how model-centric program measurement data can be composed into leading indicators and best displayed to enable assessment. The second area is exploration of how leading-edge technology and techniques (e.g., automated data collection, augmented decisions, visual analytics, etc.) can be used to collect and synthesize measurement data from digital artifacts.

The success of the leading indicators initiative has been enabled through an approach rooted in the foundational work of more than 20 collaborating organizations, with engagement of government, industry and academic stakeholders. Continued and future work will build on the foundational and emerging knowledge to achieve the research goals, and engage with other stakeholders to validate outcomes and transition research to practice.

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