

DISSERTATION

DETERMINING SYSTEMS ENGINEERING VALUE IN COMPETITIVE BIDS

Submitted by

Sandra Lynn Dawson

Department of Systems Engineering

In partial fulfilment of the requirements

For the Degree of Doctor of Engineering

Colorado State University

Fort Collins, Colorado

Spring 2023

Doctoral Committee:

Advisor: Ann Batchelor

David Arenson  
James Adams  
Steve Simske  
Dan Wise

Copyright by Sandra Lynn Dawson 2023

All Rights Reserved

## ABSTRACT

### DETERMINING SYSTEMS ENGINEERING VALUE IN COMPETITIVE BIDS

Corporations need a methodology to determine existing and new Systems Engineering (SE) effort costs in a more relevant context through deepening its connection within the competitive bidding process. The impact of Digital Engineering (DE) on SE within competitive bids is evolving as the industry is maturing its DE transition and implementation. The state of the field does not consider the impact of the current transition from traditional document-based SE (TDSE) to digital engineering (DE) and the impact on SE value.

This paper examines the effectiveness of the SE costing models that are available in the literature by introducing a process to compare completed projects using metrics of actual SE hours expended and project performance against recommended SE effort and project results. Analysis of this comparison provides justification for SE effort bid ranges and associated project results. This research endeavors to enable a more holistic and SE-centric view of SE costing with considerations of project characteristics and the ongoing DE transition. Finally, this research provides a new framework for the analysis results and references useful in the bidding of SE projects where SE bid options can be associated with project performance, DE transition progress, and references relevant to the competitive bid approach.

By applying systems thinking, using feedback loops and data from multiple organizations, understanding SE-DE impact, and empowering engineers in the DE transition, these research results enable data-driven decisions to determine SE value in competitive bids and to optimize SE using risk management.

Following this process and using an organization's data (for competitive bids and projects) will yield results specific to competitive bids, bid technical approach, and DE transition progress. These results are communicated to the competitive bids teams using a SE focused framework

## DEDICATION

This dissertation is dedicated to my loving parents,

Helen and Joe,

whose unwavering belief, support, and encouragement

enabled me to realize my goal of becoming

Dr. Dawson.

## TABLE OF CONTENTS

|   |     |
|---|-----|
| ABSTRACT.....   | ii  |
| DEDICATION.....   | iii |
| Chapter 1 Introduction.....   | 1   |
| Chapter 2 Research Proposal.....  | 6   |
| Competitive Bid Generation Process.....   | 6   |
| Organization Motivation.....  | 6   |
| Problem Statement – Need.....   | 8   |
| Research Proposal to Address Need.....  | 8   |
| Chapter 3 - Research Questions.....   | 9   |
| RQ1: How to quantify the value of Systems Engineering?.....   | 10  |
| RQ2: How to analyze this quantification to provide justification for SE value, SE bid ranges, and associated project results?.....            | 11  |
| RQ3 How to communicate SE Value to the Competitive Bid Team?.....   | 12  |
| Chapter 4 - Literature Search.....  | 15  |
| Literature Review on the Quantification of SE Value.....  | 15  |
| Literature Review on the SE Value Analysis.....   | 29  |
| Literature Review on Effectively Communicating Value.....   | 42  |
| Literature Review Summary – Key SE Value Highlights.....  | 51  |
| Chapter 5 - Research Identification.....  | 56  |
| RQ1: ‘How to quantify the value of Systems Engineering?’.....   | 57  |
| RQ2: ‘How to analyze this quantification to provide justification for bid SE effort ranges and associated project results?’.....              | 58  |
| RQ3: ‘How to communicate SE Value to a Competitive Bid Team?’.....  | 58  |
| Chapter 6 - Research Conducted.....   | 60  |
| RQ1: Research for ‘How to quantify the value of Systems Engineering?’.....  | 60  |
| RQ2: Research for ‘How to analyze this quantification to provide justification for bid SE effort ranges and associated project results?’..... | 68  |
| RQ3: Research for ‘How to communicate SE Value to a Competitive Bid Team?’.....   | 78  |
| Chapter 7 - Research Results.....   | 88  |
| RQ1: Results for ‘How to quantify the value of Systems Engineering?’.....   | 88  |
| RQ2: Results for ‘How to analyze this quantification to provide justification for bid SE effort ranges and associated project results?’.....  | 92  |
| RQ3 : Results for ‘How to communicate SE Value to a Competitive Bid Team?’.....   | 133 |
| Chapter 8 Conclusion.....   | 137 |

|   |     |
|---|-----|
| References.....   | 139 |
| Appendix – Peer-Reviewed Conference Paper.....          | 143 |
| Organizational Problem, Symptoms and Diagnosis.....     | 144 |
| Description of this Complex Problem.....                | 145 |
| Organizational Psychology Literature Research.....      | 148 |
| Systemic Identification of the Problem.....             | 151 |
| Proposed Intervention Using Systems Thinking Tools..... | 153 |
| Conclusion .....  | 157 |
| References.....   | 158 |
| Appendix (peer reviewed paper appendix) .....           | 158 |
| List of Acronyms .....                                  | 161 |

## Chapter 1 Introduction

Industry organizations (NDIA, AESS and SEI) have conducted studies to quantify the impact of Systems Engineering (SE) on project performance [3]. For example, NASA projects which spent a larger percentage of their SE in the early phase had fewer cost overruns. These studies assert that better SE leads to better system quality/value, lower cost, and on-schedule implementation. Research shows SE is important early in a project to influence the design at the stage when committed costs are low and design changes are less costly. Data from NASA projects support optimum SE efforts in the 15-20% range of the total project cost. Hamann [4] studied multiple space projects concluding that SE has a positive impact on the results of the cost and schedule of the projects. Honour [11] studied multiple projects and concluded that there appears to be a significant correlation between all eight SE activities and the project-level of success. Despite evidence that SE activities can realize project-level value, competitive budget pressures provide competitors a strong incentive to drive costs (including SE costs) as low as possible. This research analyzes the distribution of SE across multiple projects, both successful and troubled, and across their lifecycles to enable competitive bidders to have an evidence-based approach to bidding SE costs. The goals of this research are to provide evidence and options to estimate SE effort to achieve cost, schedule, and technical effectiveness with the challenge of keeping a bid competitive. The results of the research include a matrix of recommended ranges of system engineering effort for bids based on multiple factors including organization strategy, project performance, risk, and defect profiles.

When developing the response to a competitive Request for Proposal (RFP), the proposal response typically includes cost estimates for each effort and an explanation of the cost. If cost is an evaluation factor in the competitive bid, the organization scrutinizes every cost for alignment to the proposal and for justification prior to submission ensuring a lean cost estimate. The SE component of the bid is no exception. To provide justification for the SE estimate requires quantitative evidence of its relevance and impact to project execution and reference to actual costs or a recognized cost estimating relationship. To

meet this need for quantifiable evidence at the industry-level, a partnership of National Defense Industrial Association (NDIA) and Software Engineering Institute (SEI) executed a study of industry practices through survey and analysis of results [1]. The survey analyzed relationships between SE capabilities and individual projects' performance. Analysis of the survey response data generated scores based on each project's SE activity and project performance. Elm and Rassa [2] leverage the survey results to develop a SE business case noting the survey data provides quantitative evidence that projects with better SE capabilities have an increased likelihood of delivering better project performance, as measured by budget, schedule, and requirements satisfaction.

Elm [3] notes that the value of SE, disputed with positive and negative assertions, can be difficult to prove or refute. The costs are tangible in terms of resources allocated, but the benefits are less tangible, manifesting in events which did not happen, risks that did not materialize, rework that did not need to be done, customer complaints that did not occur, and product deficiencies that are circumvented. Research using regression models of SE benefit versus SE effort has provided SE efforts with references for competitive bids. Valerdi and Boehm [7] used the COSYSMO model to justify forecasted SE expenditures. Valerdi harmonizes software and SE cost estimation using the COCOMO and COSYSMO models. The analysis is conducted in a cross-reference framework between an engineering Work Breakdown Structure (WBS) representing a contract project scope and a generic organizational breakdown structure (OBS) representing five top level functions (SE, SW, HW, Supportability and Project Management) [6]. Boehm, Valerdi, and Honour present quantitative results on the Return on Investment (ROI) of SE from an analysis of the 161 software projects in the COCOMO II database. The analysis shows that, after normalizing for the effects of other cost drivers, the cost difference between projects doing a minimal job of software SE—as measured by the thoroughness of its architecture definition and risk resolution—and projects doing a very thorough job was 18% for small projects and 92% for very large software projects as measured in lines of code [10].

In addition to models, heuristics and expert judgment have yielded additional SE effort guidance. Valerdi created thirty heuristics useful to develop, calibrate, and use cost models [8]. For example, Pena and Valerdi use expert judgment on the relative impact of requirements volatility on SE effort as a function of life cycle phase [9]. Research comparing projects using SE activities and project results consistently reveal a positive correlation between SE and project success. As noted previously, Harmann studied eight projects and concluded that the most important categories of SE activities are related to requirements, (planning and management of) the design development, and technical management. Other less influential categories are also important [4]. Honour reviews SE activities and project results presenting quantified values for the relationships, indicating appropriate levels of each SE activity that correlate to optimum levels of success [5]. This analysis allows the systems engineer to communicate with the proposal or project manager to justify the SE bid. There are significant research results from models, expert judgment [7], or project comparisons demonstrating the value of SE effort relative to successful project outcomes.

Several authors have noted that future research should include SE effort and value for the –‘ilities’, emerging disciplines, regression testing, interfaces, and production [4]. Even higher ROIs would result from including the potential operational problems in business or mission cost, schedule, and performance that could surface due to inadequate systems architecting and risk resolution [10]. No firm guidelines can be given for the optimum scope of SE effort. However, it is emphasized that other factors, such as project character, size, and team composition, play an important role [4]. Further statistical work on regression models would significantly improve the correlations by correcting the level of SE effort using factors derived from the project characterization parameters. This future work promises to provide a quantified method to determine the optimum level of SE effort based on the a priori knowledge of the project characterization [5]. This research seeks to recommend levels of SE effort for inclusion in competitive bids. The recommended levels of SE value align to the capabilities identified in the survey results, the occurrence of these capabilities across the SE lifecycle and ranges of successful project cost, schedule, and technical performance.

Based on the above findings, there is a need to put existing and new efforts at SE costing into a more industrially and commercially relevant context through deepening its connection to the bidding process. The state of the field does not consider the current transition from traditional document-based SE (TDSE) to digital engineering (DE) and the impact of this transition on SE value. The digital engineering transition requires new metrics for competitive bids and consideration for a new tool suite, edited or updated processes, and a new skill set for systems engineers. Industry organizations are addressing this digital engineering transition through the identification of initial DE metrics and benefits [22]. The Department of Defense (DoD) has established a DE vision and strategic goals to guide this transition across its organization [24]. The impact of DE on SE value within competitive bids is evolving as the industry is maturing its DE transition and implementation.

The proposed research examines the effectiveness of the SE costing models that are available in the literature by comparing projects using metrics of actual SE hours expended, and project results against recommended SE effort and projected project results. These datasets are gathered from existing datasets from multiple organizations. Analysis of this comparison will provide justification for SE bid ranges and associated project results. New data from these projects will allow for a more holistic and SE-centric view of SE costing including considerations of project, team, and environment characteristics and the ongoing DE transition. Finally, this research will put the bidding of SE projects into a risk management framework where SE bid options can be associated with cost/benefit, return on investment (ROI), and risk tradeoff explanations. The resulting insights into SE value will enable more informed decision-making for engineering and project leaders and insight into the impact of SE bidding on probability of project success.

This dissertation begins with the research proposal (Chapter 2) to determine the value of SE in competitive bids and the foundation for the research questions (Chapter 3). Tasks associated with addressing these research questions are derived from the literature search (Chapter 4). The literature search, combined with academic course references, engineering practices, and data available at the

multiple organizations studied, evolve the focus and practical application of the research questions.

Related articles, studies, and presentations in the literature search are organized by research questions and enable the identification of research tasks (Chapter 5) and data analysis to be conducted (Chapter 6). The results of the research tasks (Chapter 7) address the three research questions and represent the practical application of original material and new knowledge to advance the understanding of SE value.

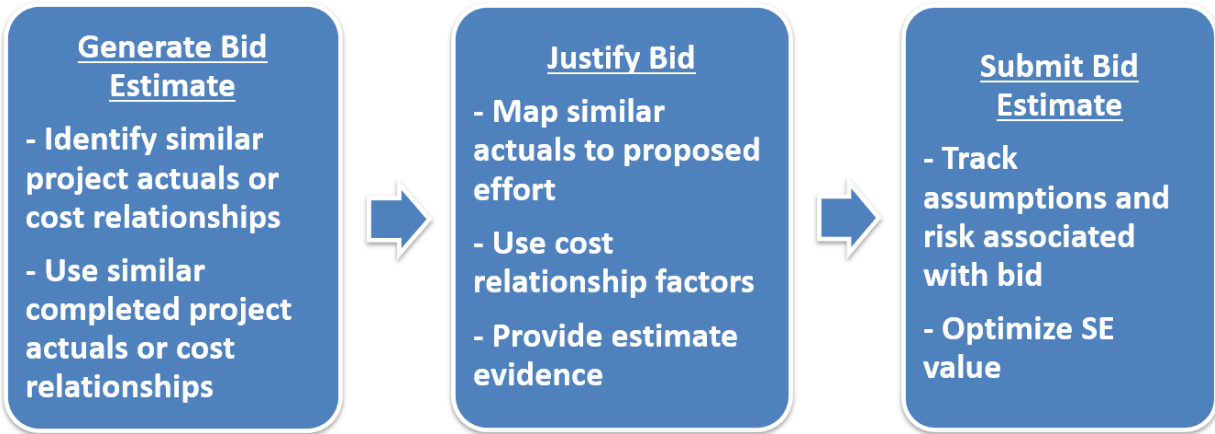
## **Chapter 2 Research Proposal**

### **Competitive Bid Generation Process**

New projects may be awarded through a competitive bid process. The competitive bid/proposal process begins with a Request for Proposal (RFP) released by a customer acquisition community. A competitive bid team submits a cost proposal to meet the proposed Statement of Work (SOW) objectives. This cost proposal includes estimated labor hours and skill mix for the tasks which accomplish the SOW objectives. The cost proposal may use historical data of a similar project such as labor hours for comparative tasks or objectives. The similarity of a historical project to the RFP is factored into the estimation with complexity adjustments. SE effort in hours is part of this cost proposal and estimation activity. The competitive bid includes cost estimates for each needed SE activity/effort and an explanation or justification of the SE cost. The proposal SE cost estimation requires quantitative evidence of SE value and impact to project execution by referencing historical/actual costs or a recognized cost estimating relationship. If cost is an evaluation factor in the competitive bid, the organization review teams scrutinize every cost for alignment to the RFP and justification prior to submission. During the competitive bid process (Figure 1), SE cost estimates, like all cost estimates, are challenged to increase the probability of win using the lowest, realistic price and shortest schedule which can be executed with SOW objectives realized.

### **Organization Motivation**

Each competitive bid generation resulting in a proposal addressing the RFP SOW objectives is a costly investment. The proposal team, assembled to generate the competitive bid, is funded typically from the organization, not the potential customers. The reviews associated with the bid generation process involve additional expert staff, also funded by these bidding organizations. If the RFP requires a demonstration or prototype of a desired capability as part of a competitive bid evaluation criteria, additional investment is required. These proposal budgets are internally funded as an investment in winning future work.



*Figure 1: Generic Competitive Bid Generation Process*

Winning future work builds a pipeline of profit for the company/organization and provides the workforce with tasking. To increase the probability of winning the RFP competition, the company/organization reviews the impact of cost and cost realism in competitive bids through customer feedback from all bids, won or lost, and through industry trends.

There are two emerging disruptors to this traditional competitive bid process: DE and new competitors in the industry. The company/organization must determine how DE impacts the technical, cost, and schedule development for the proposal and how to leverage DE in project execution. New commercial competitors are challenging the traditional, risk averse strategies employed by the established companies and are providing capabilities at a faster rate, or at lower cost, or both. The customer welcomes these benefits, especially if risky early development activities are at bidder expense. As a result of these new competitors within an industry, customer values and risk tolerance have evolved with a desire to meet mission need and requirements through quick-turn proposals/competitive bids.

Motivated to address these two disruptors to the competitive bid process, companies/organizations are committing to the DE transition to improve agility, to respond to customer mission, and to remain competitive in the RFP process. This aligns the companies better with customer/acquisition community DE expectations [24], [45].

## **Problem Statement – Need**

Traditional companies strive to remain competitive as the market and customers shift to DE and as new competitors emerge. These disruptors impact an organization's risk posture as SE is inherently involved with managing risk on a project [14]. With the DE transition, an organization needs to understand SE in competitive bids through a bid-execution feedback loop to benchmark/baseline SE in DE as DE transformation progresses. A company/organization needs the DE transition to be successful and to determine ways to accelerate the digital transformation aligning with customer expectations for technology, tools, and talent [45]. With new competitors, a company/organization must embrace the concept of fail fast and learn [4] which differs from established companies' structured and risk averse approach.

## **Research Proposal to Address Need**

This research proposal, entitled 'Determining Systems Engineering Value in Competitive Bids', focuses on enabling data-driven decisions to lower SE allocated cost per competitive bid and/or spend the SE hours more effectively. In addition, this research addresses the need to remain competitive with new competitors and for new customers by leveraging the benefits of DE. To ensure the SE hours within a competitive bid provide optimal value to the organization, research on the value of SE in previous winning bids and projects is analyzed. This analysis includes the risk and defect profiles aligned to project performance and SE hours across the project lifecycle. Complementing this analysis is the impact of DE on how SE is estimated. To leverage DE, the DE transition needs to be successful. This research recommends actions to empower engineers in this DE transition enabling a successful transition. These proposed actions support the goals of this research developing new knowledge to:

- Correlate SE bid to execution to project outcomes and create a feedback loop for more accurate estimates and successful execution.
- Correlate risk profile to project outcome and determine if a project is managing risks.
- Create a feedback loop from project execution to bid.
- Create a framework to track SE in execution and inform competitive bids.

## Chapter 3 - Research Questions

To determine SE value in competitive bids, SE value and impact in project execution must be understood. Value of SE can be measured in terms of quality, productivity, and innovation [9], [12], [14] and is impacted by the evolving nature of stakeholder issues and preferences. Industry studies (Honour [10], Elm [1], [2], NASA [11]) support an optimum SE effort (hours) in the 15- 20% range of total project effort (hours). Other industry study results indicate better technical leadership correlates to project success [11]:

- Effective SE correlates to shorter schedules by 40% or more, even with greater complexity,
- Effective SE correlates to lower development costs by 30% +.

To supplement these industry results, cost estimation models (COSYSMO, COCOMO) [6], [8] and expert judgment [7] are used to analyze the relationships between SE capabilities and project performance. With competitive bids, SE estimated cost range needs justification of value, impact/effect on project execution.

This research begins with relevant industry articles and the need to determine SE value in competitive bids considering the two disruptors, DE, and new competitors. This research determines the value of SE in competitive bids considering the DE transition within the organizations.

The following tasks form the foundation for the Research Questions (RQ):

- To quantify SE value in terms of the effectiveness of the SE costing research/models available in literature and organizational assets.
- To analyze correlations among SE effort (hours) bid, SE effort (hours) in the project and project performance, compare bids to projects using data and metrics of actual SE hours expended, and project results against recommended SE effort (hours) from literature and projected project outcome.
- To analyze the data collected for this comparison to provide justification for SE hours bid and associated project results.
- To understand the DE transition within an organization.
- To transfer the results of this quantitative and qualitative research using a holistic and SE-centric view/framework for optimized SE bids.

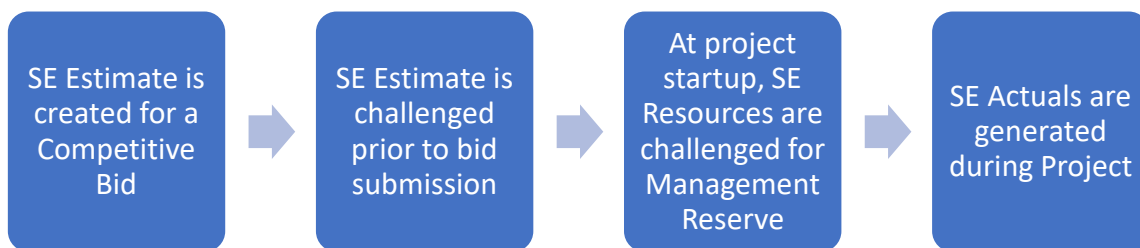
These tasks are transformed into the three research questions (RQs) for this research.

## RQ1: How to quantify the value of Systems Engineering?

Costs are tangible in terms of resources allocated, but the benefits are less tangible: avoided risks, less rework, fewer customer complaints, and product deficiencies [3]. The goal of this RQ is to quantify these benefits relative to multiple values ranges for SE effort and resource allocations. Tasks for this RQ to quantify the value of SE are:

- Task 1: Review existing SE effectiveness/cost research both published and by survey.
- Task 2: Collect project cost data (SE estimates and actuals/hours), risk registers/profiles and defect profiles from winning competitive bids and corresponding project execution and performance.

These two tasks support the RQ in quantifying the value of SE in the context of the competitive bid process. The value of SE as bid is not always the value of SE as allocated in a project. As a resource challenge, the project may allocate hours from the SE bid estimate, as well as from other bid estimates, to fund the project's technical reserve (TR). One use of TR is to mitigate project risks or to exploit project opportunities. This SE resource challenge includes an amount reallocated from bid estimates which varies in funding or percentage and may impact the overall SE hours allocated in project execution. Companies may hold TR separate to mitigate technical risks or incorporate TR into the overall project's Management Reserve (MR). MR can be applied to all project risks, not just technical risks. Figure 2 shows the relationship between the competitive bid (SE estimate) and the project's actual costs (SE actuals), including MR deduction. For this research, MR is used rather than separate TR and MR.



*Figure 2: Relationship between SE estimates of competitive bid and project actuals*

## **RQ2: How to analyze this quantification to provide justification for SE value, SE bid ranges, and associated project results?**

This RQ focuses on analysis using the research and data collected in RQ1. This analysis aligns SE value, SE effort ranges of successful project cost, schedule, and technical performance, risk management, and defect profiles with SE effort ranges for projects with challenges to the cost, schedule, and technical performance baseline and their respective risk and defect profiles. Examples of the analysis include comparing:

- SE actuals with SE bid estimates using percentage of SE hours to total project hours,
- SE actuals and SE bid estimates with industry studies,
- SE actuals distribution across the lifecycle for SE resource allocation spread compared to project performance.

Systems thinking concepts and tools to determine patterns and trends in the analysis and relate these patterns and trends to SE value is the focus of this analysis. Examples include identifying relationships with or among:

- SE actuals and project performance outcome,
- Risk/Opportunity management practiced in the project and impact,
- Defect profile of project and SE hours spread across the project lifecycle.

To accomplish RQ2 goals, data analysis tasks are:

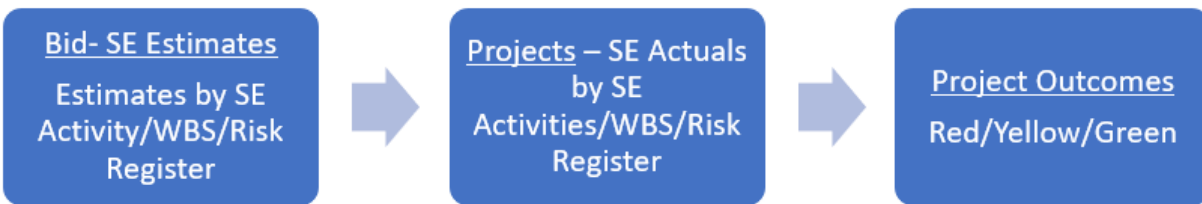
Task 1: Collect and assess existing and new efforts at SE costing, especially DE metrics.

Task 2: Consider intangibles in bid and project execution – competition, market influences, reputation, teaming agreements- when data is available.

Task 3: Determine insights into SE value enabling more informed decision-making and deepening SE costing options in bidding.

These RQ2 goals and tasks focus on the relationships among competitive bid (SE estimate) and project actual costs (SE actuals) considering project performance (successful performance against the project cost, schedule, or technical baseline), and management of risk and defect profiles. The trends and

patterns associated with these relationships provide insights into SE effort defined through SE estimates in the bid and SE actuals in the projects. This SE effort data is traditionally captured by using SE activity or SE hours per Work Breakdown Structure (WBS) element. These relationships are depicted in Figure 3 noting the SE estimate in the bid flows into the SE actuals on the project and the determination of the SE value on project outcomes which are noted as green (successful performance against cost, schedule, or technical baselines), as yellow (slight deviation from the planned cost, schedule, and/or technical baselines) or as red (significant deviation from the planned cost, schedule, and/or technical baselines).



*Figure 3: SE competitive bid estimates, project SE actuals, and project outcome analysis*

### **RQ3 How to communicate SE Value to the Competitive Bid Team?**

The focus of this RQ is to identify a means to effectively communicate (transfer) the SE value results from the RQ2 analysis using data collected in RQ1. The analysis identifies the trends and patterns associated with the relationships among SE bid estimate, SE actuals in projects, and project performance. These trends and patterns are part of the analysis and this comparison of bid to actuals to performance creates new feedback loops for the proposal/bid teams. Analysis of this comparison provides justification for SE bid ranges and associated project results. The goal of this RQ is to determine a holistic and SE-centric view or framework of SE quantification as the means of SE value communication.

To accomplish these RQ goals, tasks to determine an effective means of communication are:

Task 1: Investigate the viability of the SE-centric view as risk quantification framework where systems engineering bid options can be associated with cost/benefit and risk tradeoff explanations.

Task 2: Provide digital engineering impact on document-based SE processes and products in a bid and project execution.

Task 3: Present the spectrum of SE value and associated risk posture for more informed decisions and more competitive bids enabling the bid team to ‘dial in’ or optimize the SE estimates with risk awareness.

These RQ goals and tasks focus on effective communication of SE value. A proposed holistic SE-centric framework incorporates feedback loops among the competitive bids (SE estimates), project (SE actuals) and project outcomes as shown in Figure 4.

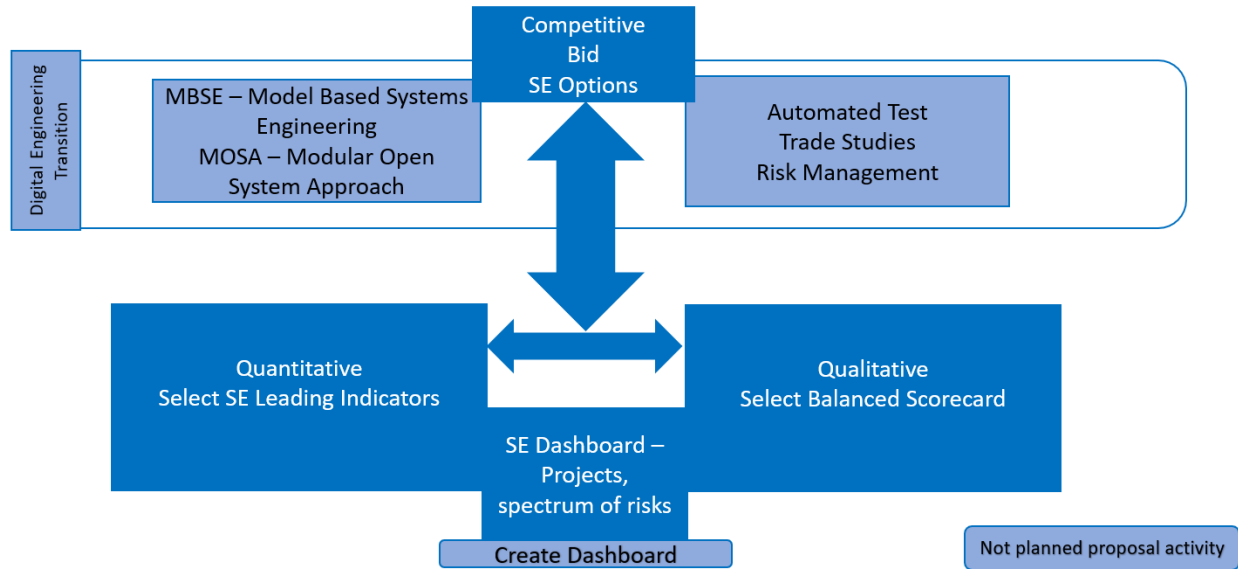


*Figure 4: Competitive bid (SE estimate), project (SE actuals) and project performance outcome analyses and feedback loops (arrows)*

The arrows represent the feedback loops comparing project performance to SE actuals and to SE estimates. These feedback loops enable more informed and data-driven decisions to be made as the competitive bid teams have access to a comparison of SE value with various ranges of SE effort and project performance. SE value is not the only contributor to project performance with other decisions and intangibles impacting project performance.

A proposed framework concept for analysis and communication of SE value is based on preliminary research and proposed as a methodology to effectively communicate these results to the competitive bid teams enabling data-driven decisions regarding SE value in the bid. This SE-centric framework to

communicate the research results is titled SEaaS (Systems Engineering as a Service) - Risk Quantification Framework (Figure 5). This framework concept evolves during this research.



*Figure 5: Proposed concept for the SEaaS-Risk Quantification Framework based on preliminary research*

This analysis enables competitive bid teams to justify SE effort bid and to make a risk-based informed decision related to an SE bid. The impact of the DE transition on an SE bid surfaces in each RQ as DE influences SE in competitive bids and project execution. The new SE-centric view/framework communicates the approach for optimized SE bids to include quantitative and qualitative perspectives. The literature search, detailed in the following section, supports the identification of the research tasks and research approach to address each RQ.

## Chapter 4 - Literature Search

To determine SE value in competitive bids, the literature search focuses on understanding SE value and the impact of SE on project execution. The Merriam-Webster Dictionary defines value as ‘the importance, utility, or usefulness of something’. Economics defines “value” as a ‘measure of benefit’. The literature search to support this research initiates with SE value and evolves with keyword searches on SE ROI, SE effectiveness, SE metrics, SE quality, SE cost, and digital engineering. The keyword searches are supplemented by author name searches with seminal contributors to the SE industry such as Eric Honour, Joseph Elm, Barry Boehm, and Ricardo Valerdi. Industry conference (INCOSE, NDIA, SERC) presentations and papers provide a state of the industry perspective on SE, SE value, and DE. The literature search, including these industry conference presentations and papers, results in over 250 artifacts. Organization presentations and Subject Matter Expert (SME) interviews complement the industry perspective. These artifacts are assessed for applicability to this research narrowing the resulting list to 155 artifacts. Analysis and synthesis of these artifacts result in 65+ key references enabling an understanding of current state of the industry, knowledge gaps, and application to this research. These references and state of the industry understanding shape the formulation of the research questions (RQs) and associated research tasks. This literature search chapter focuses on these key references and is organized around the three RQs.

### **Literature Review on the Quantification of SE Value**

The literature search begins with defining value and expands into methods of quantifying SE in terms of value, effectiveness, effort, and return on investment (ROI). Costing models for SE, which support estimation activities to generate SE value for a competitive bid, are reviewed. Finally, the impact of the Digital Engineering (DE) transition, ongoing within organizations, industries, and customer acquisition communities, on determining SE value is explored.

## *SE Value*

Rouse et al. [12] define value in terms of quality, productivity, and innovation in technology organizations without a focus only on SE. Value strategies can be formed in terms of action plans to define where and how value is provided. Delivering value to the organization includes greater emphasis on understanding, anticipating, and managing technical risks. Tradeoffs across stakeholder priorities and perceptions of value are incorporated into the value strategy. Managing technical risks and tradeoffs (trade studies) are SE activities directly aligning this general technology definition of value to SE value. This article presents a framework reflecting systems thinking to design processes enhancing value: a) Choose where to provide value, b) Decide how to provide value, c) Develop a design to enable value, d) Benchmark value, e) Determine how to close a gap on 'As Is', 'To Be', and f) Implement. Current processes are assessed for value and redesigned to add value with a focus on the series of users, not just the end user. The concept of value is complicated by the evolving nature of stakeholder priorities and concerns. A value strategy should provide expected quality (or better) at competitive cost relative to the innovative characteristics of the product or service. Strategies can provide maximum value within available budget or minimize budget for specific level of value. Organizational and cultural change are to be managed as these strategies are implemented with an expectation of resistance and apathy. A balanced scorecard has critical measures, targets, and initiatives recognizing the multi-attribute nature of value and is reviewed for value strategy progress and results. This article relates to this research for the definition of value as applicable to SE. The framework for a strategy to enhance value, track progress via scorecard, and manage change within an organization applies to an organizational DE transition. This article's application spans both the quantification of SE value and the communication of SE value with stakeholder options or tradeoffs for enhancing SE value from a cost, schedule, or technical perspective. The implementation of the value strategies includes balanced scorecards and the adaptation of the value strategy to an organization. The adaptation of value strategy is specifically applicable to the Digital Engineering (DE) transition which is ongoing in organizations and industries.

The value of SE can be found in the implementation of SE process and in the effort bid and expended in terms of labor dollars/hours and return on the SE investment. There is a significant body of work detailing SE processes and implementation. A different perspective on the implementation of SE is presented by Emes [28]. The author proposes five principles of SE management:

1. Principles govern process,
2. Seek alternative systems perspectives,
3. Understand the organization context,
4. Integrate SE and project management,
5. Invest in the early stages of the project.

Increased value from SE can be realized with enabling processes focusing on process innovation and tailoring. SE value is realized by using these processes to balance fixed requirements with a flexible system adaptable to a changing environment. This flexibility promotes an agile SE approach customizable to a project. This article has application to this research as these principles support the early lifecycle application and value of SE to project success.

This research seeks to quantify the SE value by examining the effectiveness of SE costing research and models available to industry in literature and within the organizations. Eric Honour has authored multiple papers and has completed renown studies on the understanding the value of SE. In the article exploring the value of SE [11], heuristic and statistical analysis of studies relate the quantity and quality of SE to project schedule and product quality. Of interest to this research, the results of these studies are summarized as the optimal SE effort at 15-20% of total project effort. Honour advocates a systems thinking approach to product design and risk which saves the project time and cost, contributing to the intrinsic value of SE. The value of SE is also realized by applying SE effort to reduce risk early and prevent integration and test problems from occurring. Attempting to quantify the value of SE, technical size, complexity, quality, risk project duration, and cost are defined as observable values of SE. Systems Engineering Effort (SEE) is defined as the product of SE Quality (difficult to measure) and SE Cost

divided by Project Cost and can be expressed as a percentage of total project cost. Cited studies are supplemental to this value of SE study and note the following relationships:

- Greater funds in project definition results in significantly less cost overruns during project development.
- Good processes do not necessarily create a good project. High performing teams did more boundary management/SE management tasks vs low performing teams. Technical leadership is more important than the processes used. Technical process definition is important but not sufficient.
- Use of more rigorous SE practices significantly reduced overall development time.
- Use of SE processes improves project productivity when effectively combined with the project management and test processes.
- Systems engineering has a moderate to significant impact on complex systems projects. SE has a good to excellent impact on cost. Most projects spent 6 – 10% on SE cost to total project cost (or hours).
- NASA research data shows an optimum of about 15% SE effort, hours, budget or cost to project total effort, hours, budget, or cost.

Combining these study results and limitations, the author makes three conclusions from the data. First conclusion is SE effort improves development quality. Second conclusion is optimum SE effort is 15-20% of total project effort. Third conclusion is the quality of SE effort matters. This article has application to this research as the value of SE is quantified and tied to risk management. The recommended percentage of effort or SE hours to project total effort or schedule correlates to the greatest SE value for the project. This seminal industry paper is a key reference point for determining value of SE in competitive bids.

Honour [51] builds upon previous articles using the data collected through industry surveys to quantify the ROI of SE. This paper shares an optimum percentage of SE activities to project costs with the following:

- Mission/Purpose Definition = .8%,
- Requirements Engineering = 2.2%,
- System Architecting = 1.3%,
- System Integration = 2.3%,
- Verification and Validation = 3.7%,

- Technical Analysis = 2%,
- Scope Management = .5%,
- Technical Management = 2.7%,
- Total SE = 15.5%.

This article has application to this research as determining the value of SE for competitive bids is the goal. The findings for optimum SE for the project and across SE activities can be compared to research data for SE allocation. This comparison enables the competitive bid/proposal team to make data-driven decisions using organization-specific data. Additional data points would drive confidence in the SE value in the competitive bid.

Quantitative results of the value of SE are captured as a ROI by Boehm, et.al. [10]. The ‘thoroughness’ of SE is measured by architecture definition (including operational concept, requirements, and plans) and risk resolution (identified and managed). Over 160 software/systems engineering projects were analyzed with effects of cost drivers normalized to yield the cost difference of projects with minimal SE and ‘thorough’ SE. The analysis showed a relationship between architecture definition, risk resolution, and reducing software rework: 20% of defects accounted for 80% of rework costs and these 20% were primarily due to inadequate architecture definition and risk resolution. The cost difference for small projects is 18% and very large projects is 92% with project size measured in lines of code (10KSLOC is small, 10,000KSLOC is very large with KSLOC defined as 1000 (K) Source Lines of Code). Analysis of the results estimates how much upfront or early SE is enough for projects of varying size. The ‘sweet spot’ for the percentage of schedule time for the SE effort associated with architecture definition and risk resolution is about 10% for very small projects to 37% for very large projects. These results quantify the value of SE and its impact on project success by answering the question ‘how much SE is enough?’. This article has application to this research as the value of SE is quantified and tied to specific SE activities: architecture definition and risk resolution. The recommended percentage of effort or time to project total effort or schedule correlates to the greatest SE value for the project. This industry recommendation is a

key reference point for determining value of SE in competitive bids and provides new comparison points to stakeholders.

### *SE Value and Effectiveness*

Elm's [1] study characterizes the value of SE in terms of effectiveness and the relationship of SE capabilities to project success through use of an industry-sponsored survey. The analysis of survey results provides quantitative evidence of the value of SE activities. While acknowledging the industry inconsistency with activities which comprise SE and with assessing project performance, a survey is developed to measure the application of SE activities through 'significant' SE work products/artifact (SE activities), budget/schedule, and requirement satisfaction (performance). The survey measures SE capability, project performance, and project challenge. The strength of the relationship between and among these measurements is represented through 'gamma' which is a strength of association statistic. The results of the survey indicate the strength of the relationship of 'early lifecycle' SE processes (requirements and technical solution management, architecture, and trade studies, with team capability) to project performance with project challenge as the control variable. The data resulting from the survey shows projects with better SE capabilities have an increased likelihood of delivering better project performance as measured by budget, schedule, and requirements satisfaction. Projects with high challenge, higher overall SE capabilities, especially early SE activities, are almost 50% more likely to achieve better project performance. The SE activities which begin early in the project and influence the approach to developing the technical solution have the strongest relationship/greatest impact on project success. This article has application to this research as it provides quantitative evidence of the value of SE through the strong relationship of early lifecycle SE activities to project success. This relationship provides options to competitive bid stakeholders to allocate SE earlier in the lifecycle and manage risk through a challenge to SE value later in the lifecycle.

Elm [25] expands with greater detail on the results of this survey quantifying the application of SE activities to projects and project performance outcome. Multiple engineering industry associations

supported participation in this survey. The application of SE is described as categories of SE activities and project performance is assessed as cost, schedule, and technical requirement satisfaction considering project challenge. The SE activities categories of project planning, requirements development and management, verification, and product architecture, have the strongest relationship to project success. Contributions of SE to project success are even stronger for challenging projects. Project challenge is characterized in terms of technical challenge, project value and financial stability, duration and schedule stability, requirements stability, and organizational complexity. A negative relationship between challenge and complexity is noted. The results of the study have application to this research as they provide quantitative evidence of the value of SE activities. Projects with better SE capabilities within SE activities have an increased likelihood of delivering better project performance.

### *SE Value, Effectiveness and Effort*

Effective SE and the relationship of SE to achieving project success is explored by Carson and Zlicaric [14]. A common view of SE is to manage risks on a project. SE effectiveness is assessed as “adequate SE to accomplish a purpose”, producing the intended or expected result. SE Effectiveness is decomposed into product quality/quality of SE artifact content, cost, and schedule (timeliness). There is a natural limit to overspending on SE where too many resources are devoted to SE causing overruns and diminishing returns. Comparing SE effectiveness to Earned Value, rework is unearned value. Requirement compliance and requirement quality (verifiability) are described as potential metrics to measure SE effectiveness. This article has application to this research as it notes potential metrics to measure and define SE effectiveness in terms of requirements management.

Vanek et al. [26] focus on measuring the effectiveness of SE as applied to product development in commercial organizations. In most organizations, the goal of applying SE is to provide a better system in less time and cost, with less risk. Evidence of the effectiveness of SE can often be difficult to obtain due to the challenges involved in isolating the effects of SE from other processes and the proprietary limitations of publications. Characteristics of SE metrics and metrics selection is reviewed. The presence

and experience level of SE staff is an indicator of the extent to which SE is applied to the project. The challenge of capturing SE ROI is introduced. This review has application to this research as a background literature review setting a foundation for the challenges of valuing SE in a commercial product development organization. These challenges are similar for non-commercial organizations and the optimum SE effort range referenced is less than Honour [11], [51] has recommended.

The ranges of SE effort should reflect known impact factors to SE effort. Pena and Valerdi [9] study the impact of requirements volatility on SE effort. Causes and expected levels of requirements volatility for a given phase of system lifecycle are explored using a survey. Results of the survey indicate an expectation for higher volatility during early life cycle phases and the volatility decreases over time. Volatility is not linear and peaks during transitions between lifecycle phases, which may coincide with design reviews and handoffs between organizations (i.e., development to test). The requirement change requests rate typically peaks during the requirements analysis to design phase transition. Requirements changes during the conceptual phase should be expected and treated as planned vs unplanned volatility. Requirements volatility has led to increases in project size, effort, cost, schedule duration, and rework due to higher defect rates. It is noted that some requirement changes result in reduced scope and less effort. However, deleting a requirement after development phase results in effort and cost that is lost. This article has application to this research as the study observations related to requirements volatility impact SE effort. Expected levels of requirements volatility across the system lifecycle allow SE effort to be allocated commensurate with expected volatility. The causes of volatility can be used by proposal or project SE to identify risks and to develop mitigation plans reducing the level of unplanned changes.

In addition to requirements volatility, SE effort is influenced by SE and Project Management (PM) integration. Jonkers and Shahroudi [32] study the lack of integration between SE and PM which leads to inconsistent and incomplete information exchange and contributes to project failure. The authors indicate that 85% of technology and project costs are committed prior to detailed design with little flexibility to adapt to design changes. They developed a model applying systems thinking for the effective integration

of SE methodologies, tools for effective design, and management of complex physical systems.

Knowledge can be gained early in design with system ease of change increased, leading to reduced design change costs and schedule delays. This article has application to this research using systems thinking and the inclusion and integration of PM with SE to reduce risk to cost/schedule and to impact SE effort.

One way to decrease SE effort and project cost is to reuse artifacts, components, or elements such as documentation, processes, parts, or software. Wang, Valerdi, and Roedler [27] explore quantifying SE reuse which impacts the value of SE in the competitive bid. Two reuse processes are reviewed:

Development for Reuse (DFR) and Development with Reuse (DWR). A quantitative approach for assessing reuse and reuse categories is described relative to the COSYSMO V2 model, which addresses reuse. The benefits of reuse are reviewed: reduces complexity, defects, timelines. This article has application to this research as reuse is a way to reduce complexity and decrease SE effort. Through the application of reuse, SE effort can be reduced through use of a previously proven artifact, component, or element. SE should be applied when determining a reuse opportunity and to successfully integrate the reuse into the project.

### *Estimating SE Effort*

With SE value, effectiveness, and effort reviewed in the prior sections, a key model to estimate SE effort, COSYSMO by Valerdi [7], is now reviewed. To increase the probability of a successful project outcome, SE effort is estimated for the SE activities across the systems lifecycle. To estimate the necessary SE effort, heuristics or actual/historical data is used for a bottoms-up estimate. An SE cost model, using existing data and parameters to calibrate cost, considering system difficulty and complexity, did not exist prior to COSYSMO model. To create this model, the developers used a seven-step process with a survey for data collection and with expert judgment for the analysis. The resulting model uses size drivers/predictors and cost drivers/effort multipliers determined by using the Delphi method with a group of SE experts. Activities which have the greatest impact on SE effort and duration are size drivers: numbers of system requirements, major interfaces, operational scenarios, and unique algorithms. Cost

drivers/application factors include requirements understanding, architecture complexity, level of service requirements, migration complexity, and technology maturity. Cost drivers/team factors include stakeholder team cohesion, personnel capability, personnel experience/continuity, process maturity, multisite coordination, formality of deliverables, and tool support. This article has application to this research as the development of this SE cost model considers factors which should be applied to an organization's data collection and analysis. The team factors are relevant in traditional document-based SE and should be considered with the DE transition. Lessons learned from the data collection and limitations of the model are shared. The use of the model as an SE effort validation or SE effort/cost estimation risk mitigation should consider these lessons and limitations.

Using COSYSMO, Valerdi [6] examines software and systems engineering cost models for gaps and overlaps with the intent to harmonize the estimates for the project. Software and systems engineering activities are tightly coupled and reviewing the cost estimations and assumptions associated with these models allows for more effective estimating techniques for software-intensive projects. Harmonizing efforts consider the overlap and gaps between software and systems engineering work products and activities, cost drivers, terminology, and cost models (COCOMO II and COSYSMO II). The result of the harmonizing efforts is a list of recommendations to resolve the identified gaps and overlaps. These recommendations include using requirements for the models, calibrating the data with actual/historical data to remove overlaps and gaps, documenting assumptions, leveraging COSYSMO size drivers, creating operational guidance to minimize variations in usage, and aligning phases for models using a common standard. This article has application to this research as clarity in estimating SE effort aligns to determining SE value in competitive bids. If there are gaps or overlaps with SE effort included in the bid, the result is an under or over-estimation of needed SE effort. Inaccuracy around the SE estimation drives uncertainty around the value of SE in competitive bids and the impact of SE to the success of projects.

In addition to the familiar COSYSMO model, game theory models clarify the nature of interacting decisions and distinguish between strategic choices and random variables to produce effective risk

management recommendations for allocating resources [21]. Game theory can alleviate oversimplified approaches to risk management. This article has application to this research as the relationship among the SE effort/value in competitive bids, SE in projects, risk management, and project outcome is sought for the organizations based on historical/actual data.

### *SE Effort and the Digital Engineering (DE) Transition*

With the industry and organizational transitions from traditional document-based SE to DE, SE value, effectiveness, effort, and estimation change. During the transition, SE effort (hours) is bid using models, metrics, heuristics, and actuals based on traditional SE. As DE projects execute, models and heuristics will be calibrated based on DE metrics and actuals. INCOSE and industry partners are collaborating on DE metrics and sharing the benefits of DE over traditional SE.

McDermott has published several articles on collaborative industry effort to define DE metrics. His SERC report provides a foundation for understanding DE [22]. Digital engineering is defined as an integrated digital approach that uses authoritative sources of systems' data and models as a continuum across disciplines to support lifecycle activities from concept through disposal. DoD DE strategy is defined as five strategic goals for transformation targeted to: promote the use of digital representations of systems and components and the use of digital artifacts as a technical means of communication across a diverse set of stakeholders, address a range of disciplines involved in the acquisition and procurement of national defense systems and encourage innovation in the way we build, test, field and, sustain our national defense systems, and how we train and shape the workforce to use these practices. Model-Based Systems Engineering (MBSE) is defined as a subset of DE and the formalized application of modeling to support system requirements, design, analysis, verification, and validation activities beginning in the conceptual design phase and continuing throughout the development and later life cycle phases. Digital transformation is a change process rooted in how we train and shape the workforce to use these DE processes. Two frameworks are shared linking the benefits of DE and organizational adoption of DE. Four digital transformation outcome areas (quality, velocity/agility/productivity, user experience, and

knowledge transfer) are linked to 48 DE benefit areas. Success factors linked to organization adoption of DE are categorized as organizational management, leadership, communication, measurement and data, workforce, DE processes, and environments. DE metrics, with descriptive summaries, are mapped to the digital transformation outcome areas and obstacles/enablers for DE adoption are shared. Measuring and describing the value and effectiveness of DE using these metrics is introduced with specific benefits, organizational drivers, and success metrics not yet defined. This article has application to this research as the definitions, metrics, benefits, and value of DE for the organizations needs to be understood. The impact of DE on the SE value in competitive bids and how organizations adopt DE in both competitive bids and in projects is a key element of this research. DE is a new area for the industry and metrics, benefits, and adoption concepts are evolving. This research incorporates the impact and influence of the DE transition on SE value for competitive bids.

The challenges of the DE transition are noted in a McDermott technical report [31]. As the DE transition progresses, relationships between defense acquisition community and industry change and stakeholders' perspectives on value shift. Key enablers to this transition reduce risk through better interface management, deeper collaboration, and understanding of the impact of design choices on cost and schedule. DE integrates SE, product design, development processes, project management, and related documentation to create value and reduce risk. DE is the need for technical innovation to support and to enable improved engineering processes. The key to SE is experience and the wisdom and expert judgment which accompanies experience. With DE, digital collaboration is a key enabler. Potential metrics and changes to existing SE processes with the DE transition are summarized. This technical report has application to this research with the discussion of the DE transition, including the impact of this transition on the workforce, culture, and SE value in competitive bids.

McDermott's DE research presentation [54] summarizes the initial efforts to establish DE metrics as the DoD DE strategy, vision, mission, transformation, success measure framework, and capabilities matrix concepts are explained. The survey results, used to determine DE/MBSE maturity across the industry,

indicate low maturity and management perception of greater progress in maturing DE than engineering's perception. Obstacles, enablers, and changes to accomplish the DE transition are ranked and are shared based on survey results with availability of DE processes, training, and willingness to use DE tools ranked as top three. This presentation has application to this research as initial descriptions of DE concepts, upon which SERC builds, provides foundational material for the DE transition topic and impact on existing SE value, processes, tools, and workforce/engineers.

McDermott, et.al. research into DE maturity and metrics continues modeling the DE information exchange process and uses this model to drive research priorities [53]. Organization transformation measures describe good metric traits with a focus on organization-specific metrics vs a universal set of metrics. Organizational maturity capabilities are outlined. This presentation has application to this research as the background on DE metrics development and DE transition maturity concepts are described. These concepts are relevant to the traditional SE to DE transition to be reflected in this research. An industry consortium, which includes INCOSE, published a digital engineering measurement framework [63] which includes potential measures or metrics for projects to use. Henderson, McDermott, et al [64] build on this framework by selecting and developing appropriate metrics to assess the value and benefits of MBSE and DE. This framework has application to this research through its list of potential metrics covering individual processes through organization transformation. These measures and metrics show the value of DE.

A different perspective to DE maturity is this Model-Based Capabilities Matrix (MBCM) guide [23] which provides organizations with a tool to assess the transition to DE or MBSE and to plan the development of necessary workforce capabilities to achieve a successful DE transition. This guide aligns to the DoD DE Transition strategy goals [24] allowing stakeholders to map actions to a potential customer plan. This tool is a starting point with tailoring and customization for an organization. This guide has application to this research as it provides a tool to assess and to plan a successful DE transition.

Bone et al. [30] explore the transformation of SE through the DE transition. This article defines the digital engineering vision as everything is done in models and a single source of truth (SST). The major differences between DE and traditional SE are noted as: using the SST, integrating design in models, optimizing mission effectiveness through continuous feedback from SST and trading requirements to enhance the key performance parameters (KPP). Challenges with the technical feasibility of doing everything in models is noted as: using holistic MBSE, developing a common lexicon, relating models to current (As Is) processes and fully integrating models into risk management and decision making. A DE framework (To Be) is shared with emphasis on adapting to the workforce, fluid processes, and results (not process) focus. An SE transformation roadmap for DE roll-out with modeling implementation and cross-domain integration is shared. This DE framework allows for early verification and validation by enabling authoritative data to be used through the entire lifecycle, eliminating interoperability and integration issues. DE begins with understanding the current state as well as identifying enablers and barriers to a successful transition. Three key enablers are IT infrastructure, workforce, and policy supporting models. This article has application to this research as it focuses on the DE transition and notes the key role of the workforce in enabling a successful transition. The framework and roadmap validate the challenges associated with this transition.

Agile methodology is an element of DE and efforts to apply Agile principles to SE has resulted in several artifacts. One of the more renowned Agile SE artifacts is Douglass' book on the subject [29]. The author notes that within traditional SE approaches, requirements and architecture generally contain significant errors that will require late, downstream identification, rework, and re-verification which is expensive and manifest at a time when the schedule should be wrapping up. Using models, SE can ensure data is complete, consistent, and correct before handing off to downstream engineering activities. The handoff to downstream engineering is a process, not an event. Verifiable models are required for Agile SE. Continuous integration is used to avoid late defect identification and rework. Key Performance Indices (KPI) are used to monitor engineering progress. Agile methods are about optimizing development along

two dimensions – product quality and engineering efficiency. The Agile Manifesto is tailored for SE with a focus on continuous attention to technical excellence. The primary goal of Agile SE is to develop specifications that can drive downstream engineering to create a system that meets the customer needs. The second goal of Agile SE is to enable the follow-on systems development. Requirements are organized around use cases (capability, usage, requirements, interactions). Use cases are defined as coherent operational capabilities of a system. This book has application to this research as it focuses on digital engineering concepts such as MBSE and Agile by applying Agile principles to SE. The efficiencies gained using Agile principles reduces rework through early defect identification which impacts the SE value in a competitive bid.

In summary, these references support the Quantification of SE Value RQ with the industry perspective on SE value using survey results reflected in return on investment (ROI) assessments and evidence captured as a business case. The most impactful and effective SE activities and their timing in the SE lifecycle are noted in several references by renown authors in the SE industry. The role of SE process and recommendations of ‘optimum’ values of SE effort (hours) to total project cost is detailed and is justified. Recommendations on estimating SE effort are reviewed, including the SE-focused cost model, COSYSMO. Lastly, the influence of the DE transition and its definition, scope, benefits, and impact on traditional SE value, effort, and estimation is introduced. The conclusions and recommendations of these industry and customer experts are included in the research activities to determine the value of SE for competitive bids which require, expect, or exploit DE.

### **Literature Review on the SE Value Analysis**

The literature search reviews the SE value in the competitive bid and on projects. Other performance characteristics of the projects in this analysis include project performance to the cost/schedule/technical baselines, risk, and defect profiles. Analysis includes reviewing SE leading indicators as ‘predictors’ of project problems and negative performance. The goal is to provide justification for SE effort to competitive bids teams based on historical SE effort and project results. The references supporting RQ2

explore industry-endorsed SE leading indicators and articles with evidence of SE value from renown authors including Elm, Honour, and Valerdi. The approach to and behavior towards the competitive bidding process is explored using game theory. As the DE transition progresses, the impact upon the determination of SE value, including MBSE, is explored including input from customer communities.

### *SE Leading Indicators*

Valerdi and Roedler [33] introduce thirteen leading indicators to measure technical effectiveness. A leading indicator is a measure of evaluating the effectiveness of a specific activity against a performance objective. One of the objectives for the leading indicators is to identify information needs underlying the application of SE effectiveness. Leading indicators differ from existing measures in how the information is gathered, evaluated, interpreted, and used to provide a forward-looking perspective. The value of the leading indicator lies in the insight that is provided. Using a leading indicator as a stand-alone data point is not advised. Indicators are more informative when used together in decision making and are a measure of whether an organization is doing the right things in terms of SE. For each indicator, the insight, challenges, validation, and usefulness are provided. This article relates to this research as these leading indicators have application relative to the project allocation of SE resources optimally.

Building upon these thirteen leading indicators, INCOSE provides a SE leading indicators guide [13] for evaluating the ‘goodness’ of SE on a project. Indicators can be used to assess SE effectiveness on a project. Understanding the indicators enables project leadership to adjust positive impact objectives. Leading indicators differ from traditional SE measures as they predict future behavior vs reviewing historical actuals. The leading indicators are listed with insight to be gained and applicable phases or stages of lifecycle. SE leading indicators include risk handling trend, risk exposure trend, process compliance trend, change request backlog, work product approval trend, staffing and skill level trend, and technical measures (Measures of Effectiveness, Measures of Performance). This guide has application to this research as the SE leading indicators could be useful as predictors of SE effectiveness in projects. If data exists, the leading indicators could be reviewed with recommended adjustments as part of the

balanced scorecard. These indicators are included in a metrics review completed as part of this research. The article includes an early identification of SE-related project risks. Critical success factors are mapped to each leading indicator and SE project risks. These factors could be useful as this research correlates project risk to project performance as unaddressed risk could lead to serious budget and schedule overruns.

Gilbert et al. [35] explore whether SE technical metrics provide enough information to alert SE leadership to problematic projects. Projects are reviewed, interviews are conducted, and results indicate that it is not possible to judge the health of an SE project only by reviewing technical metrics. The use of dynamic, shared, social, and technical system architectures would reduce the potential that issues of hierarchy or assumptions of colleague's contextual perspective allow problems to develop, grow, and remain undetected. This paper has application to this research as it presents a research approach related to SE metrics and explores leading indicators to predict problem projects, such as risk handling, process compliance, and change tasks.

### *Evidence of SE Value*

In addition to the value of SE leading indicators to mitigate risk to a project, evidence of the SE value to competitive bid teams is noted by revisiting the concepts of SE business case, ROI, and cost estimation models.

Elm has several articles focused on a business case for SE as introduced for RQ1 (Quantification of SE Value) in this literature search. Elm collaborated with Rassa [2] on an article using the results of an SE industry survey to provide evidence of SE activities impacting project performance. The categories of SE activities with the strongest relationships to project success begin early in the project and influence the approach to the organization of the project: product architecture, trade studies, requirements development, requirements management, and IPT utilization. These results provide a strong incentive for early

application of SE on a project. This article has application to this research as it uses survey results to provide evidence of SE value to project success with a focus on early SE activities.

Elm [3] builds upon his prior articles using the results of SE industry survey to provide quantitative evidence of the impact of SE on project performance. Over 200 usable survey responses give confidence in the conclusions drawn. Assertions about SE processes, positive or negative, are difficult to prove. The challenges of quantifying the value of SE are outlined including the inclusion of SE costs making bids non-competitive. This article has application to this research as it uses survey results to provide evidence of SE value to project success with a focus on early SE activities and a description of the challenges in valuing SE, especially in competitive bids.

Elm and Goldenson [52] share the detailed responses from the surveys which provided data and evidence for the SE business case by the authors. This paper has application to this research as an example of survey questions and detail into the results which supports the SE Business Case.

As Elm is known for his work on the SE business case with several articles, Honour is known for his work on SE ROI with several articles. This article [5] presents statistically proven relationships between SE activities and the technical, cost, and schedule success of the project. All defined SE activities positively correlate with project success. The lack of correlation between SE activities and the technical quality of the product system is noted. SE effort is optimized at about 15% and cost/schedule over runs appear to be minimized. Data is obtained through structured interviews and is grouped into three categories: project success, SE effort, and project characterization. Normalized SE effort is the product of the SE quality and SE cost over actual project cost. SE quality is a subjective assessment of interviewees. Technical quality is measured as compliance with Key Performance Parameters (KPP) that matter to stakeholders. Projects place primary emphasis on minimum requirements compliance. Threats to the validity of these results is explored. Optimum values for each of the eight defined SE activities is listed (slightly different from reference [51] and including implementation not integration [51]):

- Mission/Purpose Definition = 1%,
- Requirements Engineering = 2.5%,
- System Architecting = 2.5%,
- System Implementation = 3%,
- Verification and Validation = 7%,
- Technical Analysis = 4%,
- Scope Management = 1%,
- Technical Management = 4%,
- Total SE = 25%.

The most successful projects as measured by cost and schedule compliance expend 15 – 20% on SE. A total SE effort of 25% of the project hours exceeds the 15% recommendation proposed by other articles. This article has application to this research as it is an early publication using interviews and subjective responses to determine a recommended SE effort. It is noted that research is based on real projects for which data can be proprietary and difficult to obtain. The difference between [51] and this article [5] should be understood and the use of implementation vs integration is noted. From an organization perspective, explore threats to validity – divergent SE definitions, reporting, lifecycles, technical scope, use of traditional SE, and hand-selected project interviews/responses – for application within an organization.

In addition to the SE ROI concept, Honour offers research on optimizing the value of SE [36]. This early work measures SE value directly in terms of perceived value: system technical quality, risk avoidance, and problem discovery. System technical quality is measured against the need which the product fulfills as the objective function of the product. Stakeholders must concur on the objective function.

Requirements are not a good measure of system technical quality due to their derived nature. Risk avoidance is measured as the difference between the greatest potential project cost and the eventual final cost using the quantitative risk measurement of cost impact and probability of occurrence (Net Factored Risk). Problem discovery is the quantification of the cost avoidance with sidestepping problems.

Problems are risks which have already occurred. Project cost avoided is a result of re-planning

(requirements refining, schedule relief, technical innovation). Re-planning cost measures both problem discovery and problem resolution. This paper has application to this research as an early foundational work which attempted to measure SE value on projects by capturing a quality measure, net factored risks, and re-planning costs. While the concept of measuring SE value has evolved, there is merit in understanding these early measures.

Other authors and research into the evidence of SE value offer various perspectives. One example of another perspective [4] presents a different set of data from six space industry-related projects to answer the question of SE value and impact on project performance. This complements the Elm and Honour studies and industry survey results with similar conclusions: clear positive correlation between SE effort applied and project result. An inherent problem with research into the effectiveness of SE is that nobody ever performed two identical projects - one with and one without SE. The survey and checklist used to gather data is reviewed with the total score of a project simply calculated by counting the number of SE tasks performed and dividing by the total number of tasks performed. The character, size, and complexity of the projects are also considered when formulating the answer. The project success criteria is summarized, and the evaluation of the results are plotted with the percentage of SE to project results. The trend line and slope are a measure of the correlation. Projects are performance-driven (cost, schedule) with technical results 'always good' at the expense of cost and schedule. The project result benefits most from SE effort related to requirements, design development, and technical management. Increasing SE effort contributes most to cost and schedule and not as much impact on technical quality as projects are performance-driven. Verification-related SE effort does not change the project result much. This article has application to this research as it provides another source of data and analysis to the SE effort and ROI studies of Elm and Honour. The conclusions of this research will include the results of Elm and Honour as a more holistic industry perspective against which to compare SE effort and project results.

Valerdi [8] offers another perspective on the evidence of SE value and effort using heuristics in SE cost estimation. Heuristics which align to SE cost estimation and the COSYSMO model are shared. These

heuristics have been proven to be resilient across multiple scenarios over years and can be used for quick estimates or judgments. This article has application to this research as several heuristics relate to data collection, data analysis, and interpreting data analysis.

Browning and Honour [34] measure the Lifecycle Value (LCV) of a system and encourage systems engineers to keep LCV in mind when designing systems. SE system designers must consider how to meet specifications that satisfy stakeholders today and with technologies that satisfy stakeholders in the future as needs evolve. LCV can be determined using key parameters that change across stakeholders and over time. Examples of key parameters are shared. There is risk to determining an LCV and designing the ‘right’ amount of adaptability into the system. This paper has application to this research as the relationship of SE to LCV for a system should be understood as part of the competitive bid process. Evidence of the value of SE justifies its inclusion in LCV.

### *Competitive Bids*

Building on the evidence of SE value, this literature search expands to the nature of and behavior in competitive bids by considering game theory research. Hauksen [20] explores the basic connection of Probabilistic Risk Analysis (PRA) and game theory, different games, and approaches: series, parallel, summation systems with coordination, battle of sexes, chicken, and prisoner dilemma. Risk is affected by behavioral, technological, and natural factors, each controllable to a different extent. Game theory is a natural tool to analyze individual and collective conflicts that affect risk. This article has application to this research as game theory explores risk and competitive bids.

Ahmed et al. [15] focus on a game theory application to competitive bidding. Game theory is defined as “the study of mathematical models of conflict and cooperation between intelligent rational decision-makers”, information completeness and the way in which games are played. Adverse selection is defined as when the winner of contract has underestimated the project’s true cost. The winner’s curse is the winning bidder submits an underestimated bid and is thus cursed by being selected to undertake the

project. Reasons why the winner's curse happens: inaccurate estimates of project cost, new contractors entering the market, strong competition, differential opportunity costs, and remedy the losses through change orders. Using a game theory approach, this article aims to analyze—and potentially reduce—industry exposure to the effects of the winner's curse in construction bidding. The authors explore how learning from past bidding decisions and experiences can mitigate suffering from the winner's curse. In static games, players make decisions and take actions simultaneously without knowing the decisions chosen by other players. In dynamic games, players make decisions and take actions sequentially with the observation of other players' actions. In cooperative game theory, players cooperate to get more benefits for each and allocate the gains fairly between them. In noncooperative game theory, each player selects a strategy independently and tries to maximize the payoff, with no collusion between the players. Game theoretic models shall bar noncooperative with static moves and incomplete information. A winner is the one having the most pertinent information to true value. When an experience-based bidding model is implemented, less overall losses result. This game theory application is related to this research as game theory explores competitive bids and influences on the winning bid. The experience-based bidding model applies to an organization competitively bidding.

Ho and Hsu [16] apply game theoretic analysis to strategic interactions among project bidders. Large-scale complex project customers have been searching for ways to encourage competitive bidders to invest more effort in project planning and design during the bid process. There are strong and regular bidders with each competition and bidders know the identity of strong bidders. Offering compensation to unsuccessful bidders is one way to encourage this investment. The number of strong bidders in a competition determines planning and design effort invested. The Nash equilibrium is applied to this compensation game. Nash equilibrium is a set of strategies, each of which determines the optimal response by each player, given other players' strategies in the equilibrium. The first step is to conceptualize the problem under study and to develop a game model for the problem. The second step is to solve for the equilibrium solutions of the game model. The third step is to identify possible contextual

variables and then to derive strategy implications. The result is: with two or more strong bidders, compensation is not necessary as the investments are organically made. If there is only one strong bidder, compensation should be considered. This paper has application to this research as game theory explores competitive bids and the situation when investment in the project planning and design during competition is a worthwhile organizational investment.

Engelbrecht-Wiggins and Katok [17] apply game theoretic analysis to strategic interactions among project bidders. With sealed bids, “over bidding” occurs due to risk aversion, social comparisons, learning, and regret. Learning based on bidding experience replaces the propensity to increase a bid estimate with the propensity to balance it. The specific impulse balance point depends on the relative strength of those propensities. A bid winner who pays more than the next highest competitor’s bid is said to have ‘Money left on table – MLOT’. The bid winner sometimes wins at a price higher than the value for the item and the item is won at an unfavorable price (WAUP). In either case, the winner may regret having bid so high. A bid loser has a missed opportunity to win (MOTW) and may regret bidding so low. Sensitivity to MOTW regret generally increases bids while sensitivity to winning and paying too much generally decreases them. This paper has application to this research as game theory explores competitive bids and the role of risk and regret in the competitive bidding process.

Milgrom and Weber [18] explore the relationship between auction theory and traditional competitive theory. When bidders are assumed to behave competitively, the auction is treated as a non-cooperative game. When bidders are uncertain (risk adverse) about their value estimates, the auction generally leads to larger expected prices. Typically, competitive bidders are risk averse. This paper has application to this research as game theory explores auctions and competitive bids theory.

Laffont [19] reviews types of bidder uncertainty: uncertainty about the value of the object auctioned, strategic uncertainty relative to competitors’ strategies, and uncertainty of competitors’ characteristics

(probability distributions). Game theory is necessary to formulate a consistent equilibrium model of bidding behavior. This paper has application to this research as game theory explores bidder uncertainty.

Game theory, risk, and bidder uncertainty impact the overall competitive bid strategy. Determining the value, including SE value, of a competitive bid involves assessing competition. Within the space industry, recent disruptors such as SpaceX and Blue Origin, are influencing competitive bid strategy. Reddy [37] reviews the impact of SpaceX on launch services as new pricing competition has been unleashed by SpaceX's reusable launch vehicles for low-cost access to space. SpaceX is a disruptor to the space industry as it has been guided by innovation and bold risks. Elon Musk, Space X founder, believes that robust engineering practices and a simplified business model enable Space X to reduce the turnaround time and refurbishment cost of its launch vehicles. The company makes it an economic principle to adopt flight proven hardware and commonality in design to reduce risk and expedite development of new launch vehicles. It manufactures most of the components in-house to ensure timely delivery and keep the cost of production low. Other launch service providers have touted reliability against SpaceX's low cost in competition. This paper has application to this research as insight into a new, disruptive competitor in the space industry. Understanding the risk posture of a competitor could influence the competitive bid response, according to game theory.

#### *DE Impact on SE Value in Competitive Bids*

The evidence of SE value and the uncertainty of competitive bids is complicated by the impact of the DE transition. Traditional SE value, as determined by metrics and project actuals, must be transformed as projects transition to DE with updated SE processes, new metrics, and a workforce adapting to this change.

Zimmerman et al. [24] explain digital engineering and the transformation strategy within the DoD. DE is defined as an integrated digital approach that uses authoritative sources of systems' data and models as a continuum across disciplines to support lifecycle activities from concept through disposal. DE efforts are

implemented across industries to drive affordability, agility, quality, and efficiency. The five strategic goals to support this transition are described along with models, big data, and analytics. The Modular Open Systems Approach (MOSA) is critical to ensuring the infrastructure can adapt to innovative changes while remaining cost effective in an environment of change. DE processes define ‘what’ tasks need to be completed, methods define ‘how’ tasks are performed, and tools provide the ‘means’ to implement process and methods. Digital thread is defined as organization-level analytical framework that expedites the controlled interplay of authoritative technical data, software, information, and knowledge. Digital twin is a simulation of the as-built system, enabled by the digital thread, to mirror and to predict physical system performance. Understanding the data environment, sources, data stores, and management processes is a first step to any DE endeavor. An objective of DE is to compress the system development lifecycle. A case study example of the transition from legacy SE to MBSE provided a 18% reduction in touch labor required for interface baseline management process. DE expectations and benefits are summarized. This paper has application to this research as the DoD is transitioning to DE and outlining goals, expectations, and benefits.

With the DoD transitioning to DE, the competency of the workforce with the new DE processes and tools should be assessed to understand the risk to project success. A competency framework [38] provides guidance to the DoD acquisition community on the knowledge, skills, abilities, and behaviors required for DE professionals. The goals, methods, approaches, and preliminary results of research to develop a DE Competency Framework is described. DE updates the traditional SE practices to take advantage of the digital power of consumption, visualization, and communication with faster actions throughout the lifecycle. As the DoD transitions to DE, there is a need to develop and to maintain the acquisition workforce and culture that is literate in MBSE, DE models, tools, and methods with an understanding of DE artifacts across the lifecycle. Use cases and validation of the framework is summarized. This paper has application to this research as insight into the goals and measures which the DoD acquisition

community is using to evaluate DE competency. As a customer community which engages in the bidding process, these goals and measures should be understood and addressed in competitive bids.

The workforce competency is only one element of an organization impacted by transition. Karlsson [41] examines the capability of organizations with decentralized, project-focused life cycle processes and fragmented systems perspectives to manage complex systems. A toolkit of eighteen mechanisms supports the transformation from problem to solution and to improve an organization's SE capability. Problems are analyzed from problem, solution, and transformation perspectives. The transformation perspective considers the organizational context-aware process of bringing about the necessary change to go from the problem towards the solution space. This paper has application to this research as insight into a DE transformation using transformation perspective.

As organizational change is influenced by the DE transition, a strategy to enable an organization to implement DE should be developed. Detail on organization implementation (Organization SE) [39] of the DoD DE strategy includes roles and responsibilities in connecting the information sources. A transition to DE is expected to improve the management and exchange of exponentially growing sources of information, data, and knowledge spanning an organization. DE is a fundamental enabler for 'Organization SE' interconnecting people, process, and technologies. 'Organization SE' includes cross-project, cross-mission analysis, and decision-making within the organization. The organization should develop processes and methods that focus on interoperability and achieving a broad spectrum of needs across the organization, reducing the need for tailoring by projects. The organization can share common modeling language constructs and patterns, reusable model libraries, scripts, templates, and organizational principles. Digital models are used to answer questions, reason about solutions, support decisions, manage risks and opportunities, and communicate clearly. A standardized means of capturing information at the organization-level enables federation of information at every level of the organization. Policies governing models allow for reuse while protecting information. Transforming the culture to support DE involves training and tools strategies. This paper has application to this research as it

addresses DE from an organizational perspective. For competitive bids, DE is required or a discriminator. It enables an organization to answer to question: ‘Is this organization ready to execute within DE?’.

DE transformation is more than new tools and infrastructure [40] and requires a comprehensive change that involves people, process, technology, organizational strategy, and stakeholder commitment. The author shares a vision of using DE as an enabler to transform legacy, document-based development stovepipes into a product-centric, integrated DE organization. Business drivers and challenges for this transition are summarized. Key DE benefits are noted as cost reduction, cycle time reduction, improved systems integration, knowledge transfer, and empowered teams. Challenges include stakeholder buy-in, culture, expertise, and misconceptions. The goals of the multi-year transformation are shared and include the development of strategy and business cases to support the required investment budget. This paper has application to this research as insight into a DE transformation journey which includes DE benefits, lessons learned, and challenges.

MBSE, a key element of DE, impacts SE effort as traditional SE becomes less used. With this change, the value of SE effort is analyzed in terms of MBSE’s challenges, gains, and cost drivers [42].

Limitations of traditional SE, benefits of MBSE, and an economic analysis of both SE and MBSE are reviewed. Traditional SE cost curve and an MBSE cost curve are illustrated. For MBSE cost curve, costs are greater in the conceptual and preliminary design phase for tools, infrastructure, and training with substantial cost savings during the latter stages of design with reduced defects later in the lifecycle. The Net Present Value of both traditional SE and MBSE are comparable, and the results are inconclusive as to which is the preferred option, necessitating additional analysis on MBSE investment and gains/benefits [42]. Factors related to MBSE investment are categorized as process definition cost, infrastructure cost, training cost, and model-related costs. Benefits include identification of defects early in the system lifecycle, risk reduction, simpler change management, reduced feedback loops, increased communication efficiency, reduced rework and design iterations, data, and knowledge sharing. This paper has application

to this research as a comparison of traditional SE and MBSE cost curves, cost factors, and gains/benefits for both approaches. This comparison supports determination of the SE value in competitive bids.

In summary, these references support this RQ (SE Value Analysis) with the industry perspective on SE value reflected in evolved business case development and optimum SE effort recommendations. In analyzing the organizational data collected, insight into increasing the likelihood of successful project performance is sought by exploring historical data and understanding indicators of project problems. Game theory and competitive bid behavior provide a non-SE perspective to bid strategies. This section concludes with the DE transition and a customer perspective on enabling a successful transition and assessing the workforce DE competency during this transition. This customer perspective emphasizes the expectations of DE and the importance of ensuring a successful organizational DE transition.

### **Literature Review on Effectively Communicating Value**

The literature search reviews options to effectively communicate the analysis results of this research to organization decision-makers responsible for determining SE value in competitive bids. The communication tool is to be a holistic SE-centric framework to optimize SE bids considering quantitative and qualitative perspectives. The references supporting this RQ describe options for communicating potential elements of this framework, such as data-driven evidence for quantitative inputs and a balanced scorecard for qualitative inputs. Insight into the DE expectations and tools from a customer community is explored. The customer evaluates the competitive bids, and their perspective will influence the SE value determination for the bid. Lastly, organizational psychology and systems thinking references provide insight into empowering the workforce during this DE transition.

#### *Communicate SE Value*

The balanced scorecard is an analysis and communication tool used within business circles. Haskins [43] presents this traditional business tool in the SE context. The balanced scorecard is a holistic approach to evaluating the performance of organizations by integrating performance measurements. Using the

diverse business concerns of quality, cost, and customer satisfaction, future performance is assessed, and corrective actions are determined. The balanced scorecard supplements traditional financial measures by assessing how effectively an organization can change process, introduce new technology, and adapt to change. The scorecard is built on four processes connected to short- and long-term actions. One of the strengths of balanced scorecard is the strong cause and effect link. The scorecard helps communication and reduces information overload by limiting the number of measures used. This tool brings together elements which might not be considered or viewed holistically. Establishing the balanced scorecard starts with setting strategic goals and measures the progress towards these goals. All processes should be part of a system with feedback loops and the scorecard helps to drive this feedback. A simple SE balanced scorecard example is shared with leading and lagging indicators as strategic measurements against four strategic objectives. This paper has application to this research as this tool could be used to communicate qualitative factors to the bid team. Balanced scorecard could also be used to capture the DE transition progress across an organization.

Another way to communicate SE value is in terms of process and deliverables. Browning [44] addresses value and how the product development process can impact value. Value is driven by activities and inputs to these activities. The lack of value is influenced by unnecessary activities and necessary activities with incorrect inputs. The product development process (sequencing and coordination of activities) has a large impact on value, regardless of the value of the activities and deliverables themselves. Getting the right deliverables to the right place at the right time is important to adding value. Value can be improved by increasing benefits or decreasing cost. The purpose of product development activities is to produce information that increases the certainty of the ability of the design to meet requirements. This paper has application to this research as it defines value for product development and can be used to communicate the value of SE in terms of these value definitions.

Noting traditional SE is process and procedure driven, Kenett [50] suggests value and benefits by adopting a data-driven and evidence-based SE approach to enable better decision-making. Considerations

for an enhanced data-driven SE approach is to: provide diverse data and viewpoints, develop greater business understanding, deal with uncertainty, and recognize the importance of high-quality data. A maturity ladder for this SE change starts with random demands for reports and progresses with descriptive statistics, process focus, quality by design, learning, and discovery. Design reviews should focus on reviewing engineering decisions based on data, modeling, and simulations. This paper has application to this research as it focuses data-driven and evidence-based SE decisions. This stresses the importance of data in SE decisions which can be extended to the SE value in competitive bids.

### *Customer Insight into DE*

As the Department of Defense (DoD) transitions to DE, customer insights into expected SE value and benefits from this transition and tools to enable this transition are outlined by Baldwin [45]. This paper reviews three DoD initiatives: DE, Engineered Resilient Systems (ERS) and Modular Open Systems Approach (MOSA). ERS digitally synthesizes advanced engineering techniques with high performance computing to provide data that can enable strategic and operational decisions. MOSA provides design implementation that enables the sharing of modular components, re-configurability of system design functions, standards-based design, and rapid delivery of advanced technology. MOSA involves designing systems with highly cohesive, loosely coupled, and severable modules. This paper has application to this research as it introduces two other transformative initiatives of the DoD – ERS and MOSA. This dissertation focuses on DE and awareness of these other two initiatives is beneficial as it provides insight into the DoD implementation of DE.

DE is outlined in several articles noted in RQ2. The second initiative outlined by Baldwin [45] is ERS. Post [46] expands on ERS relating DoD concerns with the current acquisition process and system development. Although successful in the past, the methods of ‘design, build, test, repeat’ increase acquisition time and cannot keep up with the increasing complexity of modern weapons systems. This results in late discovery of design flaws, immature technology issues, and system integration problems leading to costly rework and redesign contributing to cost overruns, schedule delays, and technical

performance shortfalls. CREATE is the Computational Research and Engineering Acquisition Tools and Environments project which uses physics-based engineering software tools to ‘model, analyze, build’ reducing design flaws, costs, and schedules. These methods can be used by projects to optimize engineering designs early in the acquisition process using CREATE tools. This paper has application to this research as it focuses on a DoD acquisition community initiative, ERS, and its CREATE tools. The use of these tools by the DoD acquisition community, which releases competitive requests for proposals, emphasizes the criticality of a successful DE transition for an organization.

The third initiative outlined by Baldwin [45] is MOSA. Zimmerman [47] provides an overview for MOSA which allows the DoD to flexibly acquire full capabilities and individual components allowing for technology advances from independent vendors. The acquisition community must design systems that can be incrementally developed, are interoperable, and provide for competitiveness of system elements. Acquisition projects using MOSA have achieved a degree of modernization, cost savings, and interoperability. The use of standards is foundational for MOSA. Standardization and modularization at interfaces enable ease of integration of components in a cost-effective manner. MOSA is an integrated business technical strategy for competitive and affordable acquisition and sustainment of a new or legacy system over the system lifecycle. MOSA flexibility enables rapid and effective technical upgrade of systems and leads to the delivery of new capabilities or replacement technology. This paper has application to this research as it focuses on a DoD transformation initiative, MOSA, and its advantages for the acquisition community. The outcomes of using MOSA include capability to keep pace with technology refresh, ability to address affordability constraints, increased variety through competition, mission flexibility, security through innovation, improved production time, and enhanced capability development through interoperability. The organization should be aware of these expected outcomes and include them in competitive bids and implement on projects through a successful DE transition.

Expanding on the DoD’s ERS and MOSA, digital twin is another key concept of DE. Kusel [48] describes digital twins enabling interconnected data analysis of as-built assets throughout the lifecycle of

the asset. Digital twins are dynamic, virtual data models of real-world assets that aggregate all information on the asset and provide continuous feedback via a single dashboard. Digital twins create value by enabling owners to better understand, predict, and optimize the performance of assets, to reduce operational cost, and to ensure a better end-user experience. This article has application to this research as it focuses the advantages and value of digital twins, an element of DE.

Building on digital twins, MBSE is a key enabler for DE and Papke et al. [49] communicate the value and challenges of MBSE adoption to the internal customers within an organization. This article acknowledges the challenges of MBSE adoption within organizations and notes this adoption should have an organizational approach by presenting the DE environment as a system-of-systems. The authors do not believe MBSE changes basic system engineering processes, but it can significantly affect how systems engineers perform design and development activities. DE bridges the business processes across all functional disciplines. Successful MBSE adoption effort must address organization-level challenges. When implemented, the resulting DE organization displays all the characteristics of a System of Systems (SoS). MBSE adoption and the associated challenges must be addressed through the application of a structured SE approach. MBSE adoption affects business and engineering organizations, not just SE practices. A strategic view recommends a time-phased approach for achieving DE objectives. An operational view recommends describing how an organization will apply the DE SE processes. Engineering processes are not a concept of operations (ConOp); they are a concept of employment (ConEmp) and how to use the system as implemented. Implementing an MBSE environment is not the automation of a document-based environment. This article has application to this research as it focuses the challenges of MBSE and DE. The authors' claim that MBSE does not change basic SE processes, but do not detail 'basic' SE processes. Updated SE process or new processes will be created as part of the DE transition. The statement – 'MBSE adoption and the associated challenges must be addressed through the application of a structured SE approach' – aligns with an INCOSE conference paper (Appendix and [65]) – and the systems thinking approach to a successful DE transition.

### *Empowering Engineers in the DE Transition*

The organizational DE transition impacts established SE processes, tools, and practices which the engineers know well and have confidence in using. A successful transition requires organizational commitment. One organizational problem is the attitude and commitment of engineers to this transition. The symptoms of the organizational problem include resistance and reluctance towards this organizational change of the DE transition. Evidence of resistance and reluctance to make this change is manifest in minimal progress in the transition and in stress induced by this change. The engineers have not demonstrated behaviors which embrace the tools, processes, and practices of DE. Instead, they have relied on and continue to use trusted and proven traditional document-based systems engineering (TDSE) tools, processes, and practices. The engineers resist estimating DE cost during competitive bids or collecting DE metrics. They are reluctant to assess the return on investment of new DE tools, processes, and practices and to develop new processes and practices using these tools. Given most change initiatives fail [56], there is a negative relationship of resistance, stress, and negative attitudes towards change. There is a positive relationship between an employee's organizational commitment and willingness to accept change, if perceived as beneficial [61]. These articles have application to this research as enhancing the organizational commitment among engineers contributes to a successful organization DE transition.

Erwin [55] explores the organizational psychology concept of resistance to change from multiple perspectives including cognitive/affective dimensions of resistance, personality influences on resistance, and key concerns expressed at the announcement of change. The study focuses on the organizational change process and its influence on the resistance to change. Relevance to this research includes how resistance is influenced by the perceived negative impact to job security, power, and intrinsic rewards. The communication of the change influences the engineers' level of participation in the change and the goals of the change. There is a positive association with the ability to participate, involvement in decision-making, and the acceptance of the change. This article has application to this research as the

understanding and insight this study provides should directly influence an organizational DE transition with actions on communication and employee involvement with the change.

Vakola's [61] organizational psychology study explores resistance to organizational change. Related to this research, engineers' attitude of resistance and reluctance to demonstrating behaviors supporting the DE transition are symptoms of the DE transition problem. Engineers have spent their careers developing a level of competence and expertise in TDSE. This change negatively impacts this competence and expertise as it requires the entire engineering team from junior engineers to experts to start over in developing new competence, expertise, and skills in DE. The junior engineers may have an advantage over the senior engineers as their competence and confidence level in DE tools is likely to be greater than experienced senior engineers. The senior engineers' discrepancy of confidence and competence in a DE environment is likely associated with uncertainty and a decrease in job satisfaction. Senior engineers are viewed as technical experts and the new tools and processes of DE threaten this expertise. These senior engineers should be demonstrating organizational commitment through behaviors to initiate this transition, but stressors and experiences of strain have a negative correlation to the positive attitude of organizational commitment [61]. This article has application to this research as the understanding the engineers' resistance to organizational change allows actions to be developed to enable a successful organization DE transition.

Oreg [59] reviews organizational psychology studies relating three variables (personality, content, and resistance) to employee attitudes toward organizational change. The outcome of the change on role influences the employee attitudes and resistance to change. The study includes multiple dimensions of resistance and variables. Two findings are relative to this research. The first is the nonlinear relationship of information about the change and resistance. Not enough or too much information has a negative relationship as too much or too little information increases employee resistance and job uncertainty. The second is resistance negatively correlated with job satisfaction attributed to the stress and uncertainty

related to the change. This article has application to this research as these two findings are integrated into the proposed actions to enable a successful DE transition within the organization.

Kram and Hall [57] share organizational psychology study results which indicate a positive relationship between attitude toward mentoring and stress. The responses also note employees in early career and late career are more inclined toward mentoring as mid-career employees focus on career development. Job redesign to enable mentoring between these two employee demographics can be considered. Satisfaction with coworkers and support during transition is a direct influence on job satisfaction, organizational commitment, and change. Study results detail resources which can be employed during the intervention to enhance positive attitudes towards the change and to enable the employees' increased social support and learning associated with the change. The organization can encourage relationship building, including mentoring, and positively recognize it to reduce the stress of the change. The demographic of employees to whom mentoring appeals may be the directly applicable to the problem as senior engineers value technical expertise status and junior engineers seek organizational culture and norms guidance. These employees may be threatened and stressed by the change and mentoring, including reverse mentoring, is useful in the development of the intervention. This article has application to this research as the implementation of a targeted mentoring project and social supports enable a successful organizational DE transition.

During mentoring, technical expertise is shared by senior engineers as junior engineers learn the organization's culture and norms. Reed & Vakola [60] explore learning during organizational change and note the general defensive attitudes towards the change-associated learning. This attitude is influenced by the perception that something was done incorrectly, or the change would not be happening. This perception elicits resistance and a learning anxiety which becomes a restraining force. Recognizing the impact of learning during organizational change is one key to success. Findings expand learning opportunities beyond courses and include participation in change steering/transition committees. These committees focus on the change process and the evaluation of the organization's culture. Resistance is

influenced with the engagement and empowerment of the organization in these training activities and demonstrated through pilots. These findings are relevant to this research as actions to decrease resistance are offered while acknowledging the challenges which culture may present during organizational change. Resistance to the change is decreased through participation in steering/transition committees, continual evaluation of progress and training, and the focus on the process of change with the ability to customize the process. With the goal of decreasing the engineers' resistance to the DE transition, these findings are integrated into recommended actions to enable a successful organizational DE transition.

For this research, the role of engineers in a DE transition is explored from a systems thinking perspective. A review of engineers' patterns of behavior relative to this DE transition shows the goal-seeking behaviors influence the diagnosis of this complex problem. Goal-seeking or stability-seeking behaviors drive to a known stable state within a range of values. The engineers have not demonstrated a sufficient level of productive behaviors to enable a successful transition from traditional document-based systems engineering (TDSE) to DE, despite leadership's direction to transition. Behaviors have not demonstrated an openness to trying or embracing DE. After the initial and limited positive attitudes of the engineers, goal-seek behaviors are demonstrated as engineers revert to trusted TDSE (stability) from attempts at DE (change). Meadows [58] notes goal-seeking is a regulating or balanced feedback loop which opposes whatever direction of change is imposed on the system. The engineers are demonstrating goal-seek behaviors as they resist the change to DE. Lack of clear communication and DE training from the organization drive engineers' behavior to return to TDSE, even if DE is explored initially. DE transition negatively impacts competence and expertise as it requires the engineering team to develop new DE competence, expertise, and skills (new mental model). Engineers' attitudes reflect they are not part of this DE transition, but it is happening to them. This article has application to this research as a system thinking approach to understanding engineers' mental model and behavior drives an action plan to enable a successful DE transition.

In summary, these references support RQ3 (Effectively Communicating SE Value) with the multiple diverse perspectives on communicating the value of SE and on enabling a successful DE transition. Using a well-known business tool to communicate the qualitative benefits of SE supplements the numerous references providing quantitative evidence of SE value to project performance (RQ1, RQ2). Including multiple perspectives on communicating value in the SE-centric framework provides organizational decision-makers with enhanced understanding. As SE value in the DE transition continues to evolve, the expected benefits of DE are dependent upon the competency of the workforce. Empowering the engineers in this DE transition increases the chances of realizing these benefits. Using organizational psychology and systems thinking concepts, the organizational commitment of the workforce is increased and the uncertainty with DE is reduced, which enables a successful DE transition.

### **Literature Review Summary – Key SE Value Highlights**

Key SE Value highlights were extracted from the literature review and summarized here as a resource for competitive bids teams as SE Value is estimated over the proposed project lifecycle. Study results correlate SE value in risk reduction and contribution to successful project execution. Specific SE activities are highlighted for contribution and the importance of an experienced SE team is noted. Highlights are organized by RQ and map to the literature review section. For each highlight or collection of highlights, the specific reference [xx] is included at the end of the highlight(s) for credit and if additional detail or context is warranted.

#### *RQ1 – Quantifying SE Value*

Combining these study results and limitations, conclusions can be made from the data: SE effort improves development quality, optimum SE effort is 15-20%, quality of SE effort matters. [11]

Greater funds in project definition results in significantly less cost overruns during project development.

[11]

Good processes do not necessarily create a good project. High performing teams did more boundary management/SE management tasks vs low performing teams. Technical leadership is more important than the processes used. Technical process definition is important but not sufficient. [11]

Use of more rigorous SE practices significantly reduced overall development time. [11]

Use of SE processes improves project productivity when effectively combined with the project management and test processes. [11]

Using the data collected through industry surveys to quantify the ROI of SE, an optimum percentage of SE activities to project costs with the following:

Mission/Purpose Definition = .8%,

Requirements Engineering = 2.2%,

System Architecting = 1.3%,

System Integration = 2.3%,

Verification and Validation = 3.7%,

Technical Analysis = 2%,

Scope Management = .5%,

Technical Management = 2.7%,

Total SE = 15.5%. [51]

The ‘thoroughness’ of SE is measured by architecture definition (including operational concept, requirements, and plans) and risk resolution (identified and managed). The analysis showed a relationship between architecture definition, risk resolution, and reducing software rework: 20% of defects accounted for 80% of rework costs and these 20% were primarily due to inadequate architecture definition and risk resolution. [10]

The ‘sweet spot’ for the percentage of schedule time for the SE effort associated with architecture definition and risk resolution is about 10% for very small projects to 37% for very large projects. These

results quantify the value of SE and its impact on project success by answering the question ‘how much SE is enough?’ [10]

The results of the survey indicate the strength of the relationship of ‘early lifecycle’ SE processes (requirements and technical solution management, architecture, trade studies, and SE team capability) to project performance with project challenge as the control variable. For projects with high challenge, higher overall SE capabilities, especially early SE activities, are almost 50% more likely to achieve better project performance. [1]

Survey data shows projects with better SE capabilities have an increased likelihood of delivering better project performance as measured by budget, schedule, and requirements satisfaction. The SE activities which begin early in the project and influence the approach to developing the technical solution have the strongest relationship/greatest impact on project success. [1]

The categories of SE activities, project planning, requirements development and management, verification, and product architecture have the strongest relationship to project success. Contributions of SE to project success are even stronger for challenging projects. [25]

In most organizations, the goal of applying SE is to provide a better system in less time and cost, with less risk. Evidence of the effectiveness of SE can often be difficult to obtain due to the challenges involved in isolating the effects of SE from other processes and the proprietary limitations of publications. [26]

Results of a NASA SE study notes the optimum benefit of project definition (a typical SE activity) was 5 – 10% of overall effort. The presence and experience level of SE staff is an indicator of the extent to which SE is applied to the project. [26]

Results of the survey indicate an expectation for higher requirements volatility during early life cycle phases and the volatility decreases over time. Volatility is not linear and peaks during transitions between

lifecycle phases, which may coincide with design reviews and handoffs between organizations (i.e., development to test). [9]

Requirements changes during the conceptual phase should be expected and treated as planned vs unplanned volatility. Requirements volatility has led to increases in project size, effort, cost, schedule duration, and rework due to higher defect rate. [9]

Lack of integration between SE and PM which leads to inconsistent and incomplete information exchange and contributes to project failure. The metric of 85% of technology and project costs are committed prior to detailed design with little flexibility to adapt to design changes. [32]

From COSYSMO - Activities which have the greatest impact on SE effort and duration are size drivers: numbers of system requirements, major interfaces, operational scenarios, and unique algorithms. Cost drivers/application factors include requirements understanding, architecture complexity, level of service requirements, migration complexity, and technology maturity. Cost drivers/team factors include stakeholder team cohesion, personnel capability, personnel experience/continuity, process maturity, multisite coordination, formality of deliverables, and tool support. [7]

Key enablers to this DE transition enable reduced risk through better interface management, deeper collaboration, and understanding of the impact of design choices on cost and schedule. DE integrates SE, product design, development processes, project management, and related documentation to create value and to reduce risk. DE is the need for technical innovation to support and to enable improved engineering processes. The key to SE is experience. With DE, digital collaboration is a key enabler. [31]

Within traditional SE approaches, requirements and architecture generally contain significant errors that will require late, downstream identification, rework, and re-verification which is expensive and manifest at a time when the schedule should be wrapping up. Using models, SE can ensure data is complete, consistent, and correct before handing off to downstream engineering activities. The handoff to downstream engineering is a process, not an event. [29]

### *RQ2 – Analyzing SE Value*

The categories of SE activities with the strongest relationships to project success begin early in the project and influence the approach to the organization of the project: product architecture, trade studies, requirements development and management, and SE team utilization. These results provide a strong incentive for early application of SE on a project. [2]

Statistically proven relationships between SE activities and the technical, cost, and schedule impact the success of the project. All defined SE activities positively correlate with project success. The lack of correlation between SE activities and the technical quality of the product system is noted. SE effort is optimized at about 15% and cost/schedule over runs appear to be minimized. [5]

The project result benefits most from SE effort related to requirements, design development, and technical management. Increasing SE effort contributes most to cost and schedule and not as much impact on technical quality as projects are performance driven. [4]

These heuristics have been proven to be resilient across multiple scenarios over years and can be used for quick estimates or judgments:

- Don't do more analysis than the data are worth - analysis by paralysis,
- All models are wrong, some are useful – don't rely on models or one model only,
- Estimate using multiple methods – triangulation of results can build confidence. [8]

For MBSE cost curve, costs are greater in the conceptual and preliminary design phase for tools, infrastructure, training with substantial cost savings during the latter stages of design with reduced defects later in the lifecycle. [42]

### *RQ3 – Communicating SE Value*

Design reviews should focus on reviewing engineering decisions based on data, modeling, and simulations. [50]

## Chapter 5 - Research Identification

The next three chapters, Chapters 5 -7, describe the research and results. Chapter 5 details the identification of the research tasks associated with each RQ. Chapter 6 describes the research conducted for each RQ using the Chapter 5 research identification tasks. Chapter 7 explains the results which several organizations realized when the research described in Chapter 6 is conducted. These three chapters cover the process which an organization can implement to determine the value of SE in a competitive bid. The data, which is collected (RQ1), is analyzed (RQ2) and is communicated (RQ3), are from projects of varying size, contract type, and across multiple organizations/business sectors. They are representative contracts/projects in industry and require significant SE effort.

Applying systems thinking, using feedback loops, gathering data (which may be distributed), understanding SE-DE impact, and empowering engineers in the DE transition enables data-driven decisions to determine SE value in competitive bids and to optimize SE using risk management.

Following this process and using data (from competitive bids and projects) will yield results specific to an organization as competitive bids must be customized for the project based on actuals, historical data, technical approach, and DE transition progress. These results are communicated to the competitive bid teams using the SEaaS framework which is also organization-specific depending on competitive bid history, project actuals, and progress in the DE transition. The process detailed in these three chapters and the framework to communicate the process results are original research and can be employed to determine an organization-specific value of SE in competitive bids.

Starting with Chapter 5, the research identification tasks are detailed to respond to each RQ. These research identification tasks are expected to be iterative as data is collected, is assessed, and is analyzed. Informational interviews, surveys, and email communication iteratively increases understanding and data access. The necessary data was not centrally located from a physical or staff ownership perspective.

### **RQ1: ‘How to quantify the value of Systems Engineering?’**

As this RQ is addressed, the value of SE in competitive bids and corresponding projects needs to be assessed. In addition to SE hours, the activities which compose SE by WBS, or other structure, needs to be understood so accurate comparisons between bid and project and among bids, projects, and industry SE metrics can be confidently made. Understanding the activities included in the SE hours data is important for interpreting, using, and communicating SE value for competitive bids and projects.

The SE WBS element contains all the resources associated with systems engineering: technical planning, technical management, analysis, and support efforts for development and production activities. The systems engineer is responsible for the analysis, derivation, allocation, and traceability of requirements and interfaces. SE activities include systems definition, systems analysis, requirements analysis and allocation, interface definition and control, performance assessment and verification/validation, technical direction (SE leadership, planning, and coordination), system safety, quality assurance, product assurance, engineering services, configuration control, system documentation, algorithm development, risk management, human engineering, other specialty engineering, engineering and design, parts, material and processes, trade studies, and system studies.

In addition to the SE hours bid to execution comparison, the value of SE in the project performance is to be assessed using the risk register or risk posture and project performance against cost, schedule, and technical objectives or baselines. One way to represent project performance is to assess the project performance color (red, yellow, green) against performance criteria. Project-specific characteristics and intangibles are noted and may include contract size, customer, or market influences. In addition to project performance and risk assessment against SE hours, defect profiles against SE effort/hours are assessed. Defect data can include change tasks (CT), defect density (DD), quality notes (QN), and releases (late and/or with errors). These defects data types are defined in the Risk and Defect Data Collection section of Chapter 6. Assessing defect data provides insight into overall product quality and the effectiveness of SE processes in discovering the defects early in the lifecycle and in mitigating the defects escaping into

later lifecycle phases. Addressing defects through repair or rework can impact technical, cost, and/or schedule baselines if the rate of defects exceeds the anticipated rate planned when baselines are determined. Defect repair or rework may necessitate design and/or process changes which could impact project performance against baselines and incur the yellow or red performance rating. Understanding a trend or pattern among project SE effort, SE effort allocation, project defects, defect discovery, and project performance yields insight into SE value.

The impact of DE during transition upon current SE bid practices is investigated within organizations, industry, and customer communities. DE metrics are evolving as this transition progresses. This transition influences SE hours, tools, and practices.

**RQ2: ‘How to analyze this quantification to provide justification for bid SE effort ranges and associated project results?’**

The analysis for this RQ response is based upon the data collected to support RQ1. Analysis focuses on the SE value across the system development lifecycle in the competitive bid and corresponding project correlated to project performance (cost, schedule, technical baselines), risk posture, defect profile, and project characteristics (contract value, customer, market, SE experience level, complexity). The impact of SE value on project performance provides a justification for a bid SE effort range and project results.

Like RQ1, the impact of the DE transition upon this analysis is considered and is understood. This transition impact upon the workforce from a confidence, experience, tools, and process perspective is considered as SE value analysis is communicated to competitive bid decision makers. To understand this impact, an organization’s roadmap to DE transition is explored and DE infusion efforts targeting MBSE and Agile are explored.

**RQ3: ‘How to communicate SE Value to a Competitive Bid Team?’**

The focus of this RQ response is on how to effectively communicate the analysis completed in RQ2 using the data collected in RQ1. The framework (format and content) of the communication platform is explored to enable ease of use, timeliness, and application of SE-centric content. The goal is to provide a

holistic presentation of SE value to competitive bids teams using historical actuals. The goal is to include a set of qualitative measures based on a tailored SE balanced scorecard and quantitative metrics on SE hours, risk posture, defect profile, and project performance. The framework has application to a secondary audience of project stakeholders. By including SE leading indicators, the value of SE to projects is increased. The value of SE as risk mitigation applies to optimized SE hours. These optimized SE hours are inputs into the SE-centric framework, enabling data-driven decisions for competitive bid team to ‘dial in’ optimized SE estimates based on project trends. The framework for this communication platform is the goal of this RQ3.

Consistent with RQ1 and RQ2 organizational research, the impact of DE on the SE values communicated within this proposed framework must be understood. For this RQ response, organization research must include monitoring the organization DE transition, assessing DE transition success to determine if sufficient data exists to create and to confidently use a DE metric for SE value in competitive bids.

This chapter summarizes the organization-related research identification tasks for each RQ. After a successful Preliminary Exam obtaining doctoral committee concurrence on these RQs and research approach, organization research started and is discussed in the following chapter.

## Chapter 6 - Research Conducted

Within this research endeavor, the necessary data for analysis was pulled from different business sectors and organizations. An organization's tools to capture and to store data may change over time as tools are retired and new ones are introduced. The goals were to determine an efficient way to communicate the results of RQ1 and RQ2 and to incorporate findings into RQ3 with the development of an SE-centric framework with quantitative and qualitative perspectives for competitive bid decision-makers. This chapter details the research tasks supporting the response for each RQ. The research includes informational interviews and iterative data collection (RQ1) and analysis (RQ2) to be employed in aiding decision-makers with a framework to support the communication of SE value in bids (RQ3).

### **RQ1: Research for 'How to quantify the value of Systems Engineering?'**

The focus of the organization research is the value of SE in competitive bids. As noted in the literature search (Chapter 4), the value of SE is realized in project performance against cost, schedule, and technical objectives. Company/organizational resources and industry research shape the data collection tasks associated with this RQ. To determine the value of SE in competitive bids, the value of SE is quantified in the winning proposal projects, in execution, and in creating a feedback loop between SE effort in projects and SE effort estimated in new competitive bids. Combining background from the literature search and the research need, the data to be collected as part of this RQ is determined. Data collection tasking focused on SE hours in bids and projects and corresponding project performance, risk profile, and defect profiles. The impact of DE on SE was explored through interviews with DE transition leads and systems engineers on projects currently implementing DE. The success of this RQ data collection tasks impacts the analysis performed in RQ2.

### *New Tasks to Support the Determination of SE Value*

The tasks associated with this RQ identify activities which the organizations do not perform and would enable the understanding sought with this RQ. In pursuing the response to this RQ, the following

practices, which yield insight into SE value, are identified as not currently performed within the companies/organizations, but are needed to determine the value of SE in competitive bids:

- Compare SE effort (hours) in project execution to the SE effort (hours) bid in the competitive proposal.
- Track SE effort in bids or on projects for trends or patterns to recommend changes.
- Perform analysis on how SE effort is expended on the project and the resulting project performance.
- Correlate risk management on a project and resulting project performance.
- Correlate completed project defect profiles to a retrospective review of leading indicators as metrics which could have warned of potential project problems.
- Recommend a consistent approach to DE in bids or on projects as the DE transition is underway.

These new tasks are the foundation of this research and contribute to the organizations' need to remain competitive by determining the value of SE in competitive bids.

#### *SE Effort – Bid vs Project Comparison – Identifying Data to Collect*

Available data and analysis performed shape the tasks of this RQ comparing the SE effort (hours) in the competitive bid against the SE effort in the project. To perform this comparison, the research begins with determining the available bid and project data and if this data supports SE value assessment. With the SE effort in the bid and project actuals, the comparison focuses on how close the project actuals are to the bid using percentage of SE hours to total project hours. For competitive bids, SE effort is defined as the SE hours estimated to the total project hours in the bid. For projects, SE effort is defined as the percentage of actual SE hours executed to total actual project hours executed.

Within any organization, there are numerous possible competitive bids/proposals and corresponding projects upon which to focus this data collection task. This research begins with informational interviews influencing and identifying potential data collection sources. These data collection sources determine which proposals and projects to target for this research and analysis.

With an understanding of the goals of this research, the interviewees provide guidance or references to additional interviewees. This 'referral' process continues as the research progresses with written

information exchanges to supplement interviews. The research goals are often enthusiastically understood by the interviewees as they appreciate the need and benefit to the organization. Interviewees are receptive to a follow-up session or email exchanges. The informational interviews are captured with notes and are referenced and tracked via a contact diagram (Visio) as research progresses. Over fifty interviewees responded from multiple business sectors.

Research into SE and DE transition is completed as the informational interviews continue.

Complementing internal research is examining the industry state of the practice at SE industry conferences: Conference on Systems Engineering Research (CSER) and National Defense Industrial Association (NDIA) in Fall 2020, INCOSE International Symposium in June 2022 and INCOSE Western States Regional Conference (WSRC) in October 2022. These conferences provided insight into DE practices and challenges as the industry and customer community transition to DE. Insights from multiple presentations noted the evolving nature of DE metrics, the challenges in MBSE implementation, modeling to the appropriate level, and model maintenance. Several presentations and resources from these conferences are covered in the Literature Search (Chapter 4).

### *Selection of Projects*

Twenty-four projects were selected for this research by limiting the available project timeframes to post-2011 to make SE hours more realistic to current SE practices. Frequently, only partial data relevant to the project is available. The resulting data collection is noisy with some data gaps due to these varying sources and completeness of data. Over 500,000 data points are used in the quantitative project-level analysis. This does not include the aggregated data at the system-level analysis. The projects selected varied in contract value, scope, and complexity. Competitive bid/proposal data, SE actual and overtime hours in projects, risk (net factored risk (NFR), management reserve (MR), contract value) and defect profiles (change tasks, quality notes, releases) in the data collection are analyzed for SE value justification and are communicated within the SE-centric framework.

### *Project Performance Data Collection*

The next data collection effort focuses on project performance. To determine if the project met its cost, schedule, and technical performance objectives or if its performance exceeded thresholds, project performance data is required. In large organizations, a scoreboard-type tool is frequently employed depicting project performance rated by colors (green, yellow, red) against criteria as noted in Table 1 for cost and schedule performance and Table 2 for technical performance. Included in the following tables, generic values have been incorporated as key performance parameters to allow comparisons across different organizations. The color rating and assessment definitions are similar among most organizations.

*Table 1: Project performance parameters color rating criteria*

| <b>Project Performance Category</b> | <b>Performance assessment 'green'</b>   | <b>Performance assessment 'yellow'</b>   | <b>Performance assessment 'red'</b>   |
|-------------------------------------|---|--|---|
| Overall                             | No red or yellow subcategories  | One red subcategory and zero or one yellow<br>Two or more yellow subcategories                   | One red subcategory and two or more yellow<br>Two or more red subcategories |
| Cost                                | (Cost Performance Index) $CPI \geq .95$ and (Variance at Completion) $VAC \geq 0$<br>$CPI \geq .95$ and $VAC < 0$ and (Management Reserve) MR is sufficient | $.90 \leq CPI < .95$ and $VAC \geq 0$<br>$.90 \leq CPI < .95$ and $VAC < 0$ and MR is sufficient | $CPI < .90$   |
| Schedule                            | Schedule Performance Index (SPI) $\geq 0.95$  | $0.90 \leq SPI < 0.95$   | $SPI < 0.90$  |

Table 2: Technical performance parameters color rating criteria

| Metric   | Green Criteria   | Yellow Criteria   | Red Criteria  |
|--|--|---|---|
| <b>A.</b> Requirements Stability<br><b>B.</b> Performance Measures   | If both A and B are green,<br>AND                                  | If either A or B are red, technical rating is yellow<br>OR                      | If either A or B are red, technical rating is red<br>OR |
| <b>C.</b> Engineering Releases<br><b>D.</b> Software Performance to Plan<br><b>E.</b> Verification Testing | No red and at most one yellow (C, D, E), technical rating is green | If one (C, D, E) is red or two (C, D, E) are yellow, technical rating is yellow | Any two (C, D, E) are red, technical rating is red      |

### *Risk and Defect Data Collection*

Concurrent to the competitive bid/proposal data collection effort, the risk register information for the proposal and the project is sought. Responses vary in completeness and in usefulness. The same approach for defect profiles produced similar results. The challenge with the risk and defect data collection is interpretation as the context of the risk register or defect profile and outcome of the risk management process or impact of the defect is not always evident from the data collected.

To complement the bid and actual SE hours and project performance data collection effort, the research extends to the project risk posture and any correlation to project performance. Each project identified the top three risks. However, these risks can change frequently. Reviewing the top three risks provided little insight to the project's risk posture and the value of SE to the risk management process or project performance. Projects can extend several years over the decade under review (2011-2021). Another approach to obtaining insight into a project's risk posture is to review the Net Factored Risk (NFR), Management Reserve (MR), Contract Value (CV) for the project. SE hours might be spread differently if the change in contract value is planned or unplanned. The analysis of NFR, MR, and CV correlated

with SE hours and project performance is completed in RQ2. Alignment of data available is addressed in RQ2 analysis.

Defects identified late in the lifecycle impact project cost, schedule, and technical baselines. The research includes defect correlation with SE effort and project performance. Initial data collection efforts for defects provide limited insight due to the generic nature of the defect data. Reviewing defects captured as change tasks (CT) provides insight into the engineering change process. A change task is the implementation and release of an authorized change to correct a problem. CT data includes the number of release versions from initial to final and the number of months to develop the final release.

To enable further analysis, quality information is collected from the projects and is defined as quality notes (QN). The QN refers to an approved closed-loop system for documenting nonconformances (NCs) and recording how the nonconformances are addressed. Quality data is produced from various sources. A QN typically has a cause code reflecting the root cause and corrective action. Quality data was available for most projects and is used in the project-level and system-level defect analysis. This data supports the identification of a project defect profile against which SE hours and project performance can be analyzed. As this research is SE-focused, the quality data, associated with SE tasks, is taken from design and process categories. For each QN, there is a category description (design or process) and a corrective action code. These categories and corrective action codes contribute to identifying relevant QNs for analysis and QNs for which rework, repair, and defect averages for the referenced projects are documented. Rework and repair are defined as:

- Rework: Operations and/or engineering revisions performed that will return nonconforming material to complete compliance with the requirements in the contract, specification, or drawing.
- Repair: Operations subject nonconforming material to a process designed to reduce, but not eliminate, the nonconformance. Unlike rework, the hardware will not completely conform to the contract, specification, or drawing requirements when the repair operations are complete. But, it will be acceptable for its intended use.

Another source of project data related to defects is project releases. Releases result in a change to the technical baseline. Design releases include documents, drawings, part objects, and model files. Reasons for an updated release include routine design changes, rapid engineering changes, placeholders/TBx, and cancellations. Release data includes late releases relative to the release plan or need date and releases with errors. This release data supports the identification of a project defect profile against which SE hours and project performance can be analyzed (RQ2).

### *Overtime Hours Data Collection*

Identifying SE value trends and indicators provides insight to project challenges and risk mitigation. One indicator of project challenges is additional overtime (OT) hours expended to resolve unanticipated project issues. Overtime hour data focusing on SE effort is valuable. The data sources provide extracted SE overtime hours based on SE job titles on the projects. The SE overtime hours are categorized as total hours composed of compensated (paid) and uncompensated (not paid) hours. In most cases, there are other factors influencing the approval of paid overtime on a project including SE role, project schedule, project color (red, yellow, green), significant milestone, or event. There are external influences contributing to the approval of paid OT hours such as market forces (employment rates, market competition for SE talent, location), contract type, and internal policy. The economy may influence the SE employees' desire to work overtime – compensated and uncompensated.

### *DE Impact on SE – Metrics and Pilots*

Exploration of the DE transition within the companies/organizations focuses on DE metrics and how these metrics impact SE value in a competitive bid. A comparison among currently used metrics, SE leading indicators, and DE metrics is completed. This comparison demonstrates the alignment and gaps in a limited set of technical, SE, and DE metrics. Based on comparison of these metrics as part of this RQ, a recommendation for the addition of a risk management metric to address a gap is identified. Coordination with the Model Based Systems Engineering (MBSE) SMEs and efforts to accelerate the use

of MBSE on projects results in a research task to develop recommended Measures of Effectiveness (MOE) for MBSE. These MOEs could evolve into SE/DE metrics to measure DE transition progress within the organizations, in competitive bids, and in projects. The results of these two metrics activities are detailed in RQ3.

Supporting the DE transition aspect of this research, several pilots are initiated with the intention of collecting data, identifying observations, and prototyping solutions. As lead for each pilot, the author serves as an observer/facilitator, with no filter or intermediary. First, a project-specific DE transition pilot focusing on MBSE is initiated. Based on feedback from the SE team, additional on-demand training is established. Customer enthusiasm is strong for this change to MBSE, and the modeling is used for a significant customer review with positive results. With the conclusion of this pilot, two additional project-specific DE transition pilots are initiated. The first focuses on automation with an expert automation owner. The second focuses on knowledge transfer with a structured mentoring pilot with mentor/mentee pairings, goals, and feedback sessions. In addition, aspects of Agile SE are introduced on the project to reduce work in progress and iteratively develop design artifacts with stakeholder feedback. Results from these pilots are integrated into the DE transition summary and recommendations (RQ3).

#### *Data Collection Focusing on DE implementation*

The identification of projects which are practicing DE in some or all aspects of project execution was challenging. Informational interviews (20+) yielded feedback, advice, lessons learned, and challenges with implementing DE (RQ3). Resources for DE transition, strategy, tools, and impact of DE on SE are explored focusing on executives leading transition efforts and their leads implementing DE. This data is assessed and is communicated from an SE impact perspective in RQ3.

In summary, the data collection tasks for RQ1 are significant due to the wide distribution of data among numerous and diverse contacts, sources, owners, and tools. The data collected, though incomplete with

some data lacking granularity, is useful for analysis. Data completeness, definition, and quality are noted in RQ2 tasking. Figure 6 shows the variety of data sources supporting this RQ activity.

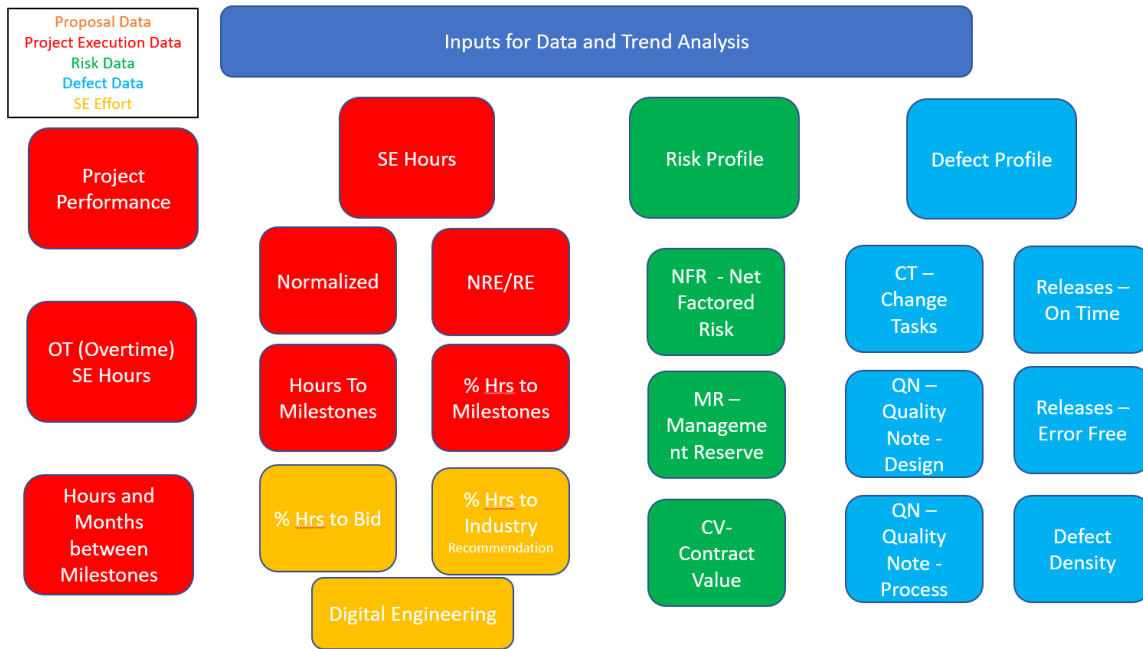


Figure 6: Categorization of supported data, collected data, and trend analysis

**RQ2: Research for ‘How to analyze this quantification to provide justification for bid SE effort ranges and associated project results?’**

The data collected as part of the SE value quantification in RQ1 is analyzed in RQ2. Project description and characteristics, SE effort in the bid and in the project, risk posture, and defect profile produce needed information. SE effort is defined as a percentage of SE hours to total project hours. Key to this research is the comparison between the SE effort estimated in the competitive bid and the SE effort expended in the execution of the project (project actual SE hours). Two other sources of comparison for the SE effort in bid and execution are: business sectors average SE effort and industry metrics as noted in the literature search. Several other factors are included in the project characterization: skill mix (project, not just SE) defined as average level in the bid estimate and as staffed in execution, project complexity as a percentage of NRE to total project hours, and hours of SE effort and months of SE effort between major review milestones, i.e., Preliminary Design Review (PDR), Critical Design Review (CDR), Operational Readiness Review (ORR). Project performance, risk, and defect profiles are part of the justification of SE

value. This analysis applies systems thinking concepts and tools, specifically the Iceberg Model, which promotes contextualizing an issue as part of a whole system [58]. By applying the Iceberg Model, the approach to RQ2 analysis considers events, patterns, structures, and values at the project-level and system-level. For this research, system-level is the collection of these projects and system-level analysis is all projects in aggregate.

Events are a single incident or occurrence noted as ‘what is happening’ within the Iceberg Model. For this research, each data point collected in RQ1 is contextualized into an ‘event’ in the project’s lifecycle. Data points (‘events’) represent values, ratings, timing, schedule event, or information for SE effort (hours), project performance (red, yellow, green rating), risk (NFR, MR), defects (CT, QN, release), and milestones (PDR, CDR, ORR),

Patterns of system behavior are noted as ‘what are the trends over time’ within the Iceberg Model. The relationship of these patterns and trends of project behavior and SE (effort and value) on the impact of project success is the focus of the data analysis. By looking below the ‘project waterline’, connecting the events (data points) collected and analyzing the data in multiple comparisons across multiple data sets for trends, the research endeavors to identify the patterns and trends demonstrating SE value and its impact on successful project execution.

System structure identifies how parts of the system are related and is noted as ‘what influences the patterns’ within the Iceberg Model. Connecting the events (data points) into patterns and trends for successful project performance across all research projects (system) identifies the SE value demonstrated (structure) impacting project performance. SE trends and patterns across the system (all projects) correlated to project performance provide insights into patterns of SE effort (hours) allocation and risk management practiced associated with successful project performance. The structure of SE within the project demonstrates its value as a contributing factor to successful performance. The structure of SE

within a project with performance challenges is also assessed to add clarity to the SE structure and its value/impact on performance.

To develop lasting solutions that target the whole system proactively rather than short term, factors shaping the system are assessed and are noted as ‘what values or assumptions shape the system’ within the Iceberg Model. For this research, beliefs and assumptions associated with the structure of SE on a project are assessed. This research includes quantitative as well as qualitative data collection activities to enable an understanding of the mental model (value) of SE and its impact on project performance.

This analysis and systems thinking tool are applied to the data collected for each project. For this RQ, tasks as detailed in the following paragraphs, including data, trends, patterns, system structure, and SE value, are addressed in each element of project data analysis. The analysis and systems thinking tool are then applied at the system-level. The system (all projects) analysis identifies trends and patterns across all referenced projects to determine SE value in competitive bids.

### *Project-Level Data Analysis*

To determine SE’s value in the competitive bids, proposal information is collected from numerous sources. The estimated SE hours, skill levels, and total project hours are noted. To determine the project risk posture, a quantitative method to capture the project’s risk profile is depicted by tracking the Net Factored Risk (NFR), Management Reserve (MR), and contract value (CV). For this analysis, this risk data is mapped to the corresponding SE hours, both Non-Recurring Engineering (NRE) and Recurring Engineering (RE), with project actuals. Total SE effort is the combination of the NRE and RE hours. The technical risks and management risks are both contained in the management risk factor and in the project MR. The NFR and MR are indicators of the project’s risk posture. If there is a strong risk posture (NFR within MR), the project is committed to managing and to mitigating risks by practicing risk management. This data is graphed in multiple data and format views seeking the portrayal of data which is most impactful. Overlaying upon the graph is project performance as noted by colors (yellow or red)

for technical, cost, schedule. An Engineering Change Proposal (ECP) changes CV. Observations resulting from this analysis and the graphs correlating risk posture, SE effort, and project performance are noted in the Chapter 7.

To determine a project's defect profile, several sources for defects are possible. The data analysis focuses on correlation among the change tasks (CTs), CT rate, CT frequency of release, and project performance. Data analysis reviews multiple aspects, in various graphs, seeking a leading indicator from the CT data. Initial analysis results for project defect profiles correlation to the relationship between SE effort and defect profile was indeterminant. Data sources for quality notes (QN) and release data which provides more complete defect data profiles with rich data sources enabled analysis with a focus on SE value using design and process QNs and releases – late/on-time, error-free/with errors – data distributed over the project lifecycle. Applied systems thinking concepts seek to identify trends and patterns in the data. Correlation among SE value and the multiple defect profiles per project is analyzed and then 'flipped' to seek patterns from the opposite perspective. For example, releases are analyzed from on-time and late perspectives and from error-free and with errors perspectives. Trends, patterns, and indicators for SE value to the project's defect profiles and performance are a key part of the project-level analysis. The following sections detail the analysis for SE Hours, project performance, risk, and defect profiles.

### *Project-level Data Analysis – SE Hours and Project Performance*

The analysis focuses initially on the data available for each project mapping SE hours over the project lifecycle and normalizing this distribution. To understand SE impact at key project milestones (PDR, CDR, ORR), the SE hours and project months to each milestone and between each milestone are reviewed and are assessed against the business sector average. SE impact on project performance is conveyed using yellow or red indicators for technical, cost, and schedule performance on the graph of SE hours over project lifecycle. This overlay of yellow and red colors indicates project issues as performance deviates from technical, cost, and schedule baselines. Project performance to baseline is green and is assumed to be the norm with only yellow or red indicators added to the graph to note

deviations. Trends, patterns, and correlations among SE hours distribution aligning to project performance is then supplemented with the SE overtime (OT) hours distribution over the project lifecycle. The OT hours are graphed from three perspectives: total SE OT hours, compensated SE OT hours, and uncompensated SE OT hours. The analysis focuses on correlations of SE OT hours as a leading indicator of project performance issues (yellow, red) and/or increases in defects. SE OT hours is quantified as a percentage of SE hours on the project as a measure of the level of OT against planned SE hours in execution. Significant SE OT may indicate the project was under-bid in the proposal. Significant SE OT around project performance issues or defect profile spikes is reactive/lagging to address a project issue or deviation from baseline.

#### *Project-level Data Analysis – Risk Profile*

The risk profile analysis focuses on determining if the project is or had practiced good risk management given the data available with NFR, MR and CV. The SE hours distribution is separately plotted in the graph with NRE, RE, and total SE hours. Risk is more likely to be associated with NRE vs RE and patterns/trends around this distribution are assessed. For each project, a risk profile summary accompanies the NFR to MR, SE Hours distribution, and CV graphs.

#### *Project-level Data Analysis – Defect Profile*

The data rich defect profile analysis enables assessments to include trends, patterns, and correlations for change tasks (CT), quality notes (QN), and releases for each project. For CT, a comparison of CT releases (time in months to develop the final release and number of releases needed before final release) is an indication of skill and expertise. The analysis graphs and compares key project milestones to determine a trend or correlation of SE hours and project defects as noted by CTs, number of releases, maturity of releases, and performance color ratings. Other project impacts do influence the number of releases such as customer-driven requirements changes and initial release to begin the procurement process.

Quality notes defect analysis begins by filtering QNs based only on design and process corrective action code descriptions, as these QNs may be impacted by SE effort. Analysis to understand a relative impact of design and process QNs to total QNs includes determining the number and percentage of design and process QNs to total QNs and comparing these numbers and percentages to the average design and process QN rate (aggregate) on these referenced projects. Analysis into the design and process corrective action codes focuses on those codes which required rework or repair as these activities can impact the technical, cost, and schedule baseline. To relate the varied numbers of QNs on the project to the SE hours, the determination of design, process, and total QNs per 1,000 SE hours on the project is calculated. This calculation is performed for each project. The average for these referenced projects is a comparison point in this analysis. The distribution of design QNs and process QNs across the project lifecycle is compared to SE hours and SE hours normalized over the project lifecycle to determine patterns, trends, and impact of SE hours on QNs. The same comparison of QNs is made to SE OT hours to determine a trend or leading indicator between QNs and SE OT hours. These graphs are included in each project's data analysis with a summary of analysis. If QN defect density data is available, analysis is completed against SE hours and SE hours normalized, project performance, and milestones to determine relationships and patterns.

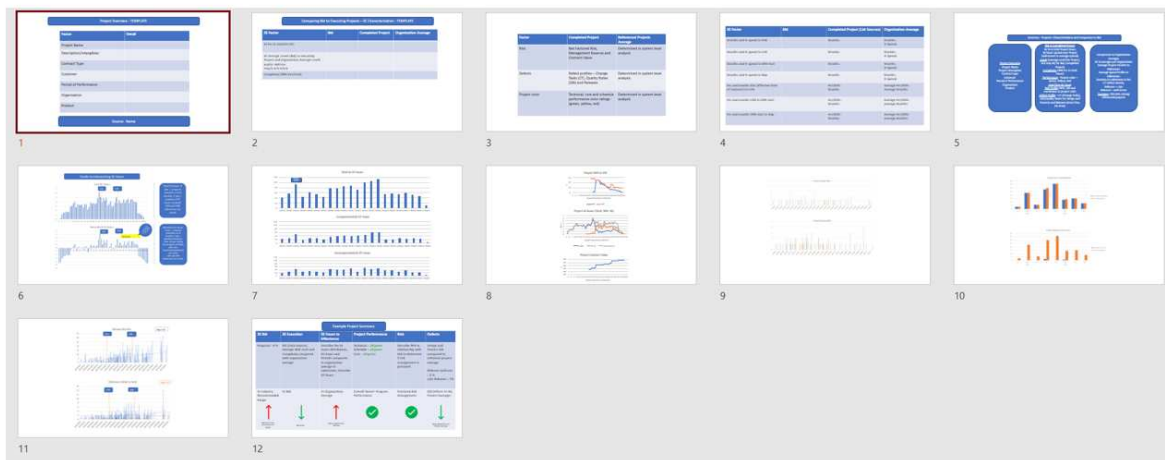
Release defect analysis begins with graphing error-free releases over project lifecycle and comparing to SE hours, normalized SE hours, SE OT hours, and SE hour (Total, NRE, RE) distributions over project lifecycle to identify patterns, trends, or correlation for SE effort to error-free releases profile. The number of releases with errors is compared to the total number of releases over the project lifecycle. The assessment seeks indicators or impacts of SE hour distributions to release errors. The average number of error-free releases is determined. Similar analysis is conducted on the opposite defect profile, releases with errors. This opposite analysis gives a different perspective on the distributions and potential relationships which may not be readily discernable with the error-free graphs and analysis. Using the on-time and late release data, the same analysis is conducted seeking to identify trends and patterns among

the various SE hours distributions and release defect profiles. Late releases may impact the technical, cost, and schedule baselines, and project performance. Focusing on this impact, on-time releases are compared against the project performance (green, yellow, red) for technical, cost, and schedule baselines and against SE hours normalized distribution.

In addition to these risk and defect profile analyses, the SE hours bid, actual SE hours in project execution, SE hours distribution, and SE hours to milestones are analyzed for each project. An example of project-level data analysis is depicted in Figure 7. Bid to project comparison is captured in Figure 8.

These analysis summaries include SE effort, distribution assessments, and a relative comparison against an average (industry, business sector, and/or reference project). This analysis summary also includes project performance (red, yellow, green) for technical, cost, and schedule baselines, risk profile and risk management assessment, and defect profile (QN, releases) against referenced project averages. This analysis summary contains graphics and colors for rapid assessment of a project-level analysis summary for a competitive bid team. An example of this analysis summary is shown in Figure 9.

## Data Analysis – Project Specific - Example



*Figure 7: Representative example of the data analysis completed for each reference project*



Figure 8: Analysis using data collection (RQ1) to compare projects to bid

Example Project Summary







| SE Bid  | SE Execution   | SE Hours to Milestones  | Project Performance  | Risk  | Defects  |
|---|--|---|--|---|--|
| Proposal = X %  | X% (Data Source); Average Skill Level and Complexity compared with organization average          | Describe the SE Hours distribution, SE Hours and Months compared to organization average to milestones; Describe OT hours | Technical = <b>all green</b><br>Schedule = <b>all green</b><br>Cost = <b>all green</b> | Describe NFR in relationship with MR to determine if risk management is practiced     | Design and Process QN compared to reference project average<br><br>Releases w/Errors = X %<br>Late Releases = Y%               |
| Vs Industry Recommended Range   | Vs Bid   | Vs Organization Average   | Overall 'Green' Program Performance  | Practiced Risk Management   | QN Defects Vs RQ Project Averages  |
| <br>Above Industry Recommended Range | <br>Below Bid | <br>Above Organization Average         |     |  | <br>Below All Referenced Projects Average |

Figure 9: Example of the analysis summary completed for each project

### System-level Data Analysis

The challenge of determining the system-level value of SE leveraging the referenced project-level data analysis (SE hours (bid, actual, normalized, total, NRE, RE, OT) distributions and project performance, risk, and defect analysis) is the next step in this RQ. The system-level data analysis continues with

identification of aggregate trends, patterns, correlations, and impacts of SE value across all referenced projects. The data is analyzed in multiple ways seeking to identify patterns or trends. Given the noisy data as explained in RQ1, no obvious SE value trend or pattern is revealed despite numerous attempts at data analysis and at identifying trends and patterns. A heat map is created using colors to indicate data over or under a relative average (industry, bid, business sector, and/or referenced projects). The intention of this heat map is to visually communicate project data against averages. However, the heat map (Figure 10) did not yield a useful SE value structure pattern. Heat maps are visualization tools and Figure 10 lists the projects by numbers down the first column and key data analysis results along the top row. The colors are defined below the data analysis column heading.

| Project | SE% Bid              | SE% on Project | SE% on Project          | Risk Mgmt | Defects                                       | Defects  | Technical Performance   | Cost and Schedule Performance | Level          | Complexity     |
|---------|----------------------|----------------|-------------------------|-----------|---|--|-------------------------|-------------------------------|----------------|----------------|
|         | over/under industry* | over/under bid | over/under org. average | yes/no    | over/under RQ project sample average (design) | over/under RQ project sample average (process) | tech green, yellow, red | cost or schedule yellow, red  | over/under avg | over/under avg |
| 1       | over                 | under          | at average              | yes       | under   | under  | green                   | red cost                      | under          | under          |
| 2       | over                 | under          | at average              | yes       | under   | under  | green                   | green                         | under          | under          |
| 3       | no bid data          | no bid data    | over                    | no        | over  | under  | green                   | red cost                      | over           | at average     |
| 4       | no bid data          | no bid data    | under                   | yes       | over  | over   | yellow, red             | red cost                      | no data        | under          |
| 5       | under                | over           | under                   | yes       | no data                                       | no data  | yellow                  | green                         | over           | under          |
| 6       | over                 | under          | at average              | yes       | under   | under  | green                   | green                         | no data        | under          |
| 7       | over                 | under          | over                    | yes       | over  | under  | yellow                  | green                         | under          | over           |
| 8       | over                 | under          | over                    | yes       | over  | under  | yellow                  | green                         | under          | over           |
| 9       | under                | over           | under                   | no        | over  | over   | green                   | red cost, schedule            | under          | under          |
| 10      | under                | over           | under                   | no        | over  | over   | yellow                  | red cost, schedule            | under          | under          |
| 11      | no bid data          | no bid data    | over                    | no        | over  | under  | green                   | red cost                      | over           | under          |
| 12      | no bid data          | no bid data    | under                   | no data   | under   | under  | no data                 | no data                       | under          | under          |
| 13      | over                 | under          | over                    | no        | over  | over   | yellow                  | red cost, schedule            | no data        | under          |
| 14      | no bid data          | no bid data    | over                    | no        | under   | under  | green                   | green                         | over           | over           |
| 15      | no bid data          | no bid data    | over                    | no data   | under   | over   | green                   | green                         | at average     | under          |
| 16      | no bid data          | no bid data    | over                    | no data   | over  | under  | green                   | green                         | under          | under          |
| 17      | no bid data          | no bid data    | over                    | yes       | over  | over   | yellow                  | green                         | under          | under          |
| 18      | no bid data          | no bid data    | over                    | no        | under   | over   | yellow                  | red cost, schedule            | over           | under          |
| 19      | no bid data          | no bid data    | over                    | no        | under   | under  | green                   | red cost, schedule            | over           | under          |
| 20      | under                | over           | under                   | no        | over  | over   | green                   | green                         | over           | under          |
| 21      | no bid data          | no bid data    | under                   | no        | no data                                       | no data  | green                   | red cost                      | over           | under          |
| 22      | no bid data          | no bid data    | under                   | no        | no data                                       | no data  | green                   | green                         | over           | under          |

Figure 10: Example of the heat map completed using colors to reflect relative averages for each project with industry recommendation at 15%

System-level data analysis continues focusing on SE hours distribution, SE hours to milestones, and SE hours compared to defect profiles to determine SE value and impact on project performance. Analysis on SE value in bid and projects over time (of these reference projects) is completed to determine a trend in the direction – increasing or decreasing – of SE value in bids and on projects. Data analysis focuses on data relative to performance and relative to averages seeking a trend or pattern identifying SE value. By continually analyzing the data for patterns and structure in different formats (tables, spreadsheets, and text), a format for communicating the relationships among the data collected, patterns, and trends within

and among the data and the influence of SE value (structure) on the patterns and data is finally identified. By aligning project data by business sector, performance (technical, cost, schedule), milestones, risk, defects, and SE effort range, the system-level impact and value of SE for competitive bids is determined. The results of this determination and of the system-level data analyses and assessments are detailed in Chapter 7.

### *SE-DE Data Analysis*

Supplementing this SE value determination is the impact of DE on SE value in a competitive bid. DE data collected in RQ1 is assessed and is analyzed to determine how SE value in a competitive bid changes if DE is included in the technical solution for the proposal. Significant data sources are the informational interviews and email exchanges with SE leads on projects which are partially or entirely DE. Analyzing and summarizing this data results in DE impacting SE in the following categories:

- SE hours in a DE Proposal,
- Benefits for SE in DE,
- Challenges in DE,
- Advice/Lessons Learned for SE in DE.

As an organization transitions from traditional document-based SE (TDSE) to DE, engineers are critical in accepting and implementing this organizational change. The DE transition impacts established engineering tools, processes, and practices in which the engineers have confidence and know well. Engineers have spent their careers developing a level of competence in TDSE. Uncertainty associated with this organizational change increases stress, decreases job satisfaction, and impacts commitment among engineers. The engineering culture reflects attitudes of resistance and uncertainty. This RQ analyzes the DE transition from organizational psychology and systems thinking approaches. The combination of these two approaches enables the identification of an intervention and recommended actions to empower engineers in the DE transition. With consideration of the organizational psychology research findings noted in the literature search and applying systems thinking tools, three actions are

proposed focusing on knowledge transfer, training, and communication. Details of these three actions to empower engineers in this DE transition are in the peer-reviewed and published paper [65] in Appendix.

In summary, the tasks for RQ2 focus on analyzing data collected in RQ1 to determine the value of SE in competitive bids. The approach to analyzing the data uses systems thinking concepts and applies the Iceberg Model systems thinking tool. Data is analyzed at the project-level for each of the referenced projects using the SE hours, project performance, risk, and defect data to identify trends, patterns, and indicators. This approach transitions from project-level to system-level by analyzing the data from all the referenced projects in aggregate to understand the structure determining SE value in competitive bids. Finally, the impact of DE on SE in competitive bids is analyzed using the data collected from projects executing DE and SE leaders implementing an organizational DE transition. With the data analysis for RQ2 complete, communicating these SE value results to decision-makers in competitive bids and projects is the focus of RQ3 tasking.

### **RQ3: Research for ‘How to communicate SE Value to a Competitive Bid Team?’**

RQ3 tasking focuses on communicating the determination of SE value resulting from the data analysis in RQ2 using the data collected in RQ1. A holistic and SE-centric framework to communicate SE value includes feedback loops among the SE effort (SE hours estimate) in competitive bids, SE effort (actual SE hours expended) in the project and project outcomes (performance, risk, and defect profiles). Figure 11 illustrates these feedback loops and expands project outcomes to include risk and defect profiles along with performance (red/yellow/green). These feedback loops are included in the comparisons and data analysis of RQ2.

The determination of SE value has a quantitative component (RQ2) and a qualitative component (RQ3). The combination of these components, along with references, form the envisioned SEaaS (SE as a Service) Risk Quantification Framework to communicate SE value.



*Figure 11: Feedback loops among SE value in competitive bids, in projects, and project outcomes*

Data analysis is supplemented with actions to empower engineers in the DE transition, DE pilots and metrics, and additional references. The quantitative and qualitative data analysis supporting SE value determination and associated references are the focus of RQ3.

### *Communicating Quantitative Data Analysis*

For the quantitative component of the SEaaS framework, the project-level and system-level data analyses and data summaries are inputs. As noted in RQ2, each project has the following data analysis:

- Project overview and characteristics: contract size, milestone dates, customer, product, contract type, staffing levels, complexity (calculation),
- Comparison of SE Effort (SE hours to total project hours) on project to competitive bid, business sector average (three business sectors),
- Comparison of skill levels, complexity, SE hours (actuals, normalized, OT, NRE, RE) and months to milestone events (PDR, CDR, ORR start) for each project and for the business sector average,
- Analysis of SE hours (actual, normalized, OT, NRE, RE) to project performance (technical/cost/schedule), risk profile, defect profiles (Change Tasks, Quality Notes for design and process, Releases (error-free, late)).

As noted in RQ2, the system (all projects) has the following summaries:

- SE Hours – Performance (all green, all non-green (yellow, red) and all performance ratings) and Milestones (hours, months),
- Overtime (OT) Hours – SE OT hours only,
- Risk Profiles – all green (practiced risk management) and all risk profiles,

- Defect Profiles – Change Tasks, Quality Notes (design, process) and Releases (Late, Error-free) including defects against referenced project averages and against performance ratings.

Systems thinking concepts and the Iceberg Model tool are applied to analyze and to summarize the project-level and system-level data and to identify trends, patterns, and indicators determining the structure of SE value. To promote correct usage and application of the data analysis and summaries, each data analysis summary section has:

- ‘Guide to Interpreting’ description (Figure 12) enabling correct interpretation and application of the analysis,
- Detail regarding the data such as source, background, details, caveats, notes, observations, gaps, and descriptions,
- Patterns and trends applicable to SE Hours, to projects, to project performance (green, yellow, red), to risk management (practiced or not practiced) and to defect profiles with details around these patterns, trends.

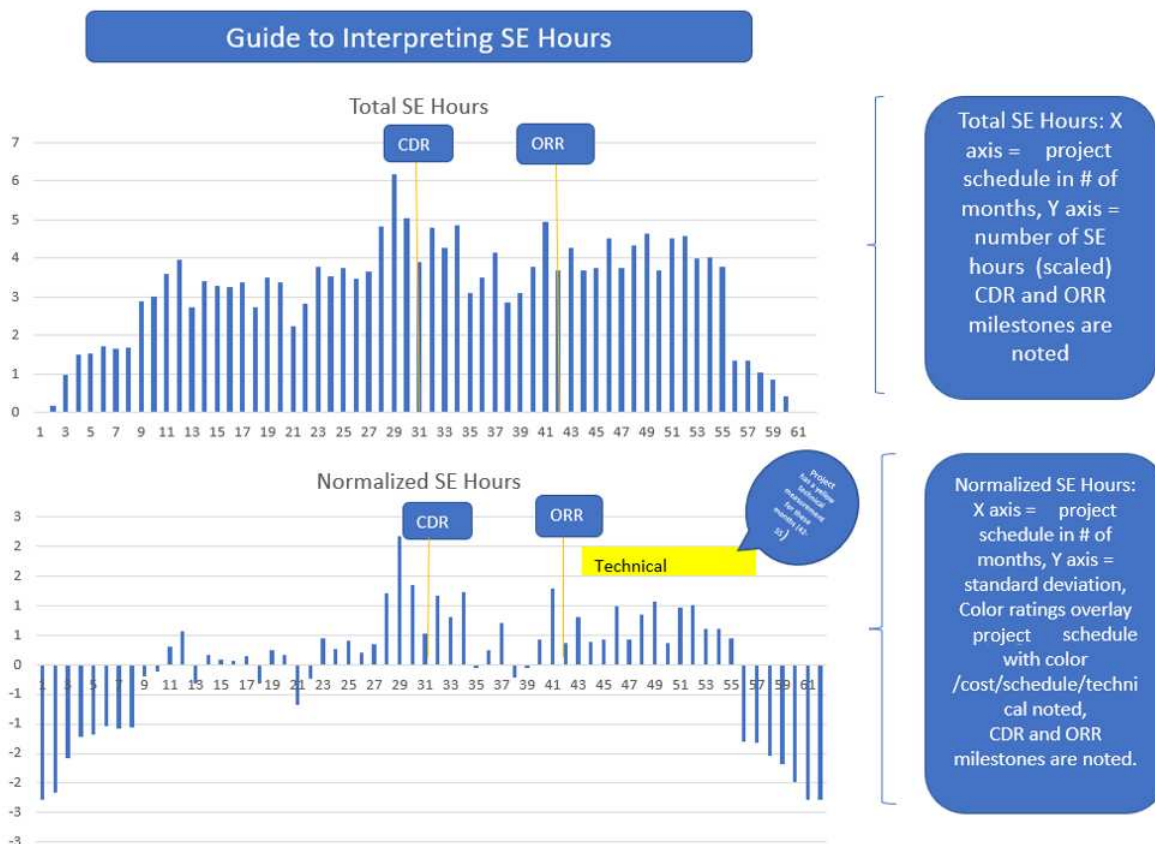


Figure 12: Example of the SE hours section "Guide to Interpreting" description enabling correct interpretation and application of the analysis.

As quantitative input into the framework, system-level data analysis summaries include:

- Determining the Value of SE in Competitive Bids (five SE effort ranges, three business sectors, multiple project performance ratings),
- SE Value and Performance – projects by business sector, by performance rating for technical, cost, schedule mapped to SE effort ranges,
- SE Value and Risk/Defect Profiles – projects by business sector, by risk management practiced, by QN design defects above or below the referenced project average and by QN process defects above or below the referenced project average mapped to the SE effort ranges,
- SE Value – Bid to Execute comparison with resulting performance rating (green, yellow, red for technical, cost, schedule) and resulting risk and defect comparisons – for each of the three business sectors including project notes with business sector and industry averages,
- SE Value – Bid to Execute with months to project milestones (PDR, CDR, ORR start, total project months) indicating above or below average months to each milestone for each of the three business sectors,
- Project characteristics – contract type, contract size, customer, product, staffing level and complexity – compared to the business sector averages for each of the three business sectors,
- Defects Profile – for each project – the percentage of releases with errors to total releases, the percentage of late releases to total releases, design defects (QN) per 1,000 SE hours and process defects (QN) per 1,000 SE hours – for each of the three business sectors,
- SE Hours to Milestone graphs for each of the three business sectors by project performance (all performance and only green performance) for three milestones (PDR, CDR, ORR),
- SE Hours Spread to Milestone graphs for each of the three business sectors for three milestones (PDR, CDR, ORR) comparison of SE Hours spread to all project hours spread to each milestone with no consideration of project performance,
- SE Hours Spread to Milestone graphs for each of the three business sectors for three milestones (PDR, CDR, ORR) comparison of SE Hours spread to all project hours spread to each milestone by technical project performance – all green and non-green – including pattern and trend notes,
- SE Hours Spread to Milestone graphs for each of the three business sectors for three milestones (PDR, CDR, ORR) comparison of SE Hours spread to all project hours spread to each milestone by cost project performance – all green and non-green – including pattern and trend notes,
- SE Hours Spread to Milestone graphs for each of the three business sectors for three milestones (PDR, CDR, ORR) comparison of SE Hours spread to all project hours spread to each milestone by schedule project performance – all green and non-green – including pattern and trend notes,
- SE Hours average spread (by %) to milestones (PDR, CDR, ORR start, ORR start to project end) by business sector for all project performance,
- SE Hours average spread (by %) to milestones (PDR, CDR, ORR start, ORR start to project end) by business sector for only green performance in technical, cost and schedule,
- SE Hours average spread (by % in ranges) to milestones (PDR, CDR, ORR start, ORR start to project end) by business sector for only green performance in technical, cost and schedule and for defects (QN) < reference project average,

- SE Hours average spread (by %) to milestones (PDR, CDR, ORR start, ORR start to project end) by business sector for only non-green performance in technical, cost and schedule,
- SE Hours average spread (by % in ranges) to milestones (PDR, CDR, ORR start, ORR start to project end) by business sector for only green performance in technical, cost and schedule, green risk (practiced risk management) and for defects (QN) < reference project average,
- SE Hours average spread (by % ) to milestones (PDR, CDR, ORR start, ORR start to project end) for each business sector for only green performance in technical, cost, and schedule, green risk (practiced risk management), and for defects (QN) > reference project average,
- SE Hours average spread (by %) to milestones (PDR, CDR, ORR start, ORR start to project end) for each business sector for only green technical performance comparing green technical performance to all performance ratings,
- SE Hours average spread (by %) to milestones (PDR, CDR, ORR start, ORR start to project end) for each business sector for only non-green technical performance comparing non-green technical performance to all performance ratings,
- SE Hours average spread (by %) to milestones (PDR, CDR, ORR start, ORR start to project end) for each business sector for only green risk performance (practiced risk management) comparing green risk performance to all performance ratings,
- SE Hours average spread (by %) to milestones (PDR, CDR, ORR start, ORR start to project end) for each business sector for only non-green risk performance comparing non-green risk performance to all risk ratings,
- SE Hours average spread (by %) to milestones (PDR, CDR, ORR start, ORR start to project end) for each business sector for only green cost performance comparing green cost performance to all cost performance ratings,
- SE Hours average spread (by %) to milestones (PDR, CDR, ORR start, ORR start to project end) for each business sector for only non-green cost performance comparing non-green cost performance to all cost performance ratings,
- SE Hours average spread (by %) to milestones (PDR, CDR, ORR start, ORR start to project end) for each business sector for only green schedule performance comparing green schedule performance to all schedule performance ratings,
- SE Hours average spread (by %) to milestones (PDR, CDR, ORR start, ORR start to project end) for each business sector for only non-green schedule performance comparing non-green schedule performance to all schedule performance ratings,
- SE Hours average spread (by %) to milestones (PDR, CDR, ORR start, ORR start to project end) for each business sector for only design defects (QN) < reference project average comparing to all design defect averages,
- SE Hours average spread (by %) to milestones (PDR, CDR, ORR start, ORR start to project end) for each business sector for only design defects (QN) > reference project average comparing to all design defect averages,
- SE Hours average spread (by %) to milestones (PDR, CDR, ORR start, ORR start to project end) for each business sector for only process defects (QN) < reference project average comparing to all process defect averages,

- SE Hours average spread (by %) to milestones (PDR, CDR, ORR start, ORR start to project end) for each business sector for only process defects (QN) > reference project average comparing to all process defect averages,
- SE Overtime (OT) Hours analysis and summary – patterns associated with project milestones, project performance issues (yellow, red for technical, cost, or schedule), defect profiles, and releases (late, with errors),
- Risk profile analysis and summary – patterns and trends associated with risk profiles (NFR, MR) and SE Hours (NRE, RE) distributions and project performance and an assessment for each project,
- Defect profile analysis and summary – CT – patterns and trends associated with the five projects which have CT release data – release duration in months and number of releases from initial to final – and the SE Hours distribution for the project and project notes,
- Defect profile analysis and summary – QN - patterns and trends – for each project - associated design and process QN and SE hours, averages for the referenced projects, number of design QN to total QN, number of process QN to total QN, number of design QN and process QN which required rework or repair, percentage requiring rework or repair to total QN and defects per 1,000 SE Hours to referenced project hours. QN defect density compared to SE Hours distribution is included when available. The summary used the if/then format sharing QN (design, process) > average and < average under certain SE Hours conditions by each of the three business sectors,
- Defect profile analysis and summary – Releases – patterns and trends – for each project – by late/on-time releases and by error-free/error releases – with project notes comparing project performance and impact of defect – using the if/then format for the summary trends and patterns.

The trends and patterns identified in the summaries are indicators of project performance mapped to SE hours distributions. By using these SE hours, project performance, risk, and defect data analysis summaries, both competitive bid teams and projects have insight and awareness of the impact of SE hours distribution on project performance. This insight can mitigate project issues by using the risk management process for the given SE value. The numerous summaries available from RQ2 data analysis form the quantitative component of the SEaaS framework.

### *Communicating Qualitative Data Analysis*

For the qualitative component of the SEaaS framework, results from a SE-DE survey and SE-DE impact summary are inputs. Similar to the quantitative component, systems thinking concepts and the Iceberg Model tool are applied to determine trends, patterns, and indicators determining the structure of SE value in a DE transition and on a project executing DE.

## *SE-DE Survey*

The SE-DE survey questions are created with the goal of gathering qualitative insight from experienced systems engineers. This qualitative insight enables decision-makers on competitive bids and on projects to have an appreciation of SE value in successful project execution. This appreciation of SE value is from the perspective of systems engineers with significant experience on both successful and challenged projects with various SE hours distributions. For example, if the competitive bid team is challenged to reduce the SE effort estimate, this qualitative data complements quantitative data and enables the bid team to understand the risks associated with a different SE value range by reviewing the survey results covering this SE effort challenge. The survey focused on:

- SE effort in competitive bids,
- SE effort in project execution,
- Impact of reduced or challenged SE hours to successful project performance,
- Impact of DE on SE.

In addition to system thinking concepts, the SE-DE survey integrates the structure of a balanced scorecard (customer/finance/process/learning) with survey questions highlighting customer/industry/organization expectations regarding SE value and DE, SE effort and cost, anticipated DE cost benefits, SE-DE process impact, and DE transition enablers (learning). The balanced scorecard structure is a qualitative way to capture the multi-attribute nature of value. The survey respondent audience is senior SE leaders with over 15 years of practical SE experience. In addition to qualitative input for the SEaaS framework, multiple organizations are using the survey results to understand SE culture in the DE transition and to shape organizational DE training plans.

## *SE-DE Impact Summary - Project Experiences*

In addition to the SE-DE survey, qualitative data related to SE-DE includes experiences with SE leaders on projects which are executing DE and with leaders who are participating in the DE transition. A transition to DE is expected to improve the management and exchange of exponentially growing sources

of information, data, and knowledge spanning an organization [39]. The qualitative data relating to these experiences are collected via informational interviews and emails. The informational interviews are held with SE representatives of the projects executing in DE either completely or partially (only limited DE applications). Email exchanges with SE leaders focus on the impact of DE on SE: guidance, benefits, and challenges with implementing DE. Relationships developed with SE leads on projects allow for multiple informational interviews and emails over 12+ months which tracked progress, challenges, and benefits of DE in project execution. Leaders, who are participating in DE transition, include those with roles establishing DE policy, tracking DE training and transition progress, and evaluating competitive bids for application of DE and anticipated savings. As the result of presenting this research at internal technical forums, several relationships and informational interviews followed from technical forum participant information exchanges. These exchanges provide an individual contributor's perspective of DE challenges and benefits in implementation. These information exchanges provide diverse perspectives on SE-DE project experiences.

### *Empowering Engineers in the DE Transition*

As noted in RQ2, as an organization transitions from traditional document-based SE (TDSE) to DE, engineers are critical in accepting and implementing this organizational change. The DE transition impacts established engineering tools, processes, and practices in which the engineers have confidence and know well. This research analyzes the DE transition from organizational psychology and systems thinking approaches resulting in three proposed actions focusing on knowledge transfer, training, and communication. The goal of this research is to empower engineers in the DE transition and impact the culture/mental model of the engineers.

As noted in RQ1, this research includes pilots and their associated results, lessons learned, and application to the SE-DE impact. From the knowledge transfer action, a structured three-month knowledge transfer activity with a kickoff, objectives, monthly feedback, evaluation, job redesign, and survey on impact and

improvements is implemented. From the training action, MBSE is introduced to the SE team and a training plan, survey, and tool specific (Cameo) training are completed. Based on feedback from the SE team after training completed, an on-demand SME/coach to accelerate learning is implemented. From the communication action, a need for an automation startup kit is identified based on experience with implementing automation on a project. Partnering with the project automation SME, an automation startup kit is created. The automation startup kit includes a framework with an automation assessment, plan structure, and business case to evaluate automation. The startup kit whitepaper provides advice, challenges, and lessons learned in implementing automation as part of a project's DE transition. By completing each of the three actions, the recommended actions to empower engineers in the DE transition is 'tested'.

The qualitative data inputs into the SEaaS framework include SE-DE survey results from experienced SE leads on projects, a summary of project experiences implementing DE on projects, and actions empowering engineers to enable a successful DE transition.

#### *Communicating Associated References*

Supplementing the quantitative and qualitative inputs into the SEaaS framework are several references supporting SE value and the impact of DE on SE. Tracking progress with the DE transition involves metrics. Although the industry is still defining DE metrics, two assessments completed for this research advance the DE metrics discussion. The first of the two assessments compares organization metrics to SERC DE metrics [22], [54] and INCOSE SE leading indicators [13]. The comparison is completed from a DE perspective and with the goal of recommending a change to the organization metrics. The second of the two assessments focuses on MBSE and with the goal of identifying Measures of Effectiveness (MOE) and mapping benefit enablers to realize reduced schedule, defects, and risk as the result of utilizing MBSE in DE.

In summary, the tasks for RQ3 focus on communicating the SE value and analysis in RQ2 with data collected in RQ1 using the new SEaaS framework. The components of this framework include quantitative and qualitative data enabling more informed decisions and greater risk awareness as competitive bid teams determine the value of SE in the proposal. The feedback loops comparing SE value in previous competitive bids and projects aligned to project performance allow for more informed decisions regarding SE value. The qualitative data available to decision makers provides an expert perspective on increasing or decreasing SE effort and potential impacts of this decision. Understanding these potential impacts enables new insights and awareness for the bid and project teams allowing risk management practices to mitigate potential negative impacts. Chapter 7 details the data analysis and results summaries enabling these insights and awareness as competitive bid teams determine SE value for their proposal and projects distribute their SE effort in hours across the project lifecycle positioning for positive project performance.

## Chapter 7 - Research Results

In completing the Research tasks detailed in the prior two chapters, the results of these tasks are documented in this chapter.

### **RQ1: Results for ‘How to quantify the value of Systems Engineering?’**

The focus of the organization research is the value of SE in competitive bids. As noted in the literature search (Chapter 4), the value of SE is realized in project performance against cost, schedule, and technical objectives. External industry research and internal organization resources shape the data collection tasks associated with this RQ. The results of RQ1 include the quantification of SE value for competitive bid teams and for projects citing external industry research. The value of SE includes DE impact on SE. With SE value defined, data is collected to support the quantification and determination of SE value in competitive bids.

#### *Industry Research Literature and Conferences*

Industry research on the value and the effectiveness of SE and cost models applicable to this research is summarized in the literature search chapter. Several notable extractions from these industry articles capture the value and effectiveness of SE:

- Delivering SE value to the organization includes greater emphasis on understanding, anticipating, and managing technical risks. Tradeoffs across stakeholder priorities and perceptions of value are incorporated into the value strategy. Managing technical risks and tradeoffs (trade studies) are SE activities directly aligning this general technology definition of value to SE value [12].
- The concept of value is complicated by the evolving nature of stakeholder priorities and concerns. A value strategy should provide expected quality (or better) at competitive cost relative to the innovative characteristics of the product or service [12].
- Increased value from SE can be realized with enabling processes focusing on process innovation and tailoring. SE value is realized by using these processes to balance fixed requirements with a flexible system adaptable to a changing environment [28].
- Of interest to this research, the results of studies are summarized as the optimal SE effort at 15-20% of total project effort. A systems thinking approach to product design and risk saves the project time and cost, contributing to the intrinsic value of SE. The value of SE is also realized

by applying SE effort to reduce risk early and prevent integration and test problems from occurring [11].

- Early studies measure SE value directly in terms of perceived value: system technical quality, risk avoidance and problem discovery [36].
- SE effectiveness is assessed as adequate SE to accomplish a purpose, producing the intended or expected result. SE effectiveness is decomposed into product quality/quality of SE artifact content, cost, and schedule (timeliness). Comparing SE effectiveness to Earned Value, rework is unearned value. Requirement compliance and requirement quality (verifiability) are shared as potential metrics to measure SE effectiveness [14].
- An inherent problem with research into the effectiveness of SE is that nobody ever performed two identical projects - one with and one without SE [4].

From these industry articles, the value of SE is defined as managing risk through SE processes, including trade studies, and assessing innovation, to deliver product meeting requirements on schedule and within budget. SE effectiveness is defined as accomplishing these product delivery goals with an understanding of quality and compliance. The components of these two definitions drive the data collection efforts for this RQ. Costing models attempt to quantify SE value with COSYSMO as the most renown model. The COSYSMO model fills a need in SE effort estimation [7]. The COSYSMO model has application to this research as the development of this SE cost model considers factors which are applied to the organization data collection and analysis. As COSYSMO evolves, other software and systems engineering cost models are reviewed for gaps and overlaps with the intent to harmonize the estimates for a project [7]. This review has application to this research as clarity in estimating SE effort aligns to determining SE value in competitive bids. If there are gaps or overlaps with SE effort included in the bid, the result is an under or over estimation of needed SE effort. Inaccuracy around the SE estimation drives uncertainty around the value of SE in competitive bids and the impact of SE to the success of projects.

### *Organization Research*

Studies and parametric estimating (cost models) are focused on SE effort and SE effectiveness.

Understanding the goal and focus of these studies, as well as existing organizational tasks, processes, practices, and feedback loops, shape this research. After reviewing organizational practices, gaps related to determining SE value for competitive bid were identified. Gaps include comparing the bid and project

SE effort, SE hours, project performance, risk management, quality (defect profiles), and the impact of DE on SE which this research assesses. The systems thinking and feedback loops, which this research applies, enable a more holistic approach to the SE value and SE effectiveness assessment. Parametric estimating practices and cost models should evolve using this research data analysis. Summarizing the literature search findings, SE value has an intrinsic definition of managing risk through SE processes, including trade studies, and assessing innovation, to deliver product meeting requirements on schedule and within budget. SE effort is expressed as the percentage of SE hours to total project hours. SE value applies to the estimate of SE hours in a competitive bid or the actual SE hours expended on a project and resulting performance. The SE value can also be found in the implementation of SE processes, in the effort bid and in expended labor dollars/hours, and via return on the SE investment. Although the focus of this research is the determination of SE value in competitive bids, the results of this RQ are applicable to projects in new change requests, re-baselining efforts, and addressing actions from periodic internal reviews, independent assessments, or risk management. For both the competitive bids and projects, SE value, quantified by percentage of SE effort (hours) to total project hours, is indicative in the successful execution of the bid and project.

### *Data Collection*

Industry studies estimate optimal SE efforts at 15-20% of total project effort [1], [2], [10], [11], [51]. This range becomes a benchmark and point for comparison as this research data collection begins. Data sources from three different organizations include:

- Reference Projects - with data collection sources including organization tools and informational interviews with data owners,
- SE Hours in projects – with data collection sources including Excel spreadsheets of organizational tools and informational interviews with data owners,
- Risk Profile – with data collection sources including Net Factored Risk (NFR), Management Reserve (MR) and Contract Value (CV) from the organizational project tracking tools and informational interviews with data owners,

- Defect Profile – with data collection sources including Change Tasks and Releases from organizational tools, Release and Quality Notes (spreadsheet) and informational interviews with data owners,
- DE Impact on SE – with data collection sources including informational interviews and email exchanges with project contacts and leads implementing the DE transition,
- DE metrics – with data collection sources including industry [22], [53], [54], [63], [64] and organization metrics assessment and development of Model Based Systems Engineering (MBSE) Measures of Effectiveness (MOE),
- DE pilots – with data collection sources including knowledge transfer, training, and communication (startup kit) initiated for this research based on recommended actions [65] in the Appendix.

RQ1: Notes and Observations collected from research and informational interviews for this research practicum

- SE value quantifies the impact of SE and cost as a function of schedule.
- SE hours bid in the proposal are typically not equal to the SE hours allocated on the project as technical or management reserve is extracted. Organizations may combine technical and management reserve and track only management reserve (MR). Note: To align data for this research from multiple organizations, MR is referenced and is used in data analysis. The contribution to MR is not included in the SE estimate, especially if historical actuals from a similar project are used as justification. SE hours distribution starts with a challenge in the project if SE hours are less than the SE effort (hours) in the bid.
- It is not unusual for two different SE teams to work the competitive bid and the project. Challenges and issues noted during the proposal may not transition into the project or be identified as risks so they can be managed. Risk management should be established early in or prior to project execution.
- The SE hours in the competitive bid are not the sole indicator or guarantee of SE quality to be performed in the project. SE effort at the recommended level does not guarantee a successful project. SE processes need to be executed by a competent SE team which creates SE value. Intangibles, internal project, and external/customer issues impact project execution. Cost overruns can still happen with good SE, but SE processes can mitigate/ 'smooth out' the impact.
- Technical management should include issue management - when issues happen, how are they identified and addressed. If a project has a failure, is the project prepared to address it. Resilience is how a system or project responds when a risk is realized.
- Optimizing SE is a highly interdependent activity with many variables. SE value is impacted by the project organizational structure, culture, and customer. Encourage trade studies to widen the solution space/optimize schedule, cost, capabilities.
- Focus on risk management, not risk mitigation [45].
- If SE hours are decreased, track the potential impacts as risks.

The goal of RQ1 is to enable competitive bid teams to quantify SE value within the proposal context and make data-driven decisions relative to the SE estimate while managing risk if the bid is less than recommended SE effort. SE value, SE effort (hours), SE effectiveness, and SE cost models were initially examined using industry articles. This examination shapes the research definition of SE value and the data collection which quantifies and qualifies it. The focus of RQ1 is the data collection supporting RQ2 data analysis. Notes and observations captured during RQ1 tasking are shared. This RQ contains original research as there are currently no organizational feedback loops between a project and its competitive bid using systems thinking concepts and a holistic perspective of SE as a contributor to project performance assessing risk profiles, defect profiles, and DE impact.

**RQ2: Results for ‘How to analyze this quantification to provide justification for bid SE effort ranges and associated project results?’**

The RQ2 research results quantify SE value using the data collected in RQ1 results. The focus of RQ2 is to review and to analyze the data and to determine any correlation of SE effort to project performance and to risk mitigation considering contract size, project characteristics, and other intangibles. Systems thinking concepts are applied and the Iceberg Model tool is utilized to determine correlations, patterns, trends, and indicators at two levels of data analysis – project and system. The data analysis is completed for each reference project at the project-level. The data analysis is also completed at the system-level assessing all project-level data analysis in aggregate. At the system-level, the value of SE in competitive bids is determined mapping the projects to SE hours ranges by business sectors and including performance (technical, cost, schedule as green, yellow, or red). Business sector and industry averages are included as benchmarks or reference points. The SE-DE impact results focus on understanding DE experiences on projects related to SE impact enabling a more informed decision regarding SE value in competitive bids as customers and organizations transition to DE. These results are based on qualitative data analysis using informational interviews, survey results, and metrics assessments. The types of analysis for each project is detailed in the next section.

## *Project-level Data Analysis Results*

For each of the 20+ projects across three business sectors, results of the data analysis include:

- Project characteristics – description, product, contract type, contract size in dollar value, business sector, customer, milestone (PDR, CDR, ORR) dates and timing relative to project lifecycle, and intangibles,
- SE Effort – bid vs project (percentage of SE hours to total project hours), compared to business sector average and industry average,
- Project (not just SE) skill mix (average level) compared to business sector average,
- Project complexity (SE NRE hours/total project hours) compared to business sector average,
- SE hours distribution or spread over project lifecycle,
- Normalized SE hours distribution or spread over project lifecycle,
- SE hours to each milestone (PDR, CDR, ORR start), compared to business sector average,
- SE hours in percentage to each milestone (PDR, CDR, ORR start), compared to business sector average representing SE spread or distribution over project lifecycle,
- SE months (number of) to each milestone (PDR, CDR, ORR start), compared to business sector average,
- Project performance against technical baseline rated green/yellow/red, rating duration (weeks or months), and placement (timing) in the project lifecycle,
- Project performance against cost baseline rated green/yellow/red, rating duration (weeks or months), and placement (timing) in the project lifecycle,
- Project performance against schedule baseline rated green/yellow/red, rating duration (weeks or months), and placement (timing) in the project lifecycle,
- Overtime (OT) hours data incurred by project staff with SE job titles for total, compensated and uncompensated SE OT hours. OT SE hours are graphed with distribution over project lifecycle and compared against regular (first 40 hours in a work week) SE hours over lifecycle. Average OT hours (percentage) compared to regular SE hours is noted. Only SE OT hours are used in this research.
- Risk Profile – assessment of risk management – Net Factored Risk, Management Reserve and Contract Value are graphed over the project lifecycle with analysis results noted,
- Defect Profiles – assessment of Change Tasks (number of months and number of releases from initial to final) over the project lifecycle with analysis results noted,
- Defect Profiles – assessment of project quality using Quality Notes (QN) for design over the project lifecycle: graphed and mapped to SE hours, to total OT hours, to SE hours normalized with a comparison using corrective action codes, number of QN for design vs all QN, percentage of design QN to reference project design QNs, number of corrective actions requiring rework or repair, percentage of corrective actions requiring rework or repair and design QN per 1,000 SE hours compared against reference project average. If available, QN defect density is mapped to SE hours and to normalized SE hours with analysis results noted.

- Defect Profiles – assessment of project quality using Quality Notes (QN) for process over the project lifecycle: graphed and mapped to SE hours, to total OT hours, to SE hours normalized with a comparison using corrective action codes, number of QN for process vs all QN, percentage of process QN to reference project process QNs, number of corrective actions requiring rework or repair, percentage of corrective actions requiring rework or repair and process QN per 1,000 SE hours compared against reference project average.
- Defect Profiles – assessment of Releases both on-time and late over the project lifecycle graphed and mapped to SE hours, to SE hours normalized, to OT hours and to SE hours (NRE, RE, total) – over the project lifecycle including project performance (technical/cost/schedule rated green, yellow, red) with analysis results noted.
- Defect Profiles – assessment of Releases both error-free and with errors over the project lifecycle graphed and mapped to SE hours, to SE hours normalized, to OT hours and to SE hours (NRE, RE, total) – over the project lifecycle including project performance (technical/cost/schedule rated green, yellow, red) with analysis results noted.
- Project-level summary includes SE value determined by SE effort bid, SE effort on project with both bid and project compared to industry and business sector averages, assessment of project performance (color ratings), risk management and defects (change task, QN, releases) against averages for referenced projects.

The data analysis at the system-level assessing all project-level data analysis in aggregate is key to the research findings and is summarized in the next section.

### *System-level Data Analysis Results*

At the system-level, the value of SE in competitive bids is determined by mapping the projects to SE hours ranges (percentages) by business sector and by including performance (technical, cost, schedule as green, yellow, or red), risk management, and defect profiles using quantitative data analysis. Business sector and industry averages are included as benchmarks or reference points. The SE-DE impact results focus on understanding DE experiences on projects related to SE impact enabling a more informed decision regarding SE value in competitive bids as customers and organizations transition to DE. These SE-DE results are based on qualitative data analysis using informational interviews, survey results, and metrics assessments. The system-level results of the data analysis, both quantitative and qualitative, by all projects, and by each of the three business sectors, include:

- Determining Value of SE in Competitive Bids - aligning each project and each business sector by SE value range (percentage) in the projects noting color rating of technical, cost, schedule performance,

- SE Value Ranges by each business sector and by all projects with data analysis results ratings (green and red) for risk, design defects and process defects against reference project averages,
- SE Value Ranges for each of the three business sectors and by all projects with data analysis results ratings (green, yellow, red) for technical, cost, schedule performance and for risk, design defects and process defects against reference project, business sector, and industry averages with notes,
- SE Value (bid and project) for each of the three business sectors and by all projects with data analysis results ratings (green, yellow, red) for technical, cost, schedule performance and for risk, design defects and process defects against reference project, business sector and industry averages and comparing the duration in months to each milestone (PDR, CDR, ORR, and total project) against the business sector average duration and noting results (red, green).

The results of this quantitative data analysis align with the findings in the literature search noting the recommended SE effort is in the range of 14-16% of project total. Factors which may impact this SE effort range include skill level/team experience, project complexity, and maturity of tools used. These results by business sector (identified by A, B, C), by business sector project (identified by a letter and number) and by SE value ranges are mapped as shown in Figure 13. From this figure, the competitive bid team has project performance results indicated as green, yellow, or red for technical (T), cost (C), or schedule (S) mapped to the project SE hours as a percentage of total project hours. Business sector C does indicate all green results for three value ranges allowing the competitive bid team the flexibility to include other factors as noted previously when recommending an SE value range.

The range with the most project success as measured by technical, cost, and schedule is the 14- 16% range which aligns to industry references of 15%. Note that the higher percentage ranges for SE value do not contain all green ratings. SE value may not be as efficiently applied on projects at higher ranges or SE is applied with diminishing returns at higher value. Lower SE value ranges do not support the minimal SE activities which contribute to successful project execution.

The next several sections detail the analysis and results which support Figure 13. SE hours distribution analysis and results describes the identification of SE hours distribution patterns and corresponding project performance with multiple variables and perspectives. SE Overtime hours distribution analysis and results are described with correlation of patterns and project performance. Risk management is

| Business Sector              | SE Value 8 – 10%         | SE Value 11 – 13% | SE Value 14 – 16%  | SE Value 16 – 18%                      | SE Value 18 – 20% |
|------------------------------|--------------------------|-------------------|--|--|-------------------|
| A                            |                          | A5 (T/C/S)        | A1 (T/C/S)<br>A2 (T/C/S)<br>A6 (T/C/S)<br>A7 (T/C/S)<br>A4 (T/C/S) | A8 (T/C/S)                             | A3 (T/C/S)        |
| B                            | B2 (T/C/S)<br>B1 (T/C/S) | B4 (T/C/S)        | B6 (T/C/S)   | B5 (T/C/S)                             | B3 (T/C/S)        |
| C                            |                          | C7(T/C/S)         | C5 (T/C/S)<br>C4 (T/C/S)<br>C6 (T/C/S)<br>C8 (T/C/S)               | C1 (T/C/S)<br>C2 (T/C/S)<br>C3 (T/C/S) |                   |
| Business Sector SE % Average |                          | B                 | A<br>C<br><b>Industry</b>  |  |                   |

Figure 13: Project performance mapped by ranges of SE hours in percent of total project hours

assessed using net factored risk (NFR), management reserve (MR) and project contract value (CV) to determine if risk management was actively practiced and the correlation of risk management to project performance. Defect profile analysis is conducted for multiple defects to identify patterns correlating to project performance. Results for each data analysis section are included with figures (Figures 14-35).

#### SE Hours Distributions Analysis and Results

Supporting the recommended SE value range identified in Figure 13, allocating SE hours over the project lifecycle was analyzed for patterns or trends of SE hours distribution (or spread) most common with successful project performance. Representative project data for the project-level data analysis results is shared in the next several figures. For each project, total SE hours and total normalized SE hours over the lifecycle is the start of the data analysis. System-level analysis is conducted using all reference projects in aggregate seeking to identify patterns and impacts among multiple SE hours distributions and various project performances. Technical, cost, or schedule yellow or red performance ratings are depicted in yellow or red blocks spanning the performance rating duration in the lifecycle. By including these key data points and conditions, patterns related to SE hours and these data points are included in the analysis.

Figure 14 is a representation of the SE hours analysis generated for each project. Key project milestones (PDR, CDR, ORR) are noted in the graphs corresponding to the time or month in the lifecycle.

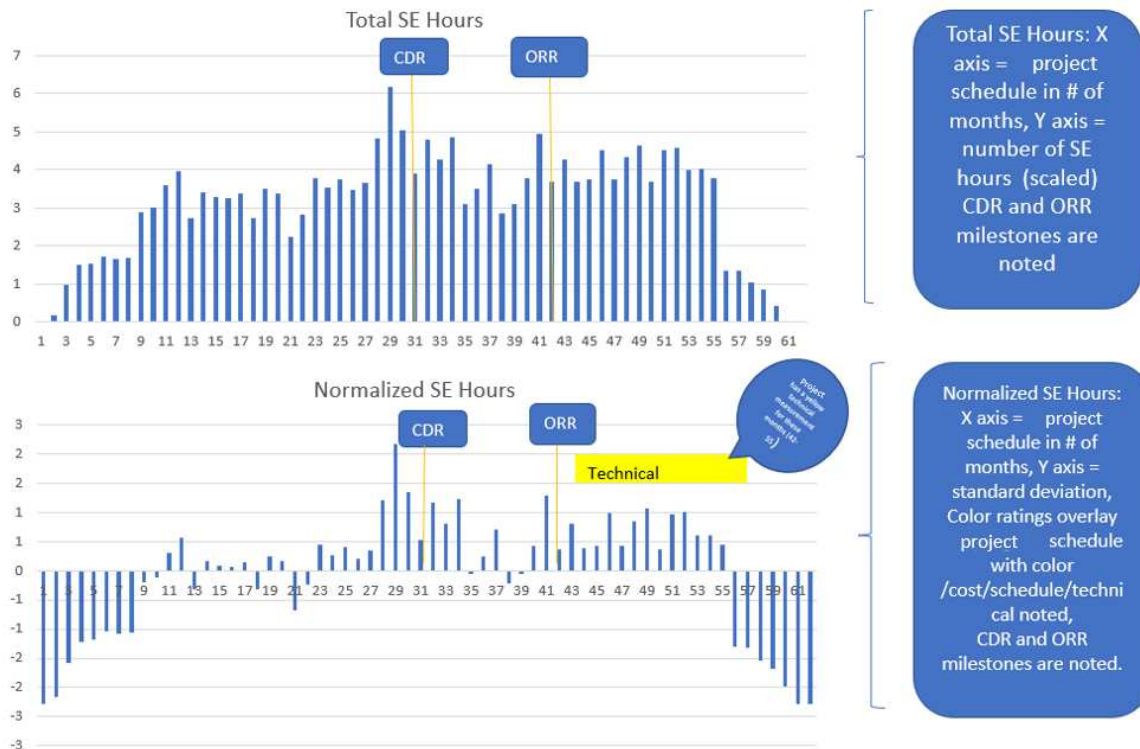


Figure 14: SE Hours - total and normalized over the project lifecycle

Figure 14 has representative project data to illustrate the SE Hours data analyzed. The graph X axis is the months (by number) of the project schedule. The graph Y axis is the scaled number of SE hours with project milestones indicated. SE hours and normalized SE hours are mapped by aligning project schedule (X axis). Additional data analysis focusing on pattern, trends, and impacts of SE hours distribution and project performance includes:

- SE Hours mapped to Technical Performance – all technical performance, only green technical performance, and only non-green (yellow, red) technical performance,
- SE Hours mapped to Cost Performance – all cost performance, only green cost performance, and only non-green (yellow, red) cost performance,
- SE Hours mapped to Schedule Performance – all schedule performance, only green schedule performance, and only non-green (yellow, red) schedule performance,
- SE Value (bid and project) for each of the three business sectors and by all projects with data analysis results ratings (green, yellow, red) for technical, cost, schedule performance and for risk,

design defects and process defects against reference project, business sector and industry averages and comparing the SE percent (spread or distribution) to/between each milestone (PDR, CDR, ORR and total project) against the business sector average duration and noting results (red if above average or green if below average),

- By each of the three business sectors, project characteristics of contract type, contract size, customer, product, staffing level and complexity with data analysis results ratings (red, green) compared to business sector average,
- SE Value, for all projects (system) and by each of the three business sectors, analysis results by PDR milestone date for a trend (increasing or decreasing) in SE effort in bid and in projects over time with results captured in a table by business sector and graph,
- SE Hours (spread/distribution) to Milestones (PDR, CDR, ORR) analysis results by each of the three business sectors and at system-level considering performance (all performance, all green tech/cost/schedule), risk management and defect profiles and graphed.
- SE Hours (spread/distribution) to Milestones (PDR, CDR, ORR) analysis results by each of the three business sectors and at system-level not considering performance with a business sector by business sector by business sector comparison of SE hour spreads across the project and by each milestone with graphs,
- SE Hours (spread/distribution) to Milestones (PDR, CDR, ORR) analysis results by each of the three business sectors and at system-level comparing green technical performance against non-green (yellow/red) technical performance and graphed with analysis results notes added,
- SE Hours (spread/distribution) to Milestones (PDR, CDR, ORR) analysis results by each of the three business sectors and at system-level comparing green cost performance against non-green (yellow/red) cost performance and graphed with analysis results notes added,
- SE Hours (spread/distribution) to Milestones (PDR, CDR, ORR) analysis results by each of the three business sectors and at system-level comparing green schedule performance against non-green (yellow/red) schedule performance and graphed with analysis results notes added,
- SE Hours (spread/distribution) to Milestones (PDR, CDR, ORR) averages by each of the three business sectors individually and by grouping two business sectors (due to available data) and by total for the three business sectors. This analysis expands the SE hours distribution to the entire project lifecycle with a summary of SE Hours through ORR and through project completion. Analysis results by each of the three business sectors and at system-level are for all performance ratings.
- SE Hours (spread/distribution) to Milestones (PDR, CDR, ORR, project end) for each business sector for green technical, cost, and schedule distributions only and comparing these green distributions against each business sector individually, against two business sectors and against the three business sector averages with analysis results notes,
- SE Hours (spread/distribution) to Milestones (PDR, CDR, ORR, project end) for each business sector for green technical, cost, and schedule distributions only and defects < reference project average and comparing these green distributions against each business sector, two business sectors, and the three business sector averages (reference projects and all business sector projects) with analysis results notes,
- SE Hours (spread/distribution) to Milestones (PDR, CDR, ORR, project end) for each business sector for non-green (yellow/red) technical, cost, and schedule distributions only and comparing these non-green (yellow/red) distributions against each business sector, two business sectors and the three business sector averages with analysis results notes,

- SE Hours (spread/distribution) to Milestones (PDR, CDR, ORR, project end) for each business sector for green technical, cost, and schedule distributions plus green risk (risk management is practiced) and defects < reference project average and comparing these green distributions against the three business sector averages with analysis results notes,
- SE Hours (spread/distribution) to Milestones (PDR, CDR, ORR, project end) average for each business sector for green technical, cost, and schedule distributions plus green risk (risk management is practiced) and defects < business sector average and comparing these green distributions against non-green (yellow/red) averages for the business sector with analysis results notes,
- SE Hours (spread/distribution) to Milestones (PDR, CDR, ORR, project end) average for each business sector for green technical comparing these green distributions against all technical performances averages for each business sector, for two business sectors and for the three business sectors with analysis results notes,
- SE Hours (spread/distribution) to Milestones (PDR, CDR, ORR, project end) average for each business sector for non-green (yellow/red) technical comparing these non-green (yellow/red) distributions against all technical performances averages for each business sector, for two business sectors and for the three business sectors with analysis results notes,
- SE Hours (spread/distribution) to Milestones (PDR, CDR, ORR, project end) average for each business sector for green cost comparing these green distributions against all cost performances averages for each business sector, for two business sectors and for the three business sectors with analysis results notes,
- SE Hours (spread/distribution) to Milestones (PDR, CDR, ORR, project end) average for each business sector for non-green (yellow/red) cost comparing these non-green (yellow/red) distributions against all cost performances averages for each business sector, for two business sectors and for the three business sectors with analysis results notes,
- SE Hours (spread/distribution) to Milestones (PDR, CDR, ORR, project end) average for each business sector for green schedule comparing these green distributions against all schedule performances averages for each business sector, for two business sectors and for the three business sectors with analysis results notes,
- SE Hours (spread/distribution) to Milestones (PDR, CDR, ORR, project end) average for each business sector for non-green (yellow/red) schedule comparing these non-green (yellow/red) distributions against all schedule performances averages for each business sector, for two business sectors and for the three business sectors with analysis results notes,
- SE Hours (spread/distribution) to Milestones (PDR, CDR, ORR, project end) average for each business sector for green risk (risk management is practiced) comparing these green distributions against all (any risk rating) averages for each business sector, for two business sectors and for the three business sectors with analysis results notes,
- SE Hours (spread/distribution) to Milestones (PDR, CDR, ORR, project end) average for each business sector for non-green (yellow/red) risk (risk management is not practiced) comparing these non-green (yellow/red) distributions against all (any risk rating) averages for each business sector, for two business sectors and for the three business sectors with analysis results notes,
- SE Hours (spread/distribution) to Milestones (PDR, CDR, ORR, project end) average for each business sector for green design defects (< average) comparing these green distributions against all design defect averages for each business sector, for two business sectors and for the three business sectors with analysis results notes,

- SE Hours (spread/distribution) to Milestones (PDR, CDR, ORR, project end) average for each business sector for non-green design defects (> average) comparing these non-green (yellow/red) distributions against all design defect averages for each business sector, for two business sectors and for the three business sectors with analysis results notes,
- SE Hours (spread/distribution) to Milestones (PDR, CDR, ORR, project end) average for each business sector for green process defects (< average) comparing these green distributions against all process defect averages for each business sector, for two business sectors and for the three business sectors with analysis results notes,
- SE Hours (spread/distribution) to Milestones (PDR, CDR, ORR, project end) average for each business sector for non-green (yellow/red) process defects (> average) comparing these non-green (yellow/red) distributions against all process defect averages for each business sector, for two business sectors and for the three business sectors with analysis results notes

The results for each of these completed analyses are summarized in the next several figures and descriptions. Figure 15 depicts the graph of the percentage of SE hours to milestones for all project performance for business sector A and B. This data analysis identifies patterns and trends relative to SE hours distribution over the lifecycle of the project and the project performance.

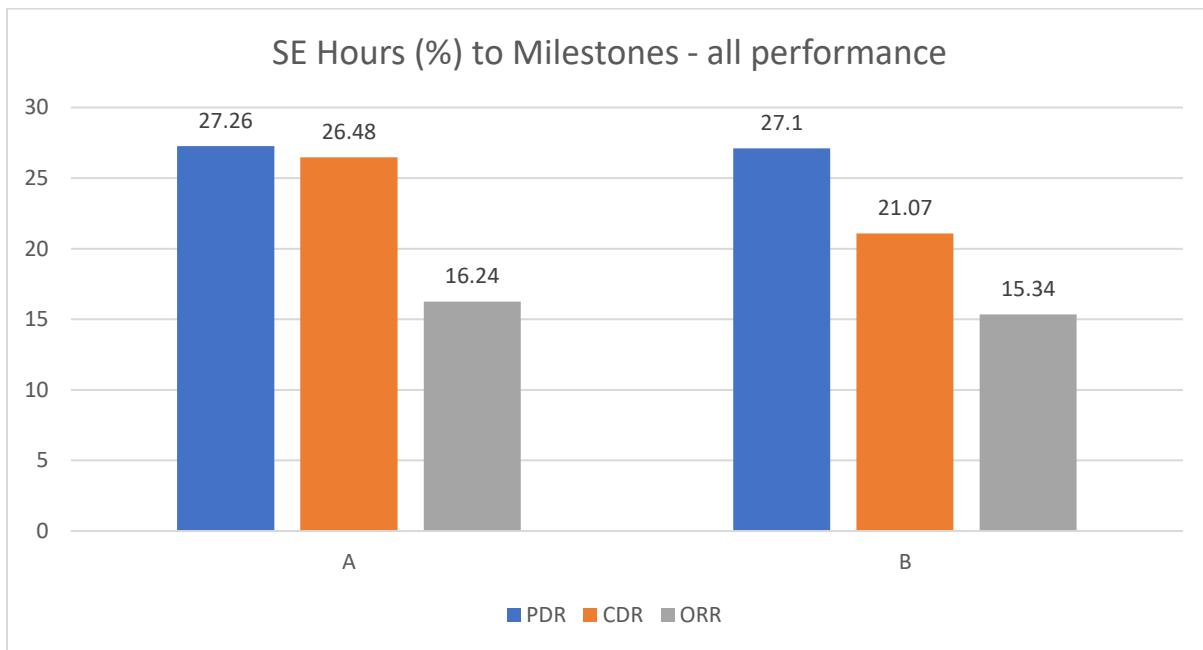
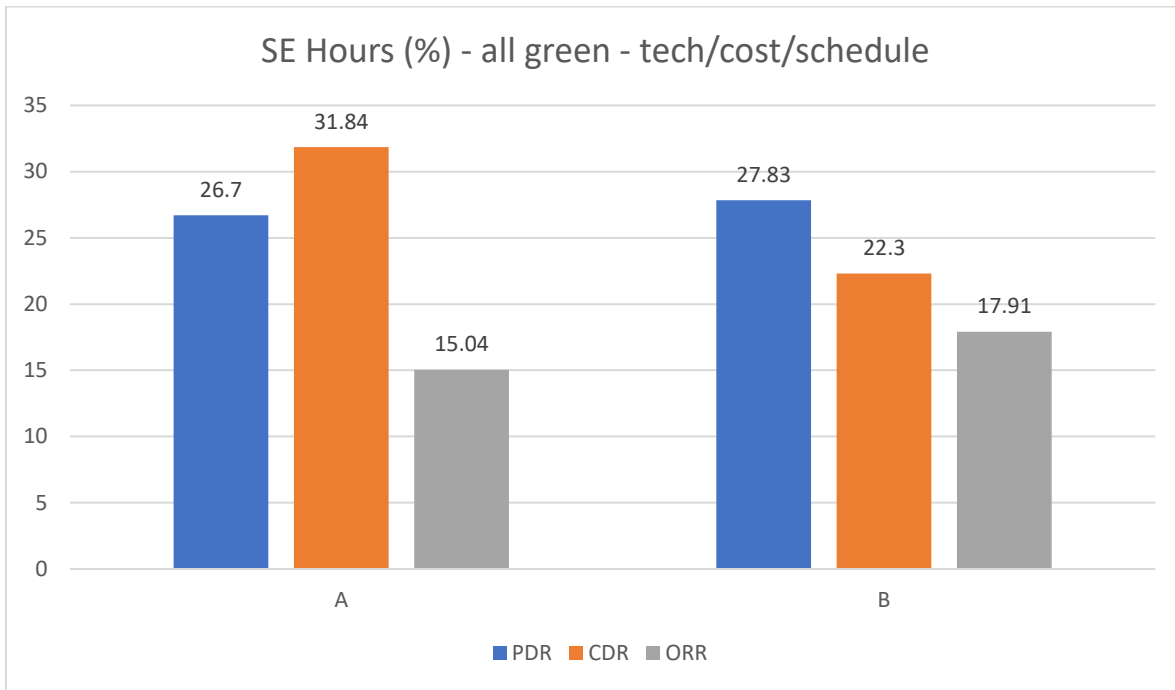


Figure 15: Distribution of % of SE hours to project milestones for all projects in two business sectors

By focusing on these three key milestone events, SE activities associated with product preliminary design, critical design, and operational readiness are represented through the percentage of SE hours supporting these milestone events relative to the entire SE hours distribution over the project lifecycle. The graph of

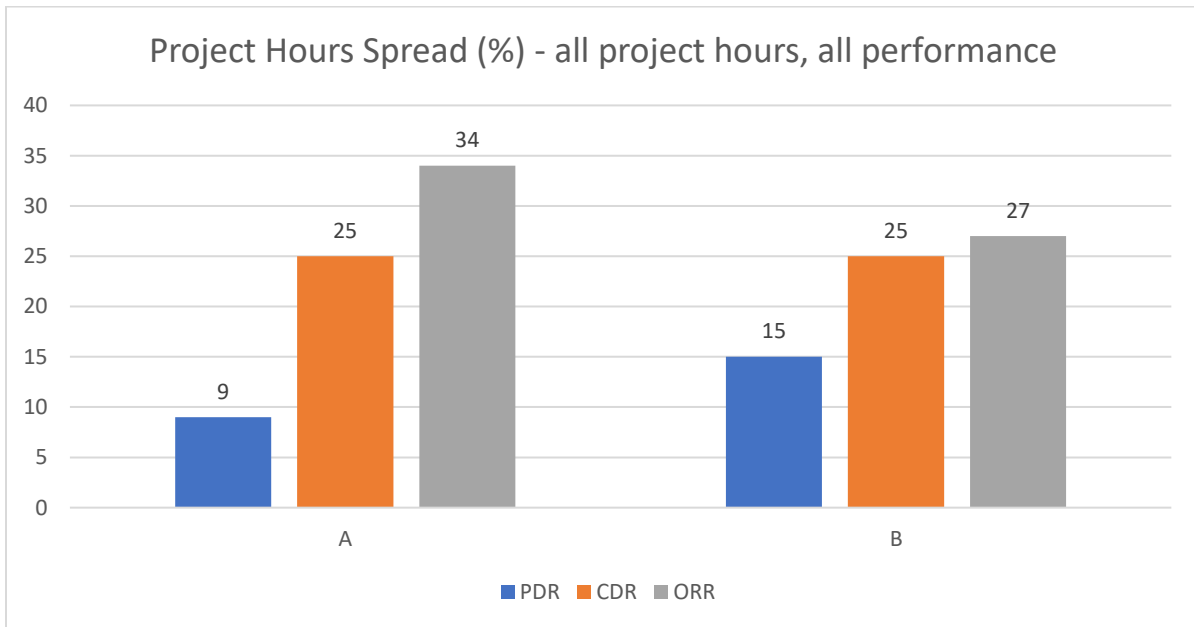
the percentage of SE hours to milestones for all projects with all green performance ratings (technical, cost, and schedule) is depicted in Figure 16. Similar to the analysis described around Figure 15, this pattern or data analysis focus is on the desired and nominal project performance of green technical, cost, and schedule green ratings.



*Figure 16: Distribution of % of SE hours to project milestones for two business sectors for projects with all green performance ratings*

The business sectors differ in organization, customer, product, and staff. Comparing business sectors for all performance and all green performance is more insightful given the business sector differences. For business sector A, the all-green performance has an average SE hours distribution which was significant at PDR, increased into CDR and then decreased. Nearly 60% of SE hours were spread to CDR allowing early identification of defects. For business sector B, the all-green performance front-loaded hours to PDR with a step down to CDR. This distribution has a more gradual decrease into CDR than the all performance distributions. The ratio of SE hours increases into CDR and gradually decrease into ORR for all green performance. The distribution compared to all performance distribution is notable and consistent with business sectors A and B.

The SE hours distribution over the project lifecycle differs from total project hours distribution as shown in Figure 17. For all project hours, the project starts at a low spread and steadily builds over the lifecycle. As project product teams ramp up, the hours are offset by other teams ramping down or with a lower distribution. This project-level data is added as a benchmark or as reference points.



*Figure 17: Distribution of % of total project hours to project milestones for the two business sectors for all performance ratings*

The results of data analysis for SE hours in percentage to milestones for projects with all green performance, practicing risk management, and with quality design and process defects less than business sector averages is shown in Figure 18. These SE hours are averages across business sectors. The average of these business sector SE hours distributions for desired project performance provide the basis for an SE hours distribution spread. Risk management and defect profile analysis and results are detailed in later sections in this chapter. This spread was determined for projects executing in TDSE, not DE. Projects executing DE are recommended to have a different SE hours distribution based on qualitative analysis detailed later in this chapter.

|                          | SE% average  | % SE Hrs to PDR Average | % SE Hrs to CDR Average | % SE Hrs to ORR start Average | Total % SE hrs for these three milestones | % SE hrs from ORR start to project completion |
|--------------------------|--------------|-------------------------|-------------------------|-------------------------------|---|---|
| Green Tech               | 14.41        | 22.23                   | 20.49                   | 13.24                         | 70.37                                     | 29.63   |
| Green Cost               | 14.68        | 21.41                   | 20.28                   | 13.73                         | 70.10                                     | 29.9  |
| Green Schedule           | 15.03        | 24.26                   | 21.94                   | 14.17                         | 75.4                                      | 24.6  |
| Green Risk               | 15.14        | 27.01                   | 26.22                   | 15.27                         | 83.64                                     | 16.36   |
| Design defects< average  | 14.2         | 25.69                   | 24.03                   | 15.03                         | 78.95                                     | 21.05   |
| Process defects< average | 15.7         | 30.55                   | 24.18                   | 16.37                         | 86.8                                      | 13.2  |
| <b>Average</b>           | <b>14.86</b> | <b>25.19</b>            | <b>22.86</b>            | <b>14.64</b>                  | <b>77.54</b>                              | <b>22.46</b>                                  |

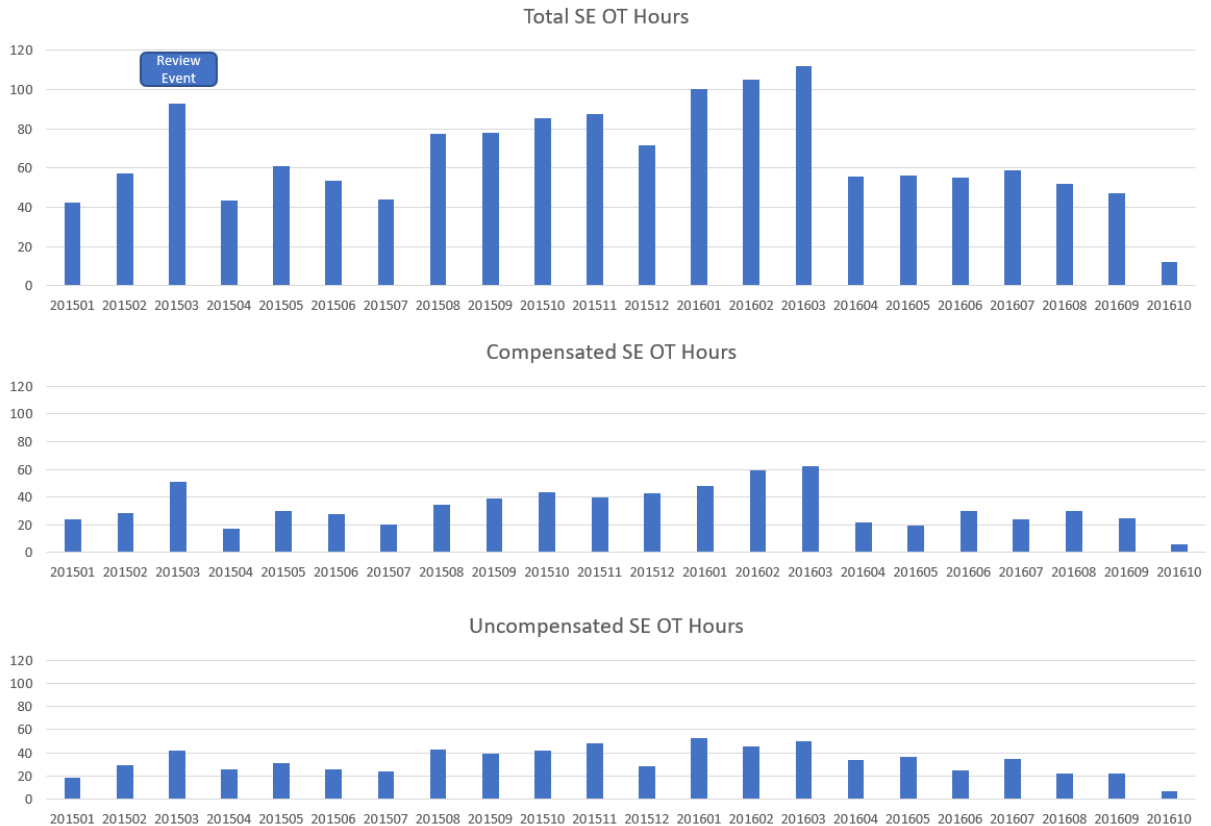
*Figure 18: Average SE Hours (%) Distribution for all green project performance, practicing risk management and quality defects less than average across all three business sectors*

#### SE Overtime Analysis and Results

SE Overtime (OT) hours are aligned to the project SE hours with performance ratings and project milestones noted. SE OT total hours include compensated and uncompensated hours for project staff with SE job titles. Data analysis included:

- SE OT hours mapped to SE Hours distribution.
- SE OT hours mapped to project milestones and mapped to SE Hours distribution (SE Hours, SE Hours normalized, NRE, RE and total SE Hours) with analysis results notes.
- SE OT hours mapped to project challenges such as increased defects, late releases, releases with errors, design defects, process defects.
- SE OT hours mapped to project performance challenges such as yellow or red technical, cost, and/or schedule performance with analysis results notes. Intangibles which influence OT are also noted in the results.

Using system thinking concepts, patterns and trends with OT hours are identified. Figure 19 has representative project data to illustrate the data analyzed. The graph X axis is the months of the project schedule. The graph Y axis is the number of OT hours with project milestones indicated. SE OT hours are mapped to SE hours by aligning project schedule (X axis) to identify patterns.



*Figure 19: Distribution of total SE overtime (OT) hours, compensated OT hours, and uncompensated OT hours over the project lifecycle*

Results of the SE overtime hours analysis identifies patterns of OT and milestones, performance, and defects. There is a positive correlation trend among SE OT hours, project milestones, and an increased defect rate. OT can be a leading indicator of performance issues as additional SE effort is applied to resolve technical issues. With this insight, planning for OT hours offsets negative cost impact. The recommendation is to spread SE hours just prior to and in the month of key milestones to mitigate the negative cost impact of OT. By understanding the pattern of releases increasing around milestone reviews and between CDR and ORR, the cost baseline can reflect this increase to mitigate negative cost baseline impact. A comparative increase in release defects correlates to an increase in releases. There is a positive correlation between an increase or peak in defect rates and OT hours to rework or repair these defects. The recommendation is to adjust the cost baseline when defects exceed the nominal project rate to mitigate the negative cost impact of OT. If the negative normalized SE hours are due to a decrease in

SE hours (fewer SE team members), then existing SE team members must work longer to address project issues or defects. Recognize that OT may be more cost effective than keeping more SE team members on the project.

## Risk Management Analysis and Results

The positive impact of actively practiced risk management is noted earlier in this chapter as a SE activity which contributes to successful project performance and adding SE value. To determine if this impact is reflected in these reference projects, risk profiles analysis includes:

- Mapping net factored risk (NFR) to SE Hours spread/distribution over the project lifecycle noting project performance (all green, non-green (yellow/red) for technical, cost, and schedule),
- Mapping management reserve (MR) to project NFR and to SE Hours spread/distribution over the project lifecycle noting project performance (all green, non-green (yellow/red) for technical, cost, and schedule),
- Mapping contract value to MR, NFR, and SE Hours spread/distribution over the project lifecycle noting project performance (all green, non-green (yellow/red) for technical, cost, and schedule).

The data analysis focused on identifying the patterns of NFR and MR over project lifecycle to determine if risk management was actively practiced on the project. The results acknowledge the positive impact of risk management which is practiced and funded early in the project lifecycle on project performance.

Results of the risk management analysis identifies patterns for projects which practiced and did not practice risk management. Projects which practiced active risk management determined net factored risk (NFR) values, defined as the probability of risk multiplied by the impact of risk, and committed management reserve funds against these NFR values. The correlation of NFR and SE hours allocation relates to project performance. A representative graph depicting the NFR and MR over the project lifecycle is shown in Figure 20. A representative graph of the SE hours distribution over the project lifecycle with total SE hours composed of SE NRE and SE RE hours is depicted in Figure 21. Figure 22 maps representative project contract value in dollars over lifecycle. As shown in Figure 20, the NFR and MR data did not track until about one third into project lifecycle. The data represented in these three

figures overlays the SE hours represented as in Figure 14 to identify patterns relating SE hours and project performance.

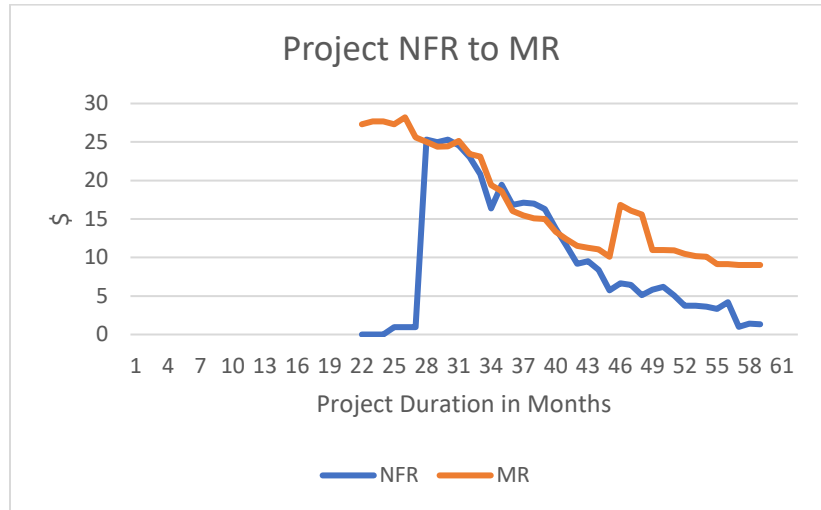


Figure 20: Distribution of NFR and MR dollars (Y axis) over the project lifecycle in months (X axis)

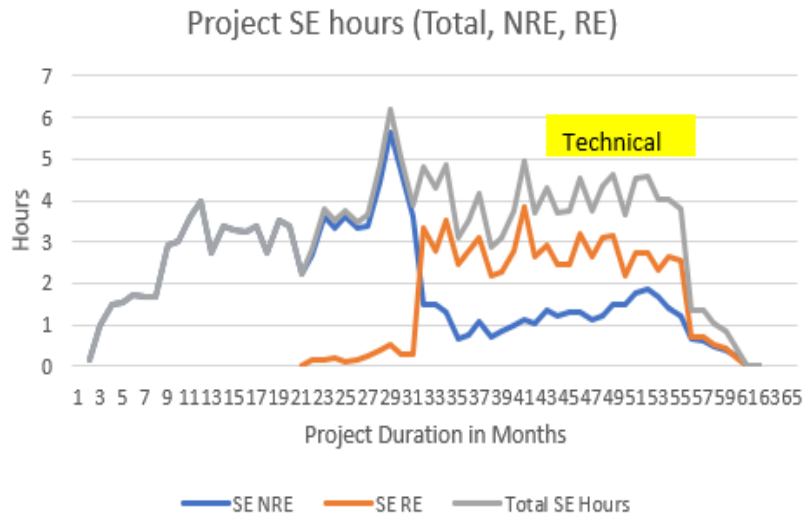
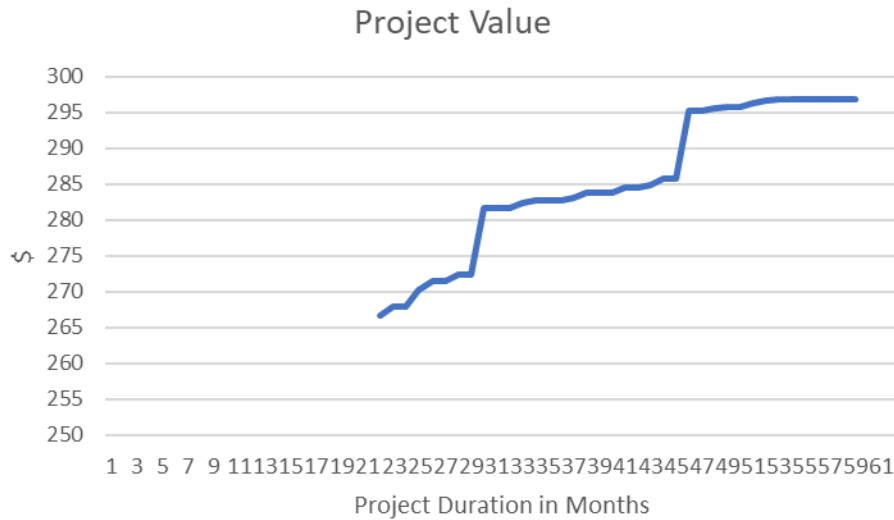


Figure 21: Distribution of total SE, NRE, and RE hours (Y axis) over the project lifecycle in months (X axis)



*Figure 22: Distribution of project value in dollars (Y axis) over the project lifecycle months (X axis)*

The results of the analyses are the identification of several patterns related to practicing risk management. If NFR starts high and decreases over lifecycle, then the projects do not have yellow or red performance ratings and the project is actively practicing risk management. Similarly, if risk management is practiced and NFR decreases as SE decreases, then the project does not have yellow or red performance ratings. If risk management is practiced, then MR should increase as the project contract value increases. If risk management is not actively practiced, the pattern is NFR oscillates with rapid and repeated increases and decreases, and project performance is red cost/schedule performance rating. If NFR and SE hours negatively correlate (move opposite), then project technical performance is yellow. Typically, SE hours increase due to yellow technical performance as the SE team responds to the technical issues. The pattern for green project is SE hours peak in the first 50% of lifecycle and the project actively practiced risk management. From the analysis results, the recommendation is to actively practice risk management by identifying risks and estimating cost impact through NFR and funding risk mitigation with MR. SE hours are allocated for risk management by front loading SE hours in the first 50% of the project lifecycle.

## Defect Profile Analysis and Results

For each project for each business sector, defect profiles for releases and QNs are compared within the business sector, compared to the other two business sectors and to all referenced projects (system). The comparisons are release error percentage by project compared to each business sector average with less than average as green and greater than average as red. A similar comparison is made for late release percentage, design defect QN per 1,000 SE hours and process defect QN per 1,000 SE hours. Data on the number of releases and the months from initial to final release per project are also analyzed for the five projects with data available. These releases with errors or late releases, along with design and process QNs, impact project performance and are documented in analysis results. The data analysis results focusing on defect profile trends and patterns are applicable to projects as results represent an optimization opportunity to re-allocate SE hours (if challenged) if defect profile trends are lower than average with minimal/low risk impact. Data analysis includes the following:

- By each of the three business sectors, defect profile with percent of releases with errors, percent of late releases, design defects per 1,000 SE hours and process defects per 1,000 hours compared to all projects (system) average by data analysis results rating (red or green),
- Defect Profiles analysis results for Change Tasks (CT) defects cover five projects (data availability). By graphing and mapping the release duration (months to develop and to finalize a CT release) along the project lifecycle, analysis for trends with SE hours, SE hours normalized, project performance and project milestones along the project lifecycle is completed. The analysis results include the average release months for a comparison point with analysis results notes. At the system-level, the results are aggregated using release duration averages (above or below averages) and SE hours to note patterns.
- Defect Profiles analysis results for Change Tasks (CT) defects cover five projects (data availability). By graphing and mapping the number of releases (initial to final) to develop and to finalize a CT release along the project lifecycle, the data is assessed for trends with SE hours, SE hours normalized, project performance and project milestones along the project lifecycle. The analysis results include the average number of releases for a comparison point with analysis results notes. At the system-level, the results are aggregated using number of release averages (above or below average) and SE hours to note patterns.
- Defect Profiles analysis results for Quality Notes (QN) for design cause codes begins with details on the data, data categories, corrective action codes, cause codes, rework, and repair. Analysis results are completed using each of these data categories for QNs. Relative analysis results are shared (table format) for each project and for each project against all referenced projects (system). Relative analysis results include design QN averages for the referenced projects (system), number of design QN to total project QN, number of design QN which

required rework or repair (representing unearned SE value), percentage of design QN requiring rework or repair to total project QN and defects per 1,000 SE Hours to referenced project total hours. The results of this relative analysis are used in the system-level analysis as points of comparison and reference. Design QNs are mapped along the project lifecycle and are assessed for trends with SE hours, SE hours normalized, project performance, and project milestones along the project lifecycle. QN defect density is mapped along the project lifecycle and is assessed for trends with SE hours, SE hours normalized, project performance, and project milestones along the project lifecycle. QN defect density average is included in the assessment for trends against SE hours and against all projects (system). Analysis results for each of these assessments are included with notes by project and by all projects (system). At the system-level, the results are aggregated using design QN averages (above or below average) and SE hours to note patterns. For each business sector, similar results are noted for design QN averages (above or below average) and SE hours to note patterns.

- Defect Profiles analysis results for Quality Notes (QN) for process cause codes begins with details on the data, data categories, corrective action codes, cause codes, rework, and repair. Analysis results are completed using each of these data categories for QNs. Relative analysis results are shared (table format) for each project and for each project against all referenced projects (system). Relative analysis results include process QN averages for the referenced projects (system), number of process QN to total project QN, number of process QN which required rework or repair (representing unearned SE value), percentage of process QN requiring rework or repair to total project QN and defects per 1,000 SE Hours to referenced project total hours. The results of this relative analysis are used in the system-level analysis as points of comparison and reference. Process QNs are mapped along the project lifecycle and are assessed for trends with SE hours, SE hours normalized, project performance, and project milestones along the project lifecycle. QN defect density is mapped along the project lifecycle and is assessed for trends with SE hours, SE hours normalized, project performance, and project milestones along the project lifecycle. QN defect density average is included in the assessment for trends against SE hours and against all projects (system). Analysis results for each of these assessments are included with notes by project and by all projects (system). At the system-level, the results are aggregated using process QN averages (above or below average) and SE hours to note patterns. For each business sector, similar results are noted for process QN averages (above or below average) and SE hours to note patterns.
- For each project, the SE effort of the project is analyzed against the design defect QN per 1,000 SE hours. The results of this analysis for each project is graphed for all reference projects (system) for visualization of the correlation of SE effort to defect profile impact for design QN. For comparison, the industry average for SE effort and this research analysis results for SE effort are noted on the graph. The design QN average (per 1,000 SE hours) for the system-level is documented. Project performance for each project – technical, cost, schedule, risk, defect (design, process) is included as reference giving additional context/impact for the QN design defect per 1,000 SE hours rate.
- For each project, the SE effort of the project is analyzed against the process defect QN per 1,000 SE hours. The results of this analysis for each project were graphed for all reference projects (system) for visualization of the correlation of SE effort to defect profile impact for process QN. For comparison, the industry average for SE effort and this research analysis results for SE effort are indicated on the graph. The process QN average (per 1,000 SE hours) for the system-level is documented. Project performance for each project is included as reference giving additional context/impact for the QN process defect per 1,000 SE hours rate.
- Defect Profiles analysis results for Releases begins with definition, description and details on a release, release process, design releases, change tasks to track release iterations, potential errors,

and reasons for late releases to provide context in understanding the release analysis results. The project-level analysis for each release defect – late (on-time), with errors (error-free) is detailed in the prior section on project-level data analysis. At the system-level, each release defect (and its desired opposite) is mapped to SE hours (SE hours, SE hours normalized, SE OT hours, SE hours (NRE, RE, total)), and project performance to identify trends and patterns. Late releases over the project lifecycle are mapped to non-green project performance for all referenced projects (system) with correlations with these two undesired conditions. Analysis results note these correlations and impacts of these SE hours and late releases on project performance (yellow and red technical, yellow and red cost, yellow and red schedule). The results are documented in an if/then format. For example, if late releases increase, then this project impact results and if SE hours < average, then late releases increase or decrease. The same analysis is completed for the opposite condition, on-time releases. The results of the on-time release analysis are also reported in the if/then format.

- Defect Profiles analysis results for Releases with errors leverages the descriptions, definitions, details, and project-level analysis results described in the prior defects analysis results description. Releases with errors (defects) over the project lifecycle are mapped to non-green project performance for all referenced projects (system) with correlations with these two undesired conditions. Analysis results note these correlations and impacts of these SE hours and releases with errors on project performance (yellow and red technical, yellow and red cost, yellow and red schedule). The results are documented in an if/then format. For example, if releases with errors increase, then this project impact results and if SE hours < average, then releases with errors increase or decrease. The same analysis is completed for the opposite condition, error-free releases. The results of the error-free release analysis are also reported in the if/then format.

Results of the Change Task (CT) defect profile is based on data analysis. These results are limited to data from five projects. The CT data tracks the number of months from initial to final release and the number of releases from initial to final. New releases may be necessary if defects are identified in the prior release. Releases may also be related to material procurement or design changes. The fewer releases or faster releases typically require less SE hours to be expended. Figure 23 depicts representative project data tracking the number of release months (Y axis) over the project lifecycle in months (X axis) with project milestones indicated. The dotted line is the trend line on number of release months as the project lifecycle progresses. The “Avg=5.8” in the blue box in this figure is an example of the average number of months per release calculated per project and used as a comparison point in the data analysis.

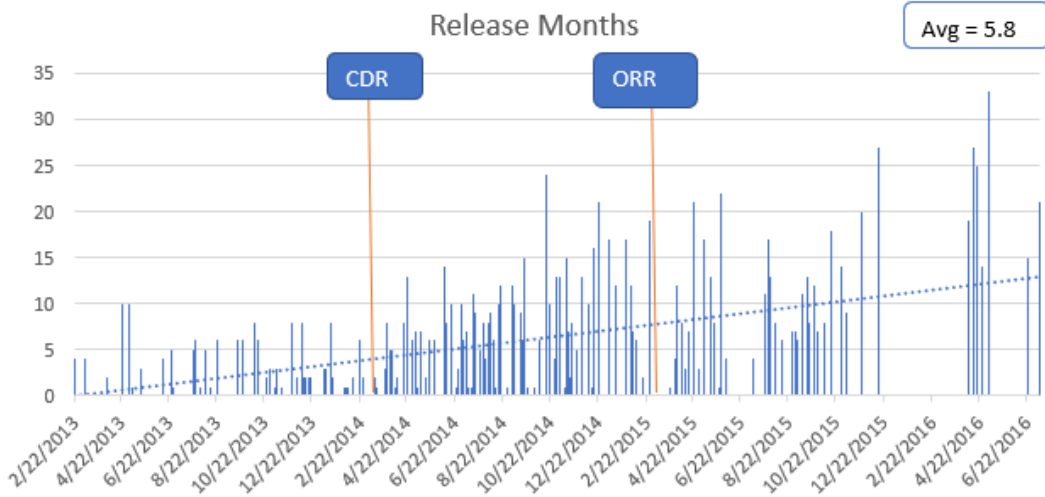


Figure 23: Distribution of release months (Y axis) over the project lifecycle (X axis)

In this figure, the number of months required to finalize the release increases as the project lifecycle progresses. Reasons for this increase include staff changes towards the end of the project and technical debt associated with complicated and complex releases which remain open as the project evolves. Figure 24 depicts representative project data illustrating the number of releases from initial to final.

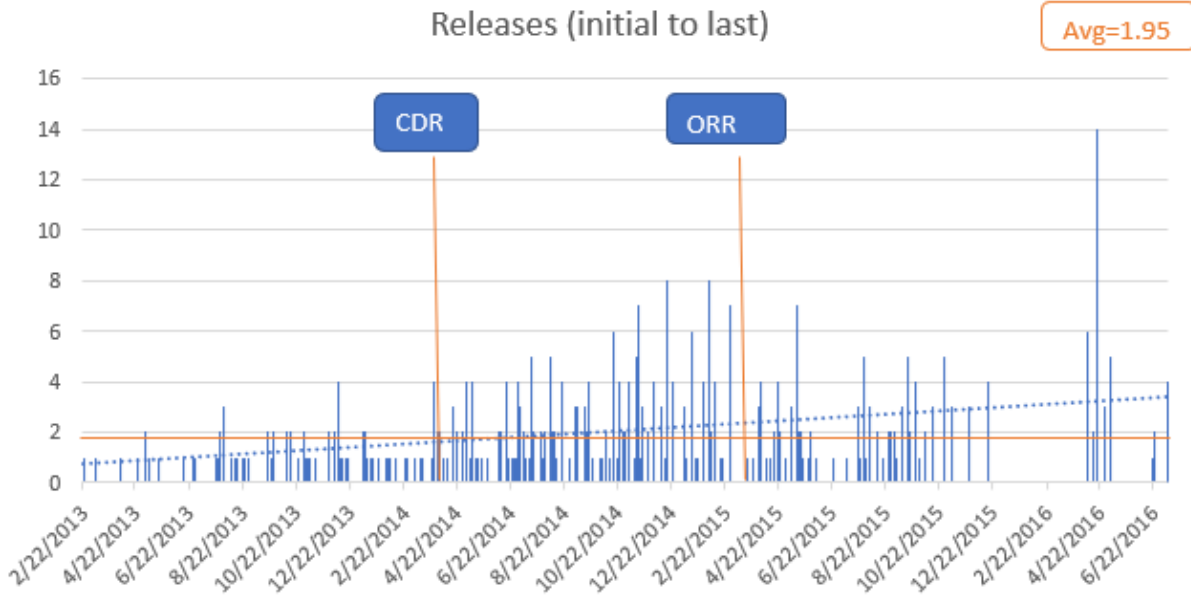


Figure 24: Distribution of the number of releases (Y axis) from initial to final release over the project lifecycle (X axis)

Similar to the months from initial to final release, each release expends SE hours and fewer releases use less SE hours. Multiple releases may be necessary due to material procurement or may be necessary due

to staffing/skill changes. The dotted trend line is increasing over the project lifecycle which is not the desired trend. The solid orange line is the average number of releases for this project and is noted by the orange “Avg= 1.95” box in the upper right corner. The desired pattern of CT defects are fewer releases and fewer months per release. Based on analysis, this pattern results in fewer changes later and fewer CT defects. The pattern of an increase in CT numbers over a business sector average is negatively correlated with the SE hours on the project. When SE hours decrease, especially at the end of the project lifecycle, the pattern is CT defects (more releases, more months per release) increase. Based on this analysis, the results include a recommendation to allocate SE hours early in the project lifecycle to support CDR and ORR yielding fewer CT defects/release changes later in lifecycle.

Results of the quality defects or quality notes (QN) data analysis are categorized by patterns and conditions related to defect and SE hour averages. If the majority of the quality defects occur earlier in the project lifecycle, especially before the CDR milestone, the SE hours are usually sufficient to address these quality defects without deviation from the technical, cost, or schedule baselines triggering a yellow or red performance rating. The SE hours are not the only contributing factor to the quality defects or performance rating as there are other influences such as subcontractor product delivery which may induce defects. If significant QNs are noted after the ORR milestone, there are typically technical, cost, or schedule impacts influencing project performance rating. These late lifecycle quality issues may require unplanned SE hours impacting the project performance against baselines. Defects are more costly and more impactful to address later in the project lifecycle. If significant defects are identified between CDR and ORR, the impact is more significant than early lifecycle, but not as significant as post-ORR and data analysis results are mixed in associated project performance. The type of QN defect correlates to impact as design QNs are more impactful to technical, cost, and schedule baselines than process QN defects which are more of an efficiency opportunity than product impact or design change. Late project lifecycle process defects do not have direct negative project performance. The planned SE hours distribution over the project lifecycle impacts the ability of the project SE team to address design or process QNs. Figure

25 depicts representative project data for the number of design QNs (Y axis) over the project lifecycle in months (X axis). The line colors represent the different cause code descriptions for design QNs.

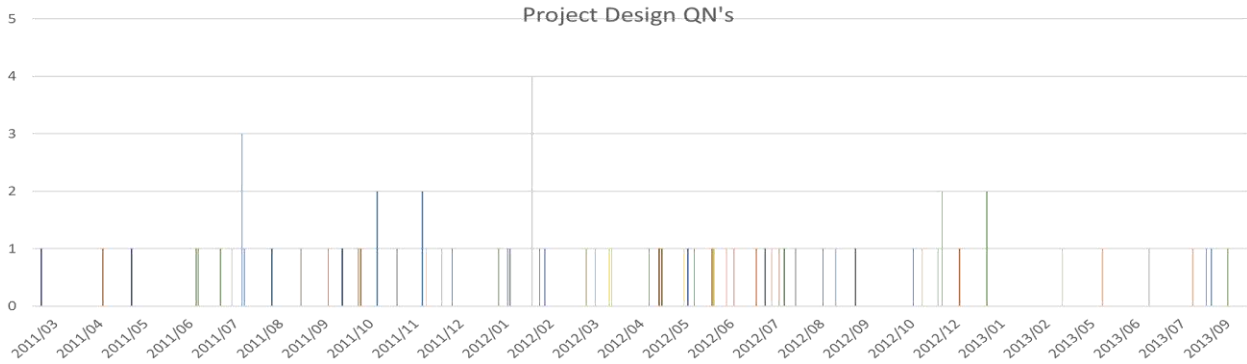


Figure 25: Design defect QNs over a project lifecycle

Similar to Figure 25, Figure 26 depicts project representative data for the number of process QNs (Y axis) over the project lifecycle in months (X axis). The line colors represent the different cause code descriptions for process QNs.

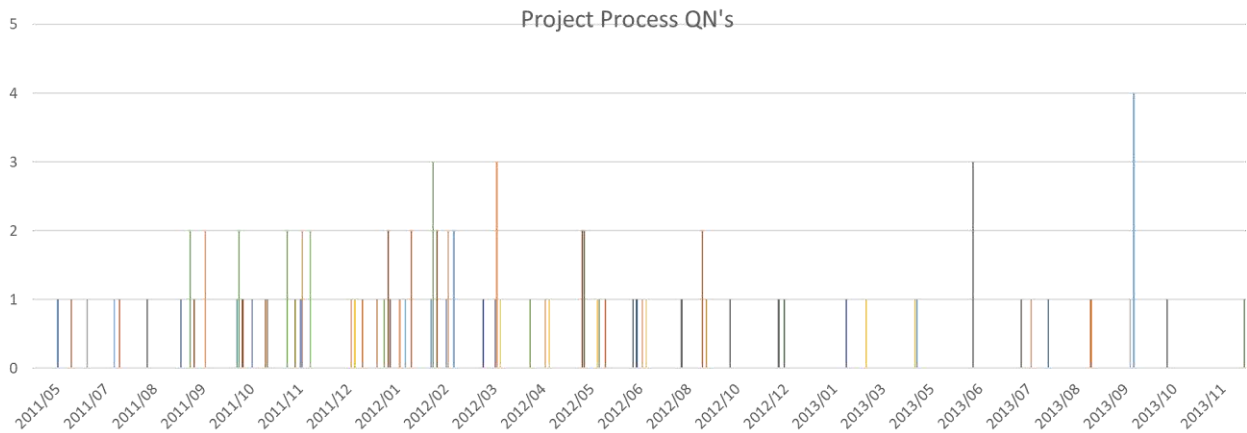


Figure 26: Process defect QNs over a project lifecycle

Both design and process defect profiles were aligned with the project SE hours and performance ratings over the project lifecycle to identify patterns of SE hours impacting or responding to both or to one of the defect profiles. For each project, the number of design and process quality defects are counted and the percentage of design and process defects to all project quality defects is documented. The number of corrective action codes which require rework or repair are documented in numbers and in percentage

against all design or process defects, as these actions are an impact to SE hours. Depending on the SE hours distribution, significant rework or repair may impact project performance against the technical, cost, or schedule baselines and may influence the project performance ratings (green, yellow, or red). An average for the percentage of design and of process defects against all defects is determined for all projects used in this research. The average is used as a relative benchmark in system-level analysis and trending.

Analysis results identify a related pattern between SE hours and defect profiles. If SE hours are above the overall project average, an effort surge to address defects is usually within margin and does not drive negative project performance. Figure 27 depicts all projects' design defect rate per 1,000 SE hours overlaying SE hours percentage. Similarly, Figure 28 depicts all projects' process defect rate per 1,000 SE hours overlaying SE hours percentage. Projects with SE hours percentage around the recommended value realize fewer design and process defects (QN). Projects are noted by business sector letter and number.

If defects are identified late in the project lifecycle when SE hours distribution typically decreases, the surge in SE hours necessary to address the defects is likely over the planned SE hours and thus impacting project performance ratings with a baseline deviation. Oscillating SE hours is an indicator of negative performance impact as these hours are driven by staff or design changes and are unplanned SE hours surges. If defects increase as SE hours (planned) are decreasing, there is a performance impact. The recommendation to mitigate the risk of late defects is to monitor the defect rate across the project lifecycle. Monitoring the actual defect rate to planned defect rate enables the project to proactively add SE hours or re-distribute SE hours to address the defects faster if the rate is trending to an unplanned increase. If the actual defect rate is lower than the planned rate early in the lifecycle, SE hours could be re-distributed to later in the project lifecycle as a risk mitigator without increasing the overall SE hours.

Green line= industry SE Hours % recommendation= 15%  
 Green shadow = research SE Hours % recommendation = 14 – 16%

SE Value and Defect Profile- Design QN

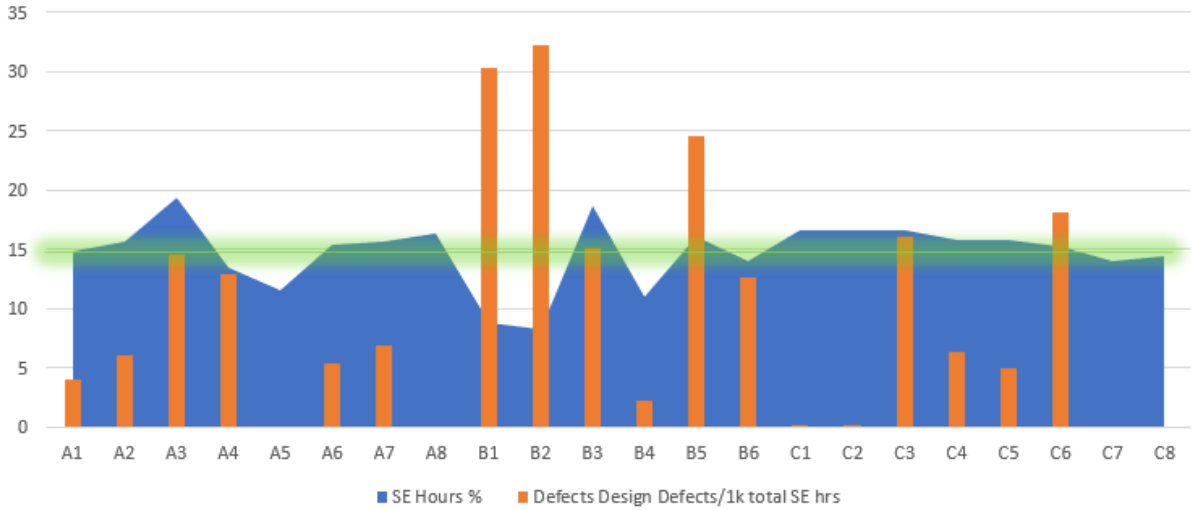


Figure 27: SE Hours (%) and Design Defect rate for all projects

Green line= industry SE Hours % recommendation= 15%  
 Green shadow = research SE Hours % recommendation = 14 – 16%

SE Value and Defect Profile - Process QNs

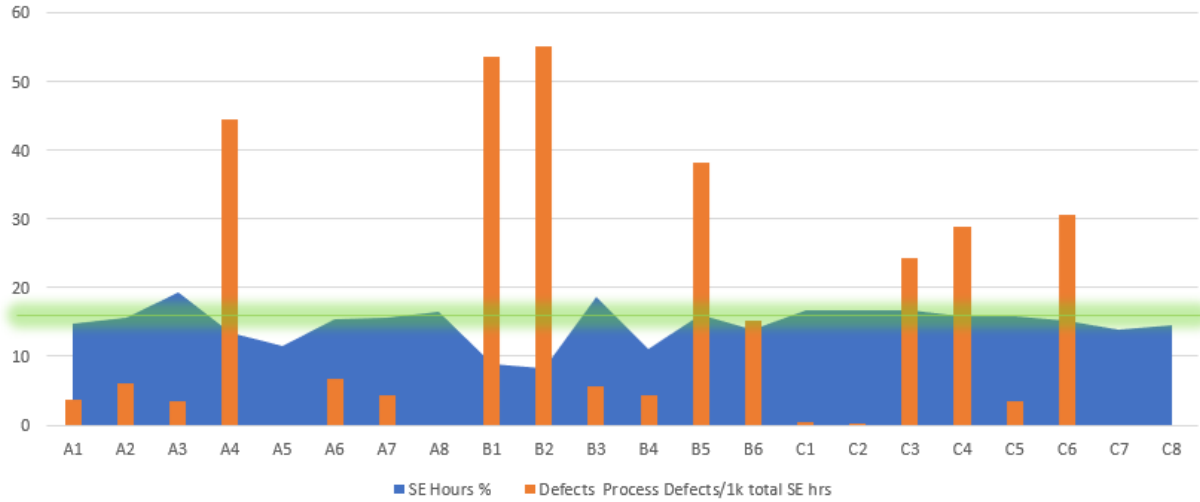


Figure 28: SE Hours (%) and Process Defect rate for all projects

Results of the release defects data analysis are categorized by patterns and conditions related to releases with/without errors, to late/on-time releases, and to SE hour project averages. Figure 29 depicts

representative project data of releases without errors (blue bar) counts (Y axis) over the project lifecycle in months (X axis). For relative comparison, total releases regardless of errors are included (orange bar).

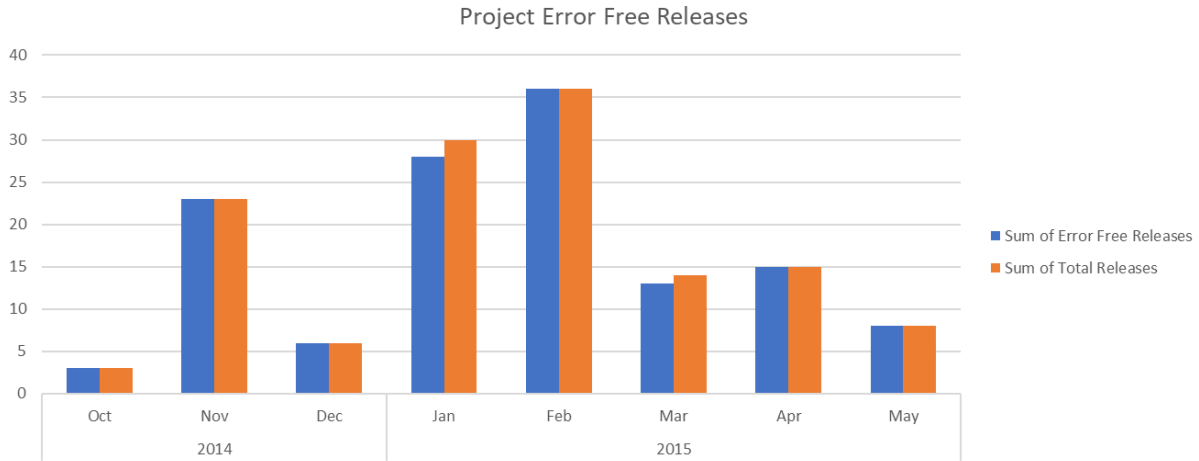


Figure 29: Releases without errors (error-free) defect profile over a project lifecycle

Figure 30 depicts the ‘opposite’ of Figure 29 noting the releases with errors (non error-free).

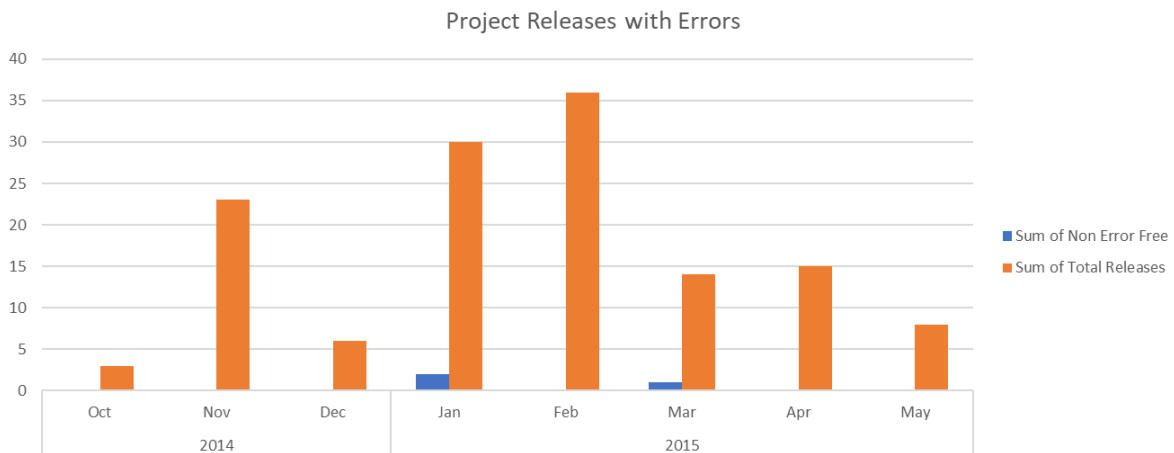


Figure 30: Releases with errors (non error-free) defect profile over a project lifecycle

This opposite view is useful in the identification of patterns. Figure 31 depicts representative project data of late release (blue bar) counts (Y axis) over the project lifecycle in months (X axis). For relative comparison, total releases regardless of timeliness are included (orange bar). Figure 32 depicts the ‘opposite’ of Figure 31 noting the on-time releases.

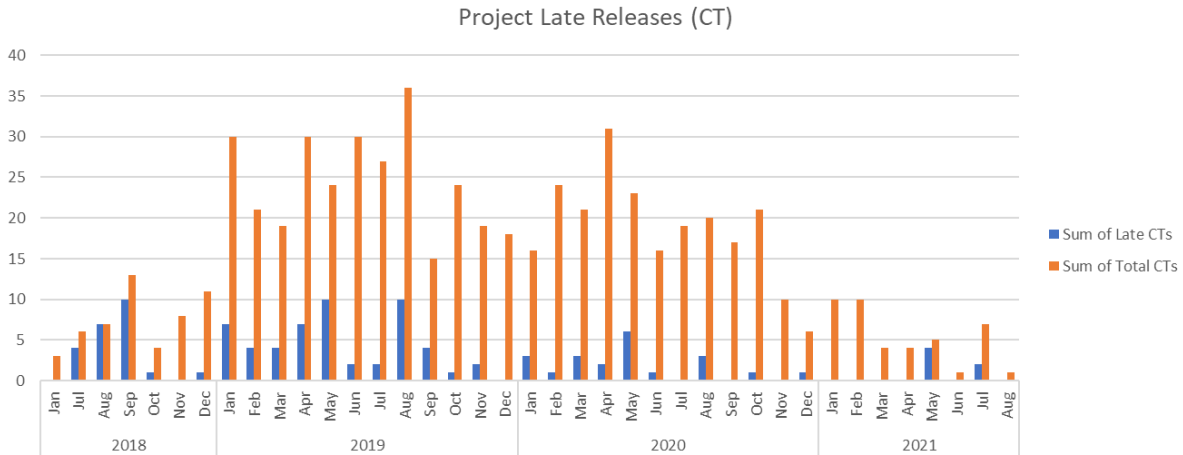


Figure 31: Late releases defect profile over a project lifecycle

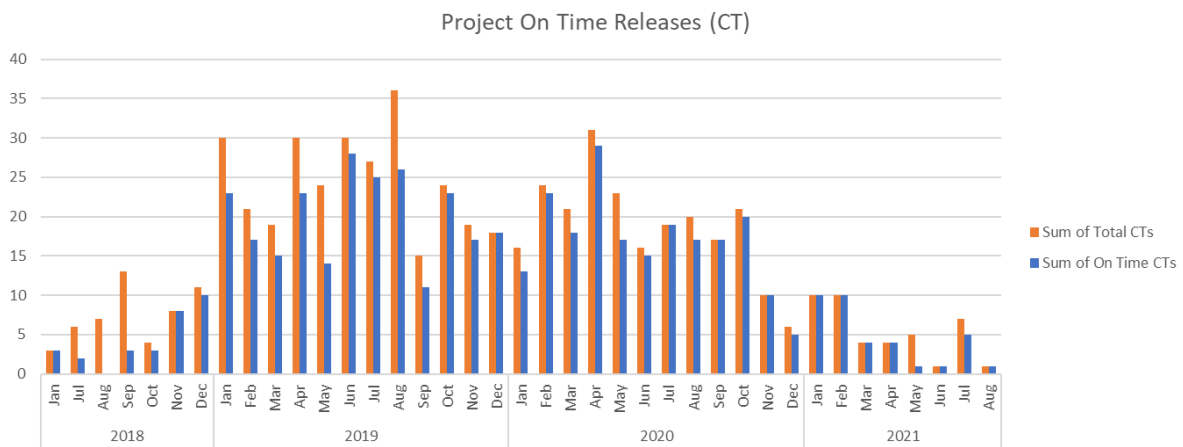


Figure 32: On-time releases defect profile over a project lifecycle

Both releases with errors and late releases defect profiles were aligned with the project SE hours and performance ratings over the project lifecycle to identify patterns of SE hours impacting or responding to both or to one of the release defect profiles. Analysis of results identifies patterns for releases without errors (error-free) as a positive correlation and releases with errors as a negative correlation to SE hours. When SE hours are increasing or are above project average, error-free releases increase. As SE hours decrease, error-free releases decrease. Releases with errors track to a decrease in SE hours, especially late in the project lifecycle. Releases with errors are influenced by other factors such as staffing changes as the project winds down and more experienced system engineers move to other projects. Similar to releases with errors, on-time releases positively correlate and late releases negatively correlate to SE

hours. Late releases increase late in the project lifecycle and may be due to staffing changes. A consistent late release pattern above the project average precedes a yellow technical rating or a red cost or schedule rating. The late release rate or trend can be monitored as a leading indicator of a yellow or red performance rating change. This indicator can be used as a risk mitigator if a surge in SE hours or OT can be applied to address the late releases before a negative impact on project performance rating. High rates of OT track to more on-time releases. Late releases increase when the project technical rating is yellow. When SE hours are below the project average, the rate of error-free releases and on-time releases decreases and defects increase. A recommendation to mitigate this risk of defect increase as SE hours decrease is to monitor the release defect rate as a leading indicator and be proactive regarding mitigation actions to address an unexpected defect increase through an increase in SE hours or OT hours.

### *Risk Management and Optimizing SE Value*

The power of systems thinking is evident in the system-level data analysis results noting the trends and patterns which the SE value structure influences. With multiple data available (events) for comparative analysis, the behavior of the projects is documented in the identified trends and patterns and is recorded even when there is no correlation between events, or no trend and patterns identified. Multiple perspectives are included in the systems thinking analysis with opposite perspectives: on-time and late, errors and error-free, green and non-green, above and below average. These perspectives yield additional insights into the system (all projects) behaviors influenced by the SE effort (SE hours and SE hours distribution) within the system. The results of the analysis provide an optimal SE effort spread and distribution based on the desired project performance behaviors of green technical, cost, schedule performance, green risk/risk management practiced, and defects < average (CT, QN, releases). Optimal SE effort distribution by business sector identifies the 'knee in the curve' for SE to optimize resource allocation. If trends and patterns are understood or acknowledged, project defect profiles can be tracked against these benchmarks from these data analysis results for effective SE resources allocation. Using defect profiles as a leading indicator/measure allows SE talent to be redistributed to other activities if

defects are lower than average and enables a SE surge if defects are higher than average. Defect profiles (CT, QN, releases) can be used as SE quality measures for the project and tracked above or below the business sector averages. If the SE value in the competitive bid deviates from this optimal SE value, the proposal or project team can recognize this deviation and apply risk management practices to mitigate the impact.

The goal of this research is to determine SE value for competitive bids and to communicate this value using a risk quantification framework (RQ3). Risk management is a key SE activity and carrying BOE assumptions, identified in the competitive bid, into the project risk register is an important step in building the initial project risk register. Organizational structure could impact this activity if the BOE approver is not part of the competitive bid or project SE team. If this deliberate transfer of risks and assumptions from competitive bid to project risk register does not happen, these risks may be forgotten, but may later be realized as project issues which could have been mitigated. BOE assumptions may identify support from SMEs, subcontractors, or functional organizations. If this support is not realized in the project or the BOE assumptions are not true or realized, cost is added to the project and SE activities are impacted. From the literature search, game theory applies – When bidders are uncertain about their value estimates, the auction generally leads to larger expected prices. Bidders are risk averse [18]. By using these research results, confidence can increase. Greater awareness of risk contributes to management and mitigation. With DE and MBSE, there may be more focus on performance and technical risks than integration risks as confidence with interface and integration management with DE tools mitigates these risks. SE still needs to be practiced in DE. For an MBSE cost curve, costs are greater in the conceptual and preliminary design phase for tools, infrastructure, and training with substantial cost savings during the latter stages of design with reduced defects later in the lifecycle [42]. There is a risk that models ‘become stale or die’ after CDR as models require labor and funding to maintain. The results from this research enable a greater awareness of risk and how to manage it for both

the competitive bid and project teams. As the data analysis results indicate, practicing risk management mitigates deviation from successful project performance against technical, cost, and schedule baselines.

The project-level and system-level data analysis results can be used to optimize SE value. Optimal cost is the correct cost as an element of a balanced solution to meet customer need rather than lowest cost. To optimize SE value, consider activities or products to reduce by asking these questions:

- Do we need to do this SE task now?
- What SE processes should be redesigned to increase value [12] and effectiveness on the project? Don't just assume a process used on another project will be valuable or effective on this project.
- Will all the SE products or documents which are bid or planned, be used? Are these SE products or documents impacting successful project performance?
- How can reuse be successfully applied and is the effort to reuse less than creating?
- Can the project leverage common products and common standards rather than creating?
- Have we considered tradeoffs within the project and with the customer to find the 'best' solution?
- Are we using appropriate tools and using them to their fullest capability for this project's needs?
- Are we developing a product that is 'good enough' to meet requirements and mission vs the 'perfect' product?
- Is the customer flexible on requirements?
- Is the customer open to trade studies to expand the solution space and manage risks?
- Is requirements volatility impacted by customer intimacy or by not understanding operational context of the design or influences within the customer environment?
- Does the customer value schedule (fast delivery) over capability?
- What is the customer's ROI and how can we support this? Is ROI impacted by schedule/project duration?
- Is the design flexible so changes can be made moving forward?
- Can we reduce or perform less test through automation? How can SE support getting to test faster?
- Are the requirements and Concept of Operations in synch such that the functions and capabilities needed are identified and requirements are decomposed to a lower level ensuring all the functions, capabilities and their interfaces are captured?

Responses to these questions empower the SE team to spend SE hours more effectively where the most SE value is generated. Responses indicating processes identified as non-valued or creating unused products should be addressed for elimination or reduction to optimize SE value. SE should identify

bottlenecks and mitigate their negative project performance impact. This mitigation includes doing certain SE tasks more effectively or in a different sequence by considering the entire project impact. For example, SE completing test support to enable a test team to execute vs keeping an entire test team waiting (inefficient) and impacting defect discovery and project performance. As discussed, the projects analyzed for this research include different contract sizes (small to large), different contract types (Firm Fixed Price (FFP), Cost Plus Award Fee (CPAF), etc.) and different products, including production of a single or multiple assets. Optimizing SE may be even more critical for small contract projects or FFP contract types. Projects that are production focused (lower NRE) have a different value of SE than development projects that create one-off, custom products (higher NRE). Risk posture is also impacted by contract size, type, and product, so balanced risk vs risk aversion should be considered in the risk management process. DE can impact SE in the early identification of defects which should be reflected in the project's risk posture. Evolutionary changes may decrease SE costs by a percentage or two of total cost. Evolutionary changes are relatively safe and low risk with pilot projects, metrics, and lessons learned to leverage. Revolutionary changes may decrease SE costs by 4 – 5% percent of total cost. Revolutionary changes alter the risk posture of the bid and project. Leveraging these options for SE optimization, the SE team can influence project cost optimization through process, flexible and balanced (good enough) design, and green technical performance.

Complementing the results from this data analysis is the influence of the organization's culture. Applying the systems thinking Iceberg Model, the greatest leverage in implementing a change is impacting the organization's mental model, culture, and beliefs. To support SE value optimization and to address an organizational need to remain competitive, a change in attitude towards failure impacts culture. DE tools and processes can identify issues, defects, and failures earlier in the lifecycle. DE enables the SE team to have data earlier, to change the design early, and to mitigate defects with earlier or faster changes. Awareness of a different culture or mental model towards SE and towards failure should be considered, especially in light of the new or non-traditional industry competitors who find ways to learn from failure.

In addition to new or non-traditional industry competitors, another perspective comes from international companies, which do not move forward in the project lifecycle until all SE is completed. In changing a staffing mental model, applying engineering aides to certain SE tasks, and focusing SMEs on complicated SE tasks may be more efficient and could be an organizational and culture change. Following the recommended actions [65] from the organizational and culture change of DE transition (Appendix), these changes can be piloted with success and challenges tracked. These changes can contribute to optimizing SE value with more effective use of SE hours to enable project performance.

### *SE Value Determination*

The results of this research are not an absolute SE value determination. There are other influences and intangibles, such as complexity, customer intimacy, team cohesion, SME access, and competitive intelligence, which impact the determination of SE value in a competitive bid and are beyond this research. There are many variables contributing to SE value and an absolute determination of SE value is difficult to quantify through only data analysis as issues contributing to negative project performance are not only SE value driven, but often have multiple contributing factors. It can be a challenge to recreate or track costs on a project as there is a dependency with correct charging, work breakdown structure, and tracking subcontractor labor/materials which are included in the cost (hours). Customer relationships are subjective and may be impacted with staffing changes. Customer intimacy can impact requirements volatility, design changes, defects, risk, and technical, cost and schedule performance.

This SE value determination provides a starting point from which deviations can be tracked with the risk management process. This SE value determination does not currently exist, is based on original research, and enables more data-driven decisions. For the referenced projects, a description of the aggregate data provides additional context for competitive bid teams when assessing system-level data analysis results:

- Projects are a mix of Hardware (HW) and Software (SW) based with production,
- Subcontractor hours are not included in the SE labor hours. SE hours per project may be different if significant subcontractor SE labor is used and not factored into this analysis.

- Projects which develop and produce multiple assets do not have SE labor hours categorized by asset. This does not allow for identification of overlapping effort in development and production between assets.
- Available data does not always cover the entire project lifecycle and earlier milestones such as PDR and SE hours are not identified in the graphs and are not factored into the analysis.
- Charging structure does not support lower-level data analysis due to labor charging granularity required.
- Project performance data (red/yellow/green) for technical, cost, and schedule baselines is not used before 4Q11 due to relevance to current SE practices.
- Some of the data is ‘dirty’/incomplete. Data quality and completeness impacts data analysis results/confidence.

The following section shares results of the research on the impact of DE on SE and on the value of SE in competitive bids and on projects.

### *SE-DE Impact Results*

The results of analysis on the impact of DE on SE includes an executive summary based on experiences from projects implementing DE, SE-DE survey results, actions to empower engineers in the DE transition, DE pilot results, and DE metrics assessments.

#### SE-DE Executive Summary based on Project Experiences and Results

The executive summary of SE-DE impact results focuses on SE effort (SE hours) in a DE competitive bid, benefits for SE in a project executing DE, challenges in DE for projects, and advice for SE in DE in bids and projects. This summary is based on informational interviews with leaders executing DE on projects or leading the DE transition. The results indicate a need for training, culture transition, and building SE in DE experience which align to the recommended actions [65] to empower engineers in a DE transition (later in this section and in the Appendix). Results of experiences from project SE leads on implementing DE and the impact on DE on SE are summarized for other proposal and projects to leverage as a reference. These results are categorized by experience related to DE benefits, DE challenges, use of DE metrics, and advice/lessons learned from five projects. The executive summary was created based on input, insight, and perspectives from 15+ informational interviews on the SE impact

when bidding DE, SE impact when executing DE, and SE impact when transitioning to DE. These interviews discuss expectations on the realization of cost savings in projects (cost avoidance in proposals) due to DE, which is a common and eagerly anticipated benefit. The importance of identifying DE metrics and transitioning the competitive bid approval process to understand, to accept and to include DE metrics in the estimating process is emphasized. Efforts are underway to estimate cost savings per DE tool. This quantified saving can be used in the competitive bid estimating process.

Regarding SE hours in a DE competitive bid or DE project, results of the qualitative analysis converge around a recommendation on the spread or distribution of SE hours over the project lifecycle. The recommendation is to spread more SE hours earlier in the project lifecycle than for a TDSE or non-DE project. There should be an increase in SE hours before System Requirements Review (SRR) or PDR. This SE hours increase enables the necessary training and DE adoption to occur during the DE transition. As the culture change around DE transition progresses, there will be a critical mass of trained systems engineers in DE. Tools, processes, and practices will be created or updated for DE over traditional document-based SE. The qualitative analysis results consensus is not to increase or decrease the overall SE hours as a percentage to project total until DE metrics are identified and consistently used to demonstrate the ability to decrease SE hours as the result of DE. Balancing this increase in SE hours distribution earlier in the project lifecycle is the expected decrease in SE hours distribution later in the lifecycle as the benefits of applying DE are realized. These benefits include reduced effort to plan and to execute design and integration activities, to model traceability, to review/approve documents, and to complete impact assessments more quickly. Late in the project lifecycle, system engineers will be more adept in using the model to rationalize about the system and to communicate the system and its capabilities to stakeholders. Data will be consolidated into one repository as a single source of truth (SSOT) using DE tools and the model. These tools and data practices enable a higher quality of information to avoid future rework. System engineers will be more efficient and will focus on systems engineering vs documentation, on more complicated tasks, and product integration.

As the DE transition progresses, the challenge of DE on a project is variation in training and experience in MBSE and model development, use, and maintenance. A mitigation to this challenge is to commit early lifecycle SE hours to address these DE transition issues. Clear expectations for model definition and modeling at each milestone should be established and communicated to all project stakeholders. Communication of the DE and model vision to all project stakeholders should occur early in the project. Bring experienced modelers onto the project for knowledge sharing, training, and communication. Establish model configuration management practices to avoid conflicting model changes. Stakeholders must support using the model vs TDSE artifacts or the SE team will be performing additional work/using SE hours to maintain DE and TDSE artifacts. Acceptance criteria must be well defined to validate the product, bound scope, and complete project verification. Automaton should be introduced to realize DE benefits and savings.

Results of DE research introduce a feedback loop for competitive bid SE cost savings for estimated (anticipated) savings due to DE (vs TDSE) and the realization, anticipated realization, or lack of realization of these cost savings on the projects. Projects leads share experiences of necessary effort with respect to DE vs TDSE and differences in SE hours distribution in DE vs TDSE.

#### SE-DE Survey and Results

A source of qualitative data relative to SE value and DE impact on SE was the SE-DE survey. The survey respondents are experienced systems engineers with the majority having 15 – 25 years of SE project experience. As discussed in Chapter 6, questions were created with the goal of gathering qualitative insight from experienced systems engineers. This qualitative insight enables decision makers on competitive bids and on projects to have an appreciation of SE value in successful project execution. This appreciation of SE value is from the perspective of systems engineers with significant experience on both successful and challenged projects with various SE hours distributions. Key survey results related to this research include:

- All respondents believed in the value of SE and a significant majority noted SE processes are worth the SE hours spent.
- For a minimally acceptable level of SE effort, about 35% of responses indicated 10-15% is an acceptable level of SE effort and about 26% indicated 15-20%.
- Responses indicated the top three SE processes contributing to a successful project outcome are: requirements management, system architecting, and system integration.
- Responses indicated the top two actions to enable the DE transition are: use of DE startup kits and pilots for DE tools/processes.
- If SE Value is challenged in a proposal, these SE activities are tagged as the top three to reduce with minimal impact to project performance: scope management, technical management, and system architecting.

These responses provide a qualitative perspective to the impact of DE on SE and can be used:

- By competitive bid teams to appreciate the value of SE relative to allocating SE hours over project lifecycle, identifying, and funding the SE processes which align to a successful project execution, and appreciating the minimal SE funding level according to these deeply experience SE respondents.
- By competitive bid teams to appreciate the change in risk posture if SE hours are challenged or reduced in the bid and how the SE effort (SE cost estimate) changes in a DE proposal.
- By competitive bid teams and by projects to understand the expectation of SE benefits due to DE related to SE hours and project hours reduced, actions current projects are taking and should take to enable the DE transition.
- By competitive bid teams and by projects to gain insight into which SE funded activity could be reduced if SE hours are challenged and to gain insight into the impact of reduced SE on project performance (risk, defects, rework increase or decrease).
- Training and growing strong systems engineers are key to reducing SE hours in bids and on projects. Reuse is also a common response and is also covered in the literature search.
- Results summarized from free text survey responses describe a definition of ‘enough SE’ as:
  - Enough to deliver a solution that meets the customer's requirements and mission objectives within cost and schedule and with risks managed at or below the customer's risk tolerance.
  - Structured process that is adequate to define, design, verify, and validate a system that meets customer needs in terms of performance and operation.

These survey responses provide qualitative results to the quantitative results in the project-level and system-level data analysis sections.

### Empowering Engineers in a Digital Engineering Transition – Actions and Pilots

The results of the combined systems thinking and organizational psychology approaches to empowering engineers in a Digital Engineering transition [65] research (Appendix) are recommended actions focused

on knowledge transfer, training, and communication (Figure 33). These recommended actions empower engineers in the DE transition and impact the culture/mental mode of the engineers. These results encourage engineers to participate in this DE transition instead of having it happen to them.

| Knowledge Transfer   | Training   | Communication  |
|--|--|--|
| Mentoring <ul style="list-style-type: none"> <li>• Surveys</li> <li>• Kickoff</li> <li>• Evaluations (feedback)</li> <li>• Job Redesign (Sr/Jr)</li> </ul>   | Training Options <ul style="list-style-type: none"> <li>• Assessment -SWOT or gap analysis</li> <li>• Interviews, surveys (feedback)</li> <li>• Training Plan</li> <li>• Tool and workflow specific</li> </ul> | Communicate organization’s vision, strategy, timeline, plan for DE transition and tailor to lower levels   |
| Social Support Options <ul style="list-style-type: none"> <li>• Peer to Peer on tools, process, expertise</li> <li>• Forums (incl online) to share Lessons Learned, Best Practices, seek advice</li> </ul> | Seek pilot projects to demonstrate new DE tools, processes   | Frequency – continual and assess timeliness and usefulness (feedback)  |
| Transition Discussions <ul style="list-style-type: none"> <li>• Tools Evaluation</li> <li>• Tool Selection</li> <li>• Create/update processes</li> <li>• Sr/Jr partnership</li> </ul>                      | Surveys as feedback loop post-training and pilot projects  | Acknowledge increased workload w/change <ul style="list-style-type: none"> <li>• Evaluation, selection of tools</li> <li>• Creation of new processes</li> <li>• Assist by creating start-up kits (recommended tools, processes, training, guidance)</li> </ul> |

*Figure 33: Recommended actions to empower engineers in a DE transition*

Results for three DE Pilots initiated for this research contribute to the realization of a practical application of these recommended actions to empowering engineers in the DE transition [65], (Appendix).

Knowledge transfer pilot begins with a survey soliciting mentoring volunteers and pairs the volunteers with two mentees to each mentor. A pilot kickoff is hosted which identified objectives and goals for the mentoring. As the pilot started, a job redesign is executed to pair junior and senior engineers. Monthly feedback is sought over the three-month pilot and an evaluation is conducted after the pilot completed assessing if objectives are met. The results of this knowledge transfer pilot are a more structured mentoring activity with more rapid learning and independent tasking vs organic or unstructured knowledge transfer. The mentor to multiple mentee pairings was positively received and multiplied the benefits of the knowledge transfer efforts and accelerated learning curves. The structure of the pilot was a forcing function for knowledge transfer which may or may not have happened organically.

Training pilot is focused on MBSE and the Cameo tool. A tool-specific and workflow-specific training plan is developed with a goal to use the tool at an upcoming CDR. A post-training assessment reveals learning gaps with tool application existed. To address this gap, a Cameo expert user is identified and is funded for on-demand practical tool application questions. The result of this pilot accelerated the learning curve resulting in technical exchange meetings using the models for productive discussions and the use of the models at the successful CDR garnering positive customer feedback.

Communication pilot focused on creating a startup kit for automation on a challenged project enabling documentation of automation practices and lessons learned filling a knowledge gap in organizational resources. The results of this pilot are an automation startup kit and accompanying white paper, technical presentation, and poster. The startup kit details an automation assessment, implementation plan, and business case which enables projects to determine if automation can benefit the project and to understand the investment and timeline required to realize the benefits of automation. The automation implementation plan consists of three phases: creating a stable foundation, hardening and innovating, and adding permanency and resiliency.

#### DE Metrics Assessments Results

A DE metrics assessment of business sector metrics begins with a comparison of metrics against SERC DE metrics [22], [54] and INCOSE SE leading indicators [13]. The results of this assessment are:

- Metrics indirectly reflect SE Value,
- Metrics have some mapping to DE,
- Metrics should reflect/have a dependency to schedule, phase of lifecycle, or Agile roadmap/increment,

Assessment results include a recommendation to consider adding a metric for risk and to include assumptions made during competitive bid process in the initial risk register for the project.

- An assessment of industry metrics related to risk upon which this new risk metric can be modeled are a combination of the INCOSE SE Leading Indicators and SERC DE metrics related to risk:

- INCOSE - Risk Exposure – track number of risks opened/closed, factored risk exposure (growth, decrease), risk burndowns,
- INCOSE - Risk Treatment – track actions being worked/age of actions, actions closed on time, actions met risk reduction plan.
- SERC - Quality - reduce risk (# risks identified, risk mitigated, risks uncovered by modeling),
- SERC - Quality - improved risk analysis (risks identified by phase – earlier and improved risk identification),
- The COSYSMO Effort Multiplier Impact [7] has factors related to risk:
  - Technology Risk is the third most impactful effort multiplier,
  - Track risks identified in bid to risks tracked in execution.

The result of this metrics assessment is the inclusion of a metric to track risk, especially risk identified in bid process, and ensure it is carried into the project. This recommendation aligns with the inclusion of risk in this research determining SE value in competitive bids and in successful project execution.

#### MBSE MOE Development Results

MBSE Measures of Effectiveness (MOE) research results in the identification of DE benefits mapped to enablers in realizing DE benefits (Figure 34). MOEs are developed to track these enablers and the realization of the benefits. The results of this MOE research is the identification of three benefits: reduced schedule, reduced defects, and reduced risk.

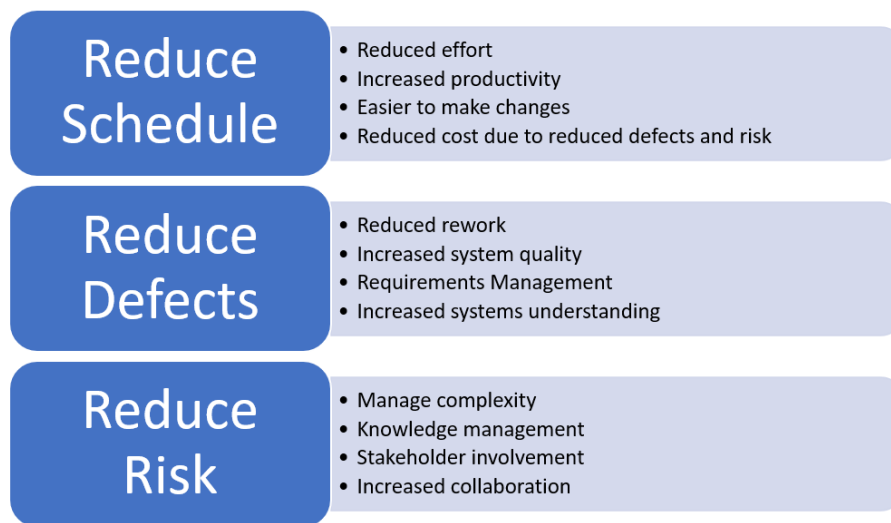


Figure 34: Summary of identified MBSE MOE to realize DE benefits mapped to benefit enablers

For each of these three benefits, MOEs and enablers are identified.

Reduced schedule MOE identifies:

- Reduced effort and increased efficiency as enablers comparing TDSE to DE for milestone reviews, lifecycle duration, and model evolution,
- Increased productivity as an enabler related to defects (resolution, severity, latency) and automation (increasing rate of use and evolution),
- Ease of changes as an enabler comparing TDSE and DE time to assess the change impact, cost estimate of change, schedule estimate to deliver change, and technical baseline impact from change.

Reduced defects MOE identifies:

- Reduced rework as an enabler comparing TDSE and DE defect profiles, defect resolution, containment, and escapes,
- Increased system quality as an enabler assessing model quality with metrics on completeness, consistency, errors, and traceability, increased use of models, of automation, and of digital artifacts,
- Requirements management as an enabler comparing TDSE and DE in traceability and requirements stability using DE models and digital artifacts,
- Increased systems understanding as an enabler assessing the number of functions and interfaces defined in the model, trade studies, or opportunities exploited and use of digital twin and digital threads.

Reduced risk MOE identifies:

- Manage complexity as an enabler comparing TDSE and DE in change request, change tasks, and change backlog. Tracking the percentage of projects using models:
  - To define the design vs drawings,
  - As primary means of communicating design to suppliers,
  - For simulation and data analysis,
  - With geometric dimensions and tolerance data embedded in model.
- Manage complexity as an enabler tracking the percentage of projects using:
  - Digital twin or simulation for risk/opportunity management,
  - Reliability model embedded in model,
  - Creating digital work instructions,
  - Tracking manufacturing non-conformances digitally during production or within digital twin.
- Knowledge management as an enabler tracking the percentage of:

- Reuse of models across organization,
- Reuse of artifacts across organization,
- Project procedures, plans, and processes updated for DE.
- Knowledge management as an enabler tracking the number of:
  - Hours to customize an existing model (reuse),
  - Models (increasing) available for reuse,
  - Engineers participating in DE through
    - Training,
    - Tools training,
    - Mentoring activities,
    - Online chat forums.
- Stakeholder involvement as an enabler tracking the percentage of:
  - digital artifacts used to visualize User Interface (UI) for:
    - early feedback,
    - requirements verification, validation,
    - end user acceptance.
  - iterative reviews using models vs document-based reviews,
  - engineers involved in driving DE transition,
  - iterative reviews using models to integrate feedback (sprint demo or other early feedback sessions).
- Stakeholder involvement as an enabler to:
  - Solicit feedback from engineers on DE transition,
  - Determine DE transition strategy communication forum, mechanism, and frequency,
  - Survey engineers' attitude toward and confidence in DE transition.
- Increased collaboration as an enabler tracking the percentage of:
  - teams within the project/organization using the model as source of truth,
  - teams on project using DE vs traditional engineering,
  - projects in business sector using DE,
  - project in business sector using DE to communicate with customer,
  - DE tools used on project,
  - traditional SE tools on project,
  - tools transitioned from traditional SE to DE tools,
  - DE tools used from organization common tools library,
  - projects using an Integrated Digital Environment,

- structured pilots at the organization or business sector level focused on DE tools, methods.

The SE-DE impact results focus on understanding DE experiences on projects related to SE impact enabling a more informed decision regarding SE value in competitive bids as customer and the organization transition to DE. When an experience-based bidding model is implemented, less overall losses result [15]. These results are based on qualitative data analysis using informational interviews, survey results, and metrics assessments. In addition to tracking SE-DE impact on bids and projects, research and recommended actions empowering engineers in this DE transition are identified and are implemented with three DE pilots. As an organization DE transition progresses, matures, and evolves, DE savings estimations in competitive bids and BOEs should be updated. As projects adopt DE (tools, processes, practices) and track DE metrics, DE savings and associated SE hours distributions should be updated with the feedback loop between these projects and new competitive bids. These qualitative SE-DE impact analysis results complement the quantitative data analysis results completed at the project and system-level. In the next section, RQ3 focuses on communicating these results.

In summary, results of data analysis at the project-level and system-level are the focus of this RQ. The system-level results include the interpretation of results in determining SE value, SE value optimization, and the impact of risk management and culture on SE value. In addition to the analysis results of quantitative data on projects and system, qualitative data analysis results focus on the DE transition and impact of DE on SE. Informational interviews and survey results capture DE experiences from systems engineers on competitive bids, projects, and DE transition leadership highlighting SE-DE benefits, challenges, and advice/lessons learned. Organizational psychology and systems thinking approaches are combined to identify recommended actions to empower engineers in a DE transition. These recommended actions are applied in three DE pilots with results shared. Supplementing these experiences is the results of two DE metrics activities: assessing business sector metrics for DE and creating MBSE MOE. The project-level and system-level data analysis results, feedback loops relating competitive bids and project performance including DE-SE cost savings bid and realized, DE-SE impact

experiences and survey results interpreted as DE-SE benefits, challenges and advice/lessons learned, DE metrics assessments, and pilot results are all original research. This original research can be used to determine the ‘knee in the curve’ for optimizing SE value/resource allocation based on data analysis, SE hours distribution, and project performance. SE can be a diversely interpreted activity and its value and impact is beyond requirements and ‘moving paper’. Communicating the value of SE based on these results is the focus of the RQ3 section which follows.

### **RQ3 : Results for ‘How to communicate SE Value to a Competitive Bid Team?’**

RQ3 research results focus on communicating the determination of SE value resulting from the data analysis in RQ2 using the data collected in RQ1. The determination of SE value has a quantitative component (RQ2) and a qualitative component (RQ2 and RQ3). The combination of these components, along with references, form the SEaaS Framework which is used to communicate SE value based on the research results to competitive bid teams. This framework (Figure 35) promotes ready access to this research data analysis results and references through hyperlinks.

With this framework, the quantitative and qualitative data is available to decision makers on competitive bids. This data enables a more informed SE value determination understanding the risks inherent with various SE value ranges and resulting reference project performance. The framework enables communication of quantitative SE value with project-level data analysis, system-level data analysis and summaries for SE hours, project performance, risk, and defect profiles. The framework enables communication of qualitative SE value using the SE-DE survey results based on balanced scorecard concepts (customer, financials, learning, growth) and using the SE-DE impact summaries (for bids and projects). Supplementing the quantitative and qualitative inputs into the SEaaS framework are several key references supporting SE value and the impact of DE on SE. With quantitative and qualitative data analysis results, feedback loops, and references available to the competitive bid teams, a more data-driven SE value determination can be made for the competitive bid. For example, if the competitive bid team is challenged to reduce its SE effort estimate, the SEaaS framework provides access to project performance

data for similar projects within this reduced SE effort range. The competitive bid team can review qualitative data (survey results) for SE leader insight into SE activities which may be candidates to absorb this reduction with minimal risk or impact to overall performance.

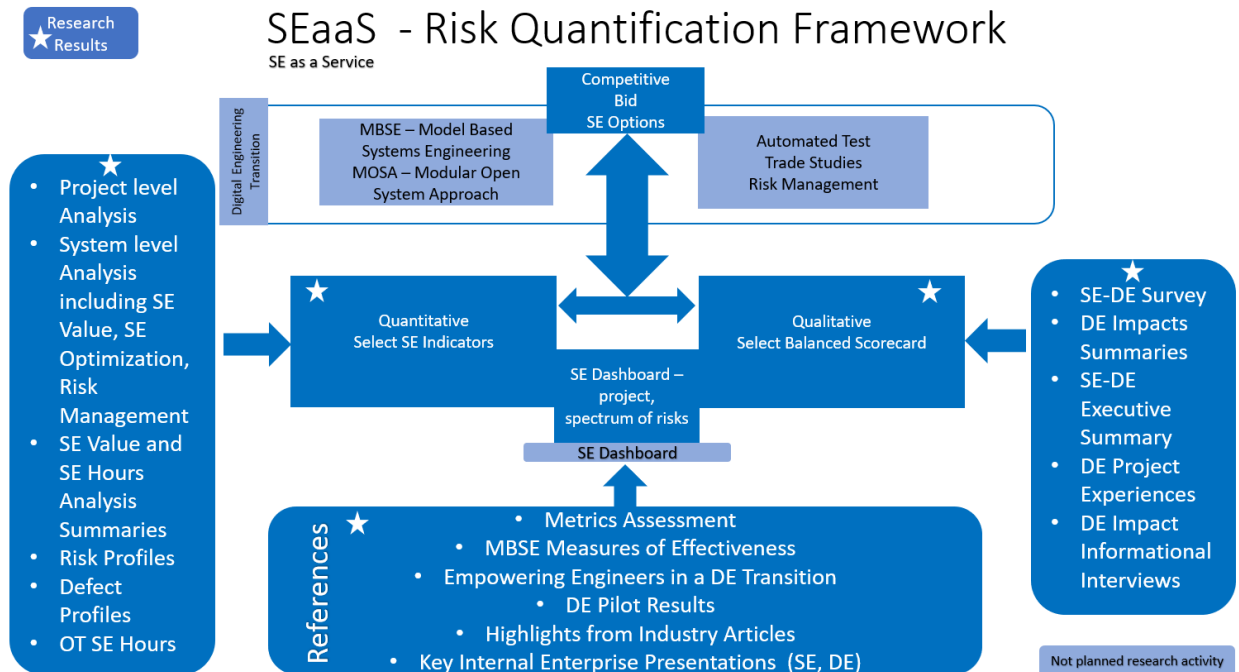


Figure 35: SEaaS Risk Quantification Framework to communicate the determination of SE value. The star indicates results of this research as input into this framework.

As organizations transition to DE, the competitive bid team can review the SE-DE impact for insight into SE hours spread for DE and other risk mitigation observations. These references are available to the competitive bids team as resources and foster greater understanding or promote the identification of risks. The SEaaS framework provides ready access to data, data analysis, and references enabling the competitive bid team to determine and to justify SE value. Inputs to the framework are the:

Quantitative Data Analysis Results:

- Project-level data analysis results for each of the 20+ projects,
- System-level data analysis results aggregating the project-level data,
- SE Value and Risk Management,
- SE Value and SE Optimization,

- Interpreting the Determination of SE Value in a Competitive Bid Results:
  - SE Value Summaries,
  - SE Hours Summaries,
  - SE Hours to Milestone Summaries and Graphs,
  - Overtime (OT) SE Hours,
  - Risk Profiles,
  - Defect Profiles – Change Tasks,
  - Defect Profiles – Quality Notes,
  - Defect Profiles – Late and Error-free Releases,
  - All Defect Profiles Summary.

Qualitative Data Analysis Results:

- Digital Engineering Impacts:
  - Executive Summary,
  - Project Experiences Summary,
  - DE Impact Interviews Summary,
  - DE Research Details.
- SE-DE Survey Results:
  - Responses summary and graphs,
  - Detailed text responses.

References:

- Empowering Engineers in a Digital Engineering Transition Peer-Reviewed Technical Paper,
  - DE Pilots and Results,
- Metrics Assessment,
- MBSE Measures of Effectiveness (MOE) research.

The framework contains hyperlinks to each of these input components for ease of use.

In addition to the SEaaS Risk Quantification Framework, results of this research are communicated within the business sectors and within industry to foster knowledge sharing of the results from this original research and to contribute to the growth in industry knowledge of SE and the impact of DE on SE. As of this writing, the following industry presentations are complete:

- INCOSE International Symposium (Detroit, MI in June 2022) - “Empowering Engineers in a Digital Engineering Transition” [65] – peer reviewed and published technical paper (Appendix) and technical presentation,
- INCOSE WSRC (Western States Regional Conference (Golden, CO in October 2022) - “Empowering Engineers in a Digital Engineering Transition” [65] with updates – technical presentation.

As of this writing, six business sector presentations are complete sharing early results of this research with 2000+ attendees. A summary of the research results, in determining SE value in competitive bids, will be presented in the upcoming year at multiple business sector forums.

In summary, RQ3 focuses on effective communication of the research and of the quantitative and qualitative data analysis results. The SEaaS Risk Quantification Framework (Figure 35) is the communication mechanism for the research results. This original research identifies, collects, and analyzes data from diverse and distributed sources, establishes feedback loops between competitive bids and projects (Figure 4), and applies systems thinking concepts and the Iceberg Model tool to analyze the data for trends and patterns influenced by the structure of SE value at the project and system-level. The research data, results from data analyses, and references are available via hyperlinks in a visually simple framework for competitive bid teams and projects to determine SE value and to make data-driven decisions. Data is the currency of competition, and the data analysis results contribute to an optimized determination of SE value in competitive bids. The goals of this research are to enable data-driven decisions for competitive bid team to ‘dial in’ optimized SE value and to allocate SE hours to generate value based on project trends. This framework allows the competitive bid team to estimate SE in an effective, optimized manner with a greater awareness of risk and how to manage it. This framework is not a recipe, and the need exists for applying systems thinking for the competitive bid using this research data analysis results. The results of this original research are communicated in the SEaaS Risk Quantification Framework and meet the research goals by enabling an organization to remain competitive with data-driven SE value determination.

## Chapter 8 Conclusion

This research achieved its goals of determining the value of systems engineering in competitive bids to meet an organization's need to remain competitive and to successfully transition to digital engineering.

The impact of the DE transition on SE value is integrated into the research tasks and RQ responses. The research is guided by answering three questions:

- RQ1: How to quantify the value of Systems Engineering?
- RQ2: How to analyze this quantification to provide justification for bid SE effort ranges and associated project results?
- RQ3 : How to communicate SE Value to a competitive bid team?

The results of the quantitative data analysis align with the findings in the literature search noting the recommended SE effort is in the range of 14-16% of project total. SE value may not be as efficiently applied on projects at higher ranges or SE is applied with diminishing returns at higher value. Lower SE value ranges do not support the minimal SE activities which contribute to successful project execution.

The system-level analysis results focus on SE value and on optimizing SE value using risk management.

The culture change associated with the DE transition is analyzed using qualitative data captured from the SE-DE survey results and informational interviews with systems engineers on projects executing DE or leading the DE transition. Results of the quantitative and qualitative data analysis are communicated using the newly created SEaaS Risk Quantification Framework. This framework allows the bid team to estimate SE in an effective, optimized manner with a greater awareness of risk and how to manage it.

Key results from this research include:

- There is a positive correlation trend among SE OT hours, project milestones, and an increased defect rate. OT can be a leading indicator of performance issues as additional SE effort is applied to resolve technical issues. The recommendation is to spread SE hours just prior to and in the month of key milestones to mitigate the negative cost impact of OT.
- The results acknowledge the positive impact of risk management, which is practiced and funded early in the project lifecycle, on project performance. The correlation of NFR and SE hours allocation relates to project performance. The recommendation is to actively practice risk management by identifying risks and estimating cost impact through NFR and funding risk

mitigation with MR. SE hours are allocated for risk management by front loading SE hours in the first 50% of the project lifecycle.

- Projects with SE hours percentage around the recommended value realize fewer design and process defects (QN).
- If defects increase as SE hours (planned) are decreasing, there is a performance impact. The recommendation to mitigate the risk of late defects is to monitor the defect rate across the project lifecycle. Monitoring the actual defect rate to planned defect rate enables the project to proactively add SE hours or re-distribute SE hours to address the defects faster if the rate is trending to an unplanned increase. If the actual defect rate is lower than the planned rate early in the lifecycle, SE hours could be re-distributed to later in the project lifecycle as a risk mitigator without increasing the overall SE hours.
- The recommendation is to spread more SE hours earlier in the DE project lifecycle than for a TDSE or non-DE project. There should be an increase in SE hours before System Requirements Review (SRR) or PDR. This SE hours increase enables the necessary training and DE adoption to occur during the DE transition.
- The qualitative analysis results consensus is not to increase or decrease the overall SE hours as a percentage to project total until DE metrics are identified and consistently used to demonstrate the ability to decrease SE hours as the result of DE. Balancing this increase in SE hours distribution earlier in the project lifecycle is the expected decrease in SE hours distribution later in the lifecycle as the benefits of applying DE are realized. A mitigation to this challenge is to commit early lifecycle SE hours to address DE transition issues.

The results of this research are not an absolute SE Value determination. There are other influences which impact the determination of SE value in a competitive bid that are beyond the scope of this research. This SE value determination provides a starting point from which deviations can be tracked with the risk management process. This research enables data-driven decisions for competitive bid team to ‘dial in’ optimized SE value and to allocate SE hours to generate the most value based on project trends. This framework is not a recipe, and the need exists for applying systems thinking for SE value in the competitive bid using these research data analysis results.

## References

- [1] Elm, J 2008. 'A Study of SE Effectiveness – Initial Results', IEEE International Systems Conference April 2008.
- [2] Elm, J and Rassa, R 2011. 'Developing a Business Case for SE', IEEE.
- [3] Elm, J 2012. 'Developing a Business Case for SE', IEEE A&E Systems Magazine July 2012
- [4] Hamann, R, Zandbergen, B and Zijdemans,P 2009. 'Does SE in Space Projects Pay?', INCOSE 2009.
- [5] Honour, E 2010. 'Systems Engineering Return on Investment', INCOSE International Symposium.
- [6] Valerdi, R et al 2010. 'Harmonizing Software and Systems Engineering Cost Estimation', International Journal of Computer Integrated Manufacturing Vol 25(4-5).
- [7] Valerdi, R, Boehm, B and Reiffer, D 2003. 'COSYSMO – A Constructive SE Cost Model Comes of Age', INCOSE International Symposium Proceedings.
- [8] Valerdi, R 2011. 'Heuristics for Systems Engineering Cost Estimation', IEEE Systems Journal March 2011.
- [9] Pena, M and Valerdi, R 2015. 'Characterizing the Impact of Requirements Volatility on SE Effort', Systems Engineering Vol 18 (1).
- [10] Boehm, B, Valerdi, R and Honour, E 2008. 'The ROI of SE', Systems Engineering Vol 11(3).
- [11] Honour, E 2004. 'Understanding the Value of Systems Engineering', INCOSE International Symposium Proceedings.
- [12] Rouse, W and Boff, K 2001. 'Strategies for Value: Quality, Productivity and Innovation in R&D/Technology Organizations', Systems Engineering Vol 4(2).
- [13] Roedler, G, Rhodes, D, Schimoller, H and Jones, C 2010. 'INCOSE Systems Engineering Leading Indicators Guide', Version 2, INCOSE-TP-2005-001-03.
- [14] Carson, R and Zlicaric, B 2008. 'Using Performance Based Earned Value to Measure SE Effectiveness', INCOSE.
- [15] Ahmed, M et al 2016. 'Construction Bidding and the Winner's Curse: Game Theory Approach', Construction Engineering Management Vol 142(2).
- [16] Ping Ho, S and Hsu, Y 2014, 'Bid Compensation Theory and Strategies for Projects with Heterogeneous Bidders: A Game Theoretic Analysis', Journal of Management Engineering Vol 30(5).
- [17] Engelbrecht-Wiggans, R and Katok, E 2007. 'Regret in auctions: theory and evidence', Economic Theory Symposium 2007.

- [18] Milgrom, P and Weber, R 1982. 'A Theory of Auctions and Competitive Bidding', *Econometrica* Vol 50(5).
- [19] Laffont, J 1997. 'Game theory and empirical economics: The case of auction data', *European Economic Review* Vol 41.
- [20] Hauksen , K 2002. 'Probabilistic Risk Analysis and Game Theory', *Risk Analysis* Vol 22(1).
- [21] Cox, L 2009. 'Game Theory and Risk Analysis', *Risk Analysis* Vol 29(8).
- [22] McDermott , T 2020. 'Digital Engineering Metrics Summary Report', SERC Report.
- [23] Hale, J and Hoheb, A 2020. 'Model Based Capabilities Matrix and User's Guide', INCOSE.
- [24] Zimmerman, P, Gilbert, T and Salvatore, F 2019. 'Digital Engineering Transformation across the Department of Defense (DoD)', *Journal of Defense Modeling and Simulation: Applications, Methodology and Technology* Vol 16(4).
- [25] Elm, J and Goldenson, D 2013. 'Quantifying the Effectiveness of SE', IEEE.
- [26] Vanek, F, Jackson, P and Grzybowski, R 2008. 'SE Metrics and Applications in Product Development: A Critical Literature Review and Agenda for Further Research', *Systems Engineering* Vol 11, Wiley Periodicals, Inc.
- [27] Wang, G, Valerdi, R, Roedler, G and Pena, M 2013. 'Quantifying Systems Engineering Reuse- a Generalized Reuse Framework in COSYSMO', INCOSE.
- [28] Emes, M 2012. 'Principles of Systems Engineering Management', INCOSE Insight Vol 20 (2).
- [29] Douglass, B 2016. *Agile Systems Engineering*, Elsevier, Waltham, MA (US).
- [30] Bone, M et. al. 2019. 'Transforming systems engineering through digital engineering', *Journal of Defense Modeling and Simulation: Applications, Methodology, Technology* Vol 16(4).
- [31] McDermott, T 2018. 'Organization System-of-Systems Model for Digital-thread Enabled Acquisition', Stevens Institute of Technology and Systems Engineering Research Center (SERC).
- [32] Jonkers, R and Shahroudi, K 2020. 'Complexity, Systems Thinking and an Integrated Systems Engineering and Project Management Model', INCOSE International Symposium.
- [33] Valerdi, R and Roedler, G 2009. 'SE Leading Indicators for Technical Effectiveness', *Systems Engineering* Vol 12 (1).
- [34] Browning, T and Honour, E 2005. 'Measuring the Lifecycle Value of a System', INCOSE.
- [35] Gilbert, D, Yearworth, M and Oliver, L 2014. 'Systems Approach to the Development and Application of Technical Metrics to Systems Engineering Projects', *Procedia Computer Science* Vol 28.
- [36] Honour, E 2001. 'Optimizing the Value of Systems Engineering', INCOSE International Symposium Vol 11(1).
- [37] Reddy, V 2018. 'The SpaceX Effect', *New Space* Vol 6(2).

- [38] Pepe, K et al 2020. 'Preparing the Acquisition Workforce: A Digital Engineering Competency Framework'. INCOSE International Symposium.
- [39] Noguchi, R and Wheaton, M 2020. 'Digital Engineering Strategy to Enable Organization Systems Engineering', INCOSE International Symposium.
- [40] Wang, G 2020. 'Implementing a Model-Based Digital Engineering Organization for a Defense Systems Integrator – an Ongoing Journey', INCOSE International Symposium.
- [41] Karlsson, E, Malvius, D and Lindberg, M 2020. 'Mechanisms for a Systems-Oriented Mindset-Towards Organizational Systems Thinking', INCOSE International Symposium.
- [42] Madhi, A and Purohit, S 2019. 'Economic Analysis of Model-Based Systems Engineering', Systems Vol 7(12).
- [43] Haskins, C 1999. 'What's the Balanced Scorecard got to do with Systems Engineering?', INCOSE International Symposium Vol 9(1).
- [44] Browning, T 2003. 'On Customer Value and Improvement in Product Development Process', Systems Engineering Vol 6(1).
- [45] Baldwin, K 2018. 'Transforming the engineering organization – applications of Digital Engineering and Modular Open Systems Approach', Journal of Defense Modeling and Simulation: Applications, Methodology and Technology Vol 16(4).
- [46] Post, D et al. 2019. 'CREATE/ERS Department of Defense acquisition reform through resilient engineering and virtual prototyping in a digital environment', Journal of Defense Modeling and Simulation: Applications, Methodology and Technology Vol 16(4).
- [47] Zimmerman, P et al. 2019. 'Considerations and examples of a modular open systems approach in defense systems', Journal of Defense Modeling and Simulation: Applications, Methodology and Technology Vol 16(4).
- [48] Kusel, K 2020. 'Model-Based Systems Engineering for Life Cycle Development of Digital Twins of Real Estate', INCOSE International Symposium.
- [49] Papke, B, Wang, G, Kratzke, R and Schreiber, C 2020. 'Implementing MBSE- An Organization Approach to an Organization Problem', INCOSE International Symposium.
- [50] Kenett, R, Zonnenshain, A and Swarz, R 2020. 'Systems Engineering as Data-Driven and Evidence-Based Discipline', INCOSE International Symposium.
- [51] Honour, E 2011. 'Sizing Systems Engineering Activities to Optimize Return on Investment', INCOSE International Symposium 2011.
- [52] Elm, J and Goldenson, D 2012. 'The Business Case for Systems Engineering Study: Detailed Response Data', Software Engineering Institute.
- [53] McDermott, T, Van Aken, E and Hutchinson, N 2020. 'DE Metrics: Categorizing the Benefits and Value of Digital Engineering', SERC for NDIA Systems and Mission Engineering Conference.
- [54] McDermott, T et. al. 2019. 'Digital Engineering Metrics', SERC Sponsor Research Review.

- [55] Erwin, D & Garman, A 2010, 'Resistance to organizational change: Linking research and practice', *Leadership & Organization Development Journal* Vol 31(1).
- [56] Kotter, J 1995. 'Why transformation efforts fail', *Harvard Business Review*, Vol March-April.
- [57] Kram, K & Hall, D 1991. 'Mentoring as an antidote to stress during corporate trauma', *Human Resource Management*, Vol 28(4).
- [58] Meadows, D 2008. *Thinking in Systems*, Sustainability Institute Earthscan, London (UK).
- [59] Oreg, S 2006. 'Personality, context, and resistance to organizational change', *European Journal of Work and Organizational Psychology*, Vol 15(1).
- [60] Reed, J & Vakola, M 2006. 'What role can a training needs analysis play in organizational change?', *Journal of Organizational Change Management*, Vol 19(3).
- [61] Vakola, M & Nikolaou, I 2005. 'Attitudes towards organizational change: What is the role of employees' stress and commitment?', *Employee Relations*, Vol 27(2).
- [62] Organization Space Digital Project Policy (Internal website) \_Last accessed Feb 12, 2022.
- [63] INCOSE 'Practical Software and Systems Measurement (PSM) Digital Engineering Measurement Framework', INCOSE Product Number: INCOSE-TP-2022-002-01: May 18, 2022, Version 1.
- [64] Henderson, K, McDermott, T, Van Aken, E, Salado, A 2022. 'Towards Developing Metrics to Evaluate Digital Engineering', *Systems Engineering*, 1-29 2022, Wiley Periodicals, Inc.
- [65] Dawson, S, Batchelor, A 2022. 'Empowering Engineers in a Digital Engineering Transition', INCOSE International Symposium, 2022.
- [66] Van den Heuvel, S, Freese, C, Schalk, R & van Assen, M 2017, 'How change information influences attitudes toward change and turnover intention', *Leadership & Organization Development Journal*, vol. 38, no. 3, pp. 398-418.
- [67] Yousef, D 2017, 'Organizational commitment, job satisfaction and attitudes toward organizational change: A study in the local government', *International Journal of Public Administration*, vol. 40, no. 1, pp. 77-88.

## **Appendix – Peer-Reviewed Conference Paper**

This appendix contains a copy of the peer-reviewed technical paper, Empowering Engineers in a Digital Engineering Transition [65], detailing the results of the combined systems thinking and organizational psychology approaches to empower engineers in a Digital Engineering transition. Figure 33 shows the proposed recommended actions focusing on knowledge transfer, training, and communication. These results encourage engineers to participate in this DE transition instead of having it happen to them.

This peer-reviewed technical paper is published and was presented at the INCOSE International Symposium (June 2022) and INCOSE Western States Regional Conference (October 2022).

### **Empowering Engineers in a Digital Engineering Transition: Applying organizational psychology and systems thinking approaches to define the problem and to develop recommended actions**

**Summary** As an organization implements an organization organizational change: transition from Traditional Document-based Systems Engineering (TDSE) to Digital Engineering (DE), engineers are critical in accepting and implementing the change. The DE transition impacts established engineering tools, processes, and practices in which the engineers have confidence and know well. Engineers have spent their careers developing a level of competence in TDSE. Uncertainty associated with this organizational change increases stress, decreases job satisfaction, and impacts commitment among engineers. The engineering culture reflects attitudes of resistance and uncertainty.

This paper analyzes the DE transition from organizational psychology and systems thinking approaches. The combination of these two approaches enables the identification of an intervention and recommended actions to empower engineers in the DE transition. With consideration of the research findings in the organizational psychology literature search and applying systems thinking tools, three actions of the intervention are proposed focusing on knowledge transfer, training, and communication.

## **Organizational Problem, Symptoms and Diagnosis**

A familiar challenge facing many engineering organizations is the transition from Traditional Document-based Systems Engineering (TDSE) to Digital Engineering (DE). This transition includes adopting Model Based Systems Engineering (MBSE). Engineers within an organization may not be embracing or enabling the organizational change of this transition. Combining organizational psychology and systems thinking approaches, this paper addresses the attitudes and behaviors which engineers may be demonstrating regarding this change and the resulting common organizational problem related to this transition. This paper is targeted to organizations which are struggling with this DE transition by referencing the organizational problem, symptoms, diagnosis, and proposed intervention.

The DE transition impacts established tools, processes, and practices which the engineers know and have confidence in using. A successful transition requires an organizational commitment. However, the attitudes and commitment of engineers to this transition introduces a challenge. The symptoms of the organizational problem include resistance and reluctance towards the DE transition. Evidence of resistance and reluctance to make this change is manifest in minimal progress in the transition and stress induced by this change. The engineers have not demonstrated behaviors which embrace the tools, processes, and practices of DE. Instead, they have relied on and continue to use trusted, proven TDSE tools, processes, and practices. The engineers resist estimating DE cost during competitive bids or collecting DE metrics. They are reluctant to assess the return on investment of new DE tools, processes, and practices, and to develop new processes and practices using DE tools.

Behaviors demonstrated by the engineers influence the diagnosis of this problem. The engineers have not demonstrated a sufficient level of productive behaviors to enable a successful DE transition: selecting tools, creating processes, collecting metrics, integrating DE into proposals. Many engineers have not demonstrated the motivation to foster this change due to insufficient organizational commitment, inability to have ownership, lack of training, and stress generated by this change.

Engineers' attitudes of resistance and reluctance to demonstrating behaviors [61] supporting the transition are symptoms of the DE transition problem. Engineers have spent their careers developing a level of competence and expertise in TDSE. This change negatively impacts this competence and expertise as it requires the entire engineering team, from junior engineers to experts, to start over in developing new competence, expertise, and skills in DE. Junior engineers may have an advantage over the senior engineers as their competence and confidence level in DE tools is typically greater than experienced senior engineers. The senior engineers' unease in a DE environment is frequently associated with uncertainty and a decrease in job satisfaction. Senior engineers are viewed as technical experts and the new tools and processes of DE threaten this expertise. These senior engineers should be demonstrating organizational commitment through behaviors to initiate this transition, but stressors and experiences of strain have a negative correlation to the positive attitude of organizational commitment [61].

Based on this problem description, the motivations, attitudes, and behaviors of the engineers in this organizational change are the focus of the organizational psychology literature review in this paper. The research findings in the relevant articles were used to develop the proposed intervention actions to enable a successful DE transition. The goal of the intervention is to positively influence the engineers' attitudes by increasing job satisfaction and organizational commitment while decreasing resistance, stress, uncertainty, and identity threat.

### **Description of this Complex Problem**

Describing this organizational problem in systems thinking terms, systems in this complex problem of engineers in the DE transition include System of Interest (SOI), Enabling System (ES) and System Context (SC) as shown in Figure A-1. SOI is the culture of engineers in this transition. ES is the organization that is committed to this DE transition. SC is DE across the product development lifecycle. The lack of positive influence of the systems and feedback loops on the engineers' culture (mental models) results in resistance and uncertainty of the engineers to make this change and manifests in minimal progress in transition. The emergent behavior originates within the systems and with interfaces

and feedback loops among the three systems. The focus of this SOI is based upon the ongoing DE transition within multiple industries. The goal is to provide technical leadership with a problem description and recommended actions (solutions) developed using organizational psychology and systems thinking approaches.

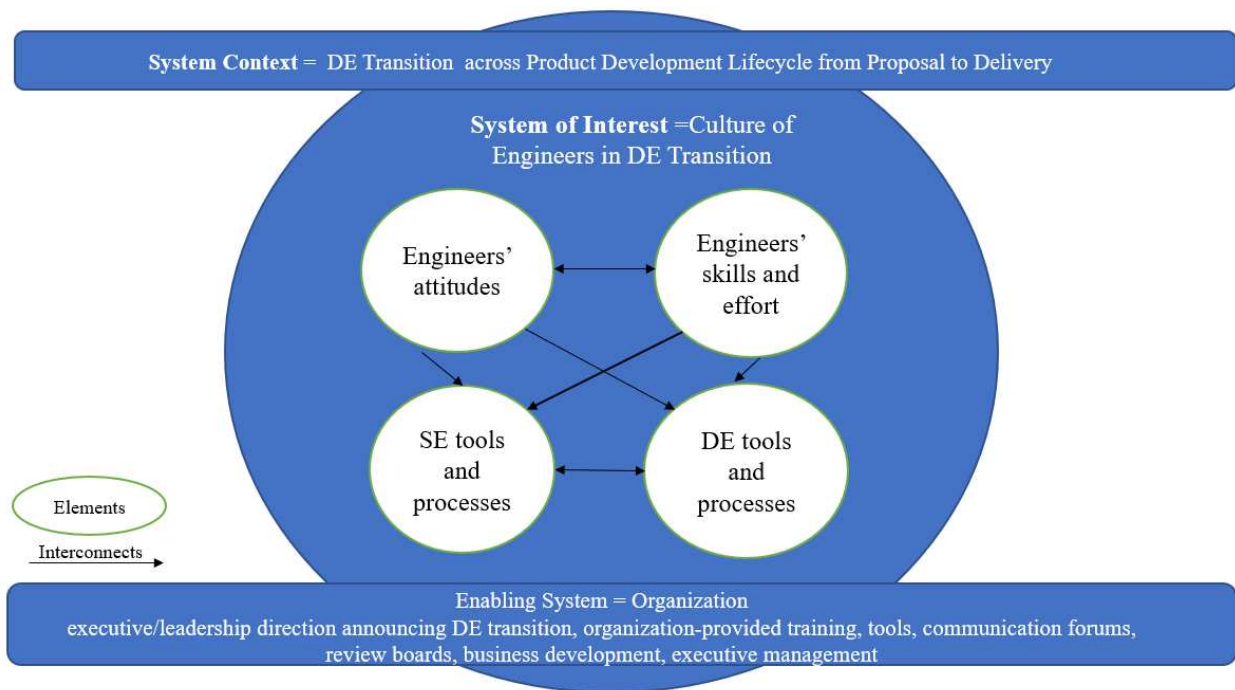
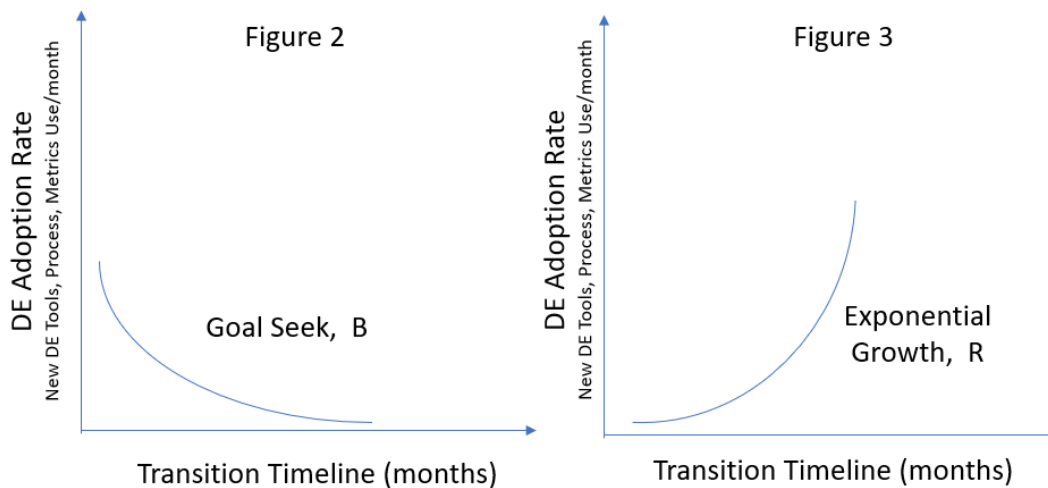


Figure A-1. Three systems of this organizational problem

With the systems defined, the events and data points relating to this problem indicate the engineers may not have demonstrated the changed mental model to accept DE. A review of engineers' patterns of behavior relative to this DE transition may show goal seeking behaviors influencing the diagnosis of this complex problem. The engineers may not have demonstrated a sufficient level of productive behaviors to enable a successful transition from TDSE to DE, despite leadership's direction to transition. Behaviors have not demonstrated an openness to trying or embracing DE. Attempts at the DE transition are abbreviated as the product development (SC) pressure to meet schedule and cost objectives manifests (Figures A-2, A-3). Figure A-2 depicts the impact of engineers' behavior on the DE adoption rate. After the initial and limited positive attitudes of the engineers, goal seek behaviors are demonstrated as

engineers revert to trusted TDSE (stability) from attempts at DE (change). Goal seeking or stability seeking behaviors drive to a known stable state within a range of values. Goal seeking is a regulating or balanced feedback loop which opposes whatever direction of change is imposed on the system [58]. The engineers are demonstrating goal seek behaviors as they resist the change to DE. Figure A-3 depicts the desired behavior of engineers embracing the transition from TDSE to DE and enabling the organizational change. The DE adoption rate exponentially increases over time. The difference between actual behaviors of Figure A-2 and desired behaviors of Figure A-3 is the organizational problem. Lack of clear communication and DE training from the organization (ES) drives engineers' behavior to return to TDSE, even if DE is explored initially. DE transition negatively impacts competence and expertise (SOI) as it requires the engineering team to develop new DE competence, expertise, and skills (new mental model). Engineers' attitudes reflect they are not owners of this DE transition, but rather it is happening to them.



*Figures A-2 and A-3. Actual and desired engineers' DE adoption rate over the DE transition*

With the organizational problem defined from both organizational psychology and systems thinking approaches, research into the sources of the organizational problem is conducted. For the organizational psychology approach, a literature search yields studies and findings detailed in articles focusing on

attitudes and behaviors related to organizational change. For the systems thinking approach, the systems are identified in terms of elements, boundaries, lifecycle, and feedback loops. Combining the research findings with the system identification, the basis for the organizational problem intervention and recommended actions is explained.

### **Organizational Psychology Literature Research**

To develop an intervention for this organizational problem of the engineers' negative attitudes of resistance and reluctance to demonstrate productive behaviors supporting the DE transition, several articles focusing on organizational change, organizational commitment, attitudes, and stress are reviewed as part of this literature search. The articles are summarized referencing research, key findings, and relevancy to this problem and proposed intervention.

Multiple studies conclude organizational change increases uncertainty and stress on employees and decreases performance, job satisfaction, and communication [61]. Employees' attitudes toward the change can be positive or negative. Positive attitudes contribute to a higher probability of a successful change while negative attitudes reduce the probability of a successful transition. Given most change initiatives fail [56], there is a negative relationship of resistance, stress, and negative attitudes towards change [61]. There is a positive relationship between an employee's organizational commitment and willingness to accept change, if perceived as beneficial. Study findings [61] link work relationships with supportive colleagues, adequate training, and effective communication to reducing uncertainty and resistance to change. By recognizing the additional workload due to the change and adjustments in the work environment and schedule, stress is reduced.

Building on the previously described organizational commitment relationship to employee's accepting and enabling organizational change, Yousef [67] emphasizes the role of job satisfaction in organizational commitment and its influence on a successful organizational change. Satisfaction with co-workers has a direct influence on affective attitudes and behaviors towards the change. These findings are useful to the

problem as the intervention should emphasize co-worker relationships to increase job satisfaction, organizational commitment and positively influence attitudes towards the change.

Augmenting this co-worker relationship influence on attitudes toward change, the authors [57] focus on mentoring as a resource for social support and learning in times of change. Affiliation with others is a means of reducing stress. The authors measure job attitudes and employee stress through interviews and questionnaires, which include self-reporting questions on mentoring. Results indicate a positive relationship between attitude toward mentoring and stress reduction. The responses also note employees in early career and late career are more inclined toward mentoring as mid-career employees typically focus on career development. Job redesign, to enable mentoring between these two employee demographics, could be considered [57]. The organization can encourage relationship building, including mentoring, and positively recognize it to reduce the stress of the change. The demographic of employees to whom mentoring appeals may be directly applicable to the organizational problem as senior engineers value technical expertise status and junior engineers seek organizational culture and norms guidance. These employees may be threatened and stressed by the change and mentoring, including reverse mentoring, is useful in the development of the intervention.

Recognizing the impact of learning during organizational change is one key to success. Findings [60] extend training beyond courses to participation in change steering/transition committees. This participation focuses on the change process and continual evaluation and assessment of the training relative to the change progress. These evaluations and assessments are used to identify the training needs. Learning through experience and correcting errors through shared lessons learned is emphasized to mitigate a legacy culture of hierarchy and blame. Reed & Vakola [60] note balance should be struck between a standard and customized learning approach based on the organization's subgroups and their cultures. These findings [60] are relevant to the organizational problem as actions to decrease resistance are offered while acknowledging the challenges which culture may present during organizational change. Resistance to the change is decreased through participation in steering/transition committees, continual

evaluation of progress and focus on the process of change with the ability to customize the process. With the goal of decreasing the engineers' resistance to the DE transition, these findings are integrated into the proposed intervention.

Research [55] also focuses on the organizational change process and its influence on the resistance to change. Relevance to the problem includes how resistance is influenced by the perceived negative impact to job security, power, and intrinsic rewards. The communication of the change influences the employees' level of participation in the change and the goals of the change. There is a positive association with the ability to participate, involvement in decision-making and the acceptance of the change. The understanding and insight which the authors [55] provide should directly influence the intervention on communication and employee involvement with the change.

Findings in prior articles note the importance of employee engagement and leadership communication during organizational change and the positive influence which both have on employee attitudes toward the change. Van den Heuvel et al. [66] recommend communication on a continual basis and assessing its timeliness and usefulness in addressing employee concerns regarding the change. In addition to effective communication, the authors [66] note a positive relationship between employee engagement and attitude toward the change. These relationships are relative to the problem and are included in the proposed intervention. Findings on communication include a continual evaluation aspect for the frequency, timing, and content of the communication to ensure it is effective for employees as the change occurs. Leaders can communicate, but this continual evaluation helps to ensure the communication is effective resulting in the desired positive influence on employee attitudes towards the change.

Oreg [59] reviews research related to employee attitudes toward organizational change. Two findings are relative to this organizational problem. The first finding is the nonlinear relationship of information about the change and resistance. Not enough or too much information has a negative relationship as too much or too little information increases employee resistance and job uncertainty. The second finding is

resistance negatively correlates with job satisfaction attributed to the stress and uncertainty related to the change. These two findings [59] are integrated into the proposed intervention and supplement previously noted research on resistance and communication.

The research and findings summarized in these articles are integrated into the proposed intervention with the goal to positively influence engineers' attitude toward the DE transition and to decrease resistance and uncertainty with this organizational change. In the following section, the systems thinking approach is used to frame the problem. With this approach, systems thinking tools are used to develop proposed intervention actions providing practical recommendations to address this organizational problem.

### **Systemic Identification of the Problem**

Complementing the organizational psychology research findings, the organizational problem is identified using systems thinking concepts. This problem is not industry specific. Although systems engineering is prevalent in the aerospace and defense industries, these concepts can be applied to any industry which uses the systems engineering lifecycle including automotive, transportation, and construction industries. If the organization is transitioning from TDSE to DE, this organizational problem and intervention actions can be applied. The system (SOI) of the engineers' culture is identified by its boundaries, elements, lifecycle, and feedback loops. The systemic identification of the problem, combined with the organizational psychology findings, enable the development of the intervention and recommended actions for this organizational problem.

In Figure A-1, the organizational problem is depicted as three systems. The system boundaries of the SOI is the culture of the engineers in this DE transition. The ES is the supporting infrastructure of the organization. The SC is the product which the engineers create. Unwanted emergent behavior within and among systems and feedback loops define the complex problem of this DE transition.

The elements of the SOI include the engineers' attitudes (confidence, reluctance) and skills (expertise, knowledge) with TDSE and DE tools and processes. The ES elements are the organization's

communication, training, tools, and leadership. The SC elements are the phases of the product development lifecycle. Interconnections among the SOI elements are the links between the engineers and their tools and processes. These interconnections are influenced by attitudes and manifest by emergent behaviors. The stated purpose of the systems is to create the required product.

The lifecycle of the system is the anticipated duration of the DE transition, as it impacts or is impacted by the SOI, ES and SC. From the systems thinking approach, the lifecycle includes the changed mental model of the engineers' culture (SOI) to demonstrate desired, productive behaviors: to explore, trust and use DE tools, processes, and practices to create products (SC). Elements of the SOI change over this lifecycle as tools, processes, and practices evolve from TDSE to DE through the recommended actions of the intervention for this organizational problem.

In assessing the organizational problem using systems thinking concepts, there are four feedback loops among the systems. These feedback loops contribute to the goal seek behavior demonstrated (Figure A-2) and are:

- among all three systems (SOI, ES, SC) - leadership issued the transition to DE direction (ES) without evidence of this transition in the product development (SC) or with the engineers' culture (SOI),
- within the SOI - engineers are not confident in their roles post-DE transition and expertise is threatened,
- between SOI-ES - uncertainty within SOI on DE transition communication (ES): uncertainty surrounds the timeline, role/expertise, transition expectations, tools selection, and process impacts as/if DE is not understood,
- between SOI-SC - product development continues in TDSE vs DE: engineers' goal seek behavior is influenced by their culture and SC pressures on cost, schedule which drive continued use of TDSE.

The organizational psychology literature search focuses on research and findings that are relevant to the problem. Systems thinking concepts characterize the organizational problem in terms of systems, their elements, interactions, and feedback loops. The next section leverages this research and system

identification to develop an intervention for this organizational problem and recommended actions using systems thinking tools.

### **Proposed Intervention Using Systems Thinking Tools**

Using systems thinking tools, these study findings are leveraged into actions which should drive positive attitudes and productive behaviors to empower the engineers in a successful DE transition. To address the organizational problem, an intervention is developed consisting of three recommended actions reflecting the organizational psychology literature search and findings related to organizational change attitudes and behaviors. The result of the systems thinking tools application are the intervention's recommended actions: 1) engineers must participate in knowledge transfer (SOI, SC), 2) leadership must provide DE training (SOI, ES) and 3) engineers and leadership must create and communicate the DE transition plan (SOI, ES, SC).

The proposed intervention addresses the complex problem of the culture of engineers to this DE transition and the emergent behavior resulting from within the systems, the interfaces among the three systems and feedback loops. Iceberg Model, Double Loop Learning (DLL) and Causal Loop Diagrams (CLD) are the systems thinking tools applied. In Table A1, the Iceberg Model summarizes the current events and behaviors: TDSE/not DE is practiced, infrastructure supports TDSE/not DE, and the engineers' mental model of technical expertise remains with TDSE/not DE. Through feedback and changes, highest leverage is addressing the mental model associated with the engineers' culture (TDSE/not DE) and interface with organization (ES) and product development (SC) using TDSE/not DE. With systems thinking, change should be accompanied by structural, behavior changes which foster confidence and skills in DE (changed engineers' culture and mental model to DE, not TDSE) and a successful transition. The actions to drive these changes are noted in the 'desired culture/mental model' column of Table A1.

Table A1: Iceberg Model

| Iceberg Model                           | Current Culture of Engineers in DE Transition   | Actions to foster desired Culture/Mental Model of Engineers in DE Transition   |
|---|---|--|
| Events – what is happening              | Continued use of TDSE tools, processes, practices, metrics with little use of new DE tools, processes.  | Share evidence of new DE tool selection and usage, update DE processes, drive change through DE metrics, and bid DE in proposals.  |
| Patterns of Behavior – trends over time | Resistance, reluctance to use DE tools, create DE processes, metrics, bid DE in proposals.<br><br>Continued use of TDSE tools, processes, metrics, TDSE bids reflect engineers’ culture.  | Recognize successful mentoring relationships which promote a <b>knowledge sharing</b> culture; Encourage engineers to conduct DE tool trade studies and share updated processes to reflect DE. Make DE <b>training</b> part of the engineers’ performance goals; Share <b>communication</b> directives and impacts to projects and culture.  |
| Systems Structure – influences patterns | Engineers’ skills, expertise, knowledge, and confidence in TDSE tools, processes, metrics favor status quo; No incentive to change, lack of skills, confidence, knowledge of DE tools, and practices; DE tools and processes are not yet part of engineering infrastructure; no current roadmap for DE transition.<br><br>Focus on delivering product and performing a DE transition is a distraction, yielding added work. | Promote <b>knowledge sharing</b> as engineers transition to DE: establish structured mentoring projects, create online chat forums; Encourage and foster DE learning, select DE tools, create new or updated processes for DE, identify and collect new DE metrics and provide <b>training</b> in DE practices; Issue <b>communications</b> on how DE will change the organization’s structure, <b>training</b> , priorities, goals. Recognize engineers who embrace DE and participate in DE knowledge sharing. |
| Mental Models – values, beliefs         | TDSE expertise is highly valued in the culture; engineer’s reputation, role in organization is valued in context of current TDSE tools, processes; DE is a threat for engineers’ culture.   | Transition the culture to embrace DE as the ‘future’, value efforts to develop DE skills and expertise, change perspective on TDSE as reliable but not as effective or efficient as DE.<br><br>Transition mental model to DE - it’s more beneficial for the engineers and the organization.  |

The second systems thinking tool used as part of this proposed intervention is DLL. With the changes proposed using the Iceberg Model, DLL provides the feedback loops necessary to assess the proposed intervention progress and to foster the needed change in the engineers’ culture through the mental models embracing, rather than rejecting, DE. The three primary actions derived from the Iceberg Model are knowledge transfer, training, and communication. The DLL adds feedback to each of those actions as

shown in Figure A-4. With knowledge transfer DLL, the engineers' culture changes to accept DE as DE skills increase in value with mentoring and online chat forums. With training DLL, learning gap feedback drives DE tools/modeling training and decreases resistance with new skills and DE pilot project results. With communication DLL, engineers contribute to the DE transition through participation in transition steering/planning committees and through DE tool selection/startup kit creation to accelerate DE on projects. These feedback loops reinforce the positive actions resulting in a high leverage change of culture.

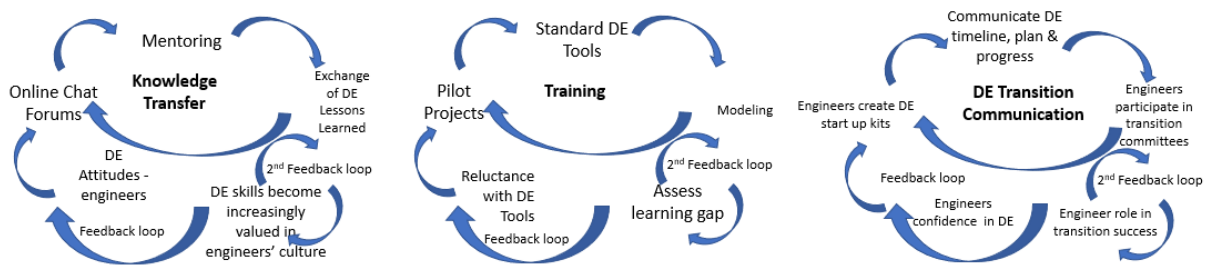


Figure A-4. Double Loop Learning applies feedback loops to the three recommended actions

The third systems thinking tool applied is CLD. For each of the three recommended actions, CLD is summarized in Appendix Figures 1A – 4A. Reinforcing (R) feedback loops and the changed mental model impact the SOI, ES and SC systems with their interfaces resulting in balanced (B) loop for engineers' culture in DE transition as shown in Figure 4A.

**Knowledge transfer**, through mentoring and online chat forums, enable the DE transition as engineers' skills and expertise are developed through peer social networks which empower the engineers to learn DE together. This approach decreases the threat to the engineers' role post-transition as a culture of peer-to-peer learning is fostered through mentoring, online chats, sharing lessons learned and best practices with DE tool selection, process edits/creation, metrics collection, and new proposal bids. Without knowledge transfer, the engineers' attitudes of reluctance and resistance persist and the threat to the engineers' skills and expertise, valued within the culture, increases. Real-world application includes three-month pilots

with monthly feedback session using senior/junior engineer pairings for knowledge transfer and fostering ownership. The knowledge transfer focuses on current assigned tasks and a weekly commitment. Structure of this pilot enables knowledge transfer which may not happen organically without this catalyst. Leaders should assess team composition and determine if job redesign to enable mentoring between these two employee demographics could be considered [57]. Metrics to measure success include knowledge transfer objectives met, ability of mentees to perform tasks independently and participation in monthly feedback sessions.

**Training** on new DE tools and modeling provides a baseline upon which the engineers can build their new skills and expertise. Sponsoring pilot projects, to test the validity of new DE tool trade studies, processes, and metrics collection, build confidence in DE with results shared across projects. Engineers gain confidence in DE tools and processes, grow their skills and expertise, and change the culture to accept DE. Without training, engineers may not feel part of the DE transition and may not trust the new tools and processes. The culture continues to rely on TDSE vs DE, slowing transition. Real-world application includes self-paced training and dedicated weekly time with an expert to answer questions within tool application for the engineer's task. Metrics to measure success include the number of engineers trained, hours of training, use of DE tools in tasking, and reliance on experts declining over time. Feedback loops can occur during career discussions, organizational meetings, and progress checks on tasks which use the new DE tools.

**Communication** of the DE timeline, plan, and strategy should include the engineers' perspectives with feedback loops via transition committees to validate the realism of the timeline, plan, and strategy. Participation and feedback loops enable the engineers to be part of the DE transition and not believe it is just happening to them. Creating DE startup kits build engineers' skills, expertise and knowledge contributing to a culture change. Real-world application includes communication of the DE plan and progress updates using existing communication formats – webinar, email, meetings – to create awareness of the DE transition and participation options. Periodic feedback in group and/or individual meetings

should be sought and used to drive action to increase participation. Demonstrations of startup kits increase DE awareness. Metrics to measure success include the feedback received and increased use of DE startup kits.

With the application of these actions, the complex problem of the emergent behavior of the engineers' culture (SOI) interfacing with the ES and the product development lifecycle (SC) changes to positive behaviors and a changed mental model of the engineers' culture accepting DE. Leadership can encourage engineers to embrace the DE transition through these actions by seeking participants, discussing action benefits within organizational meetings, and through individual discussions around career development or performance. Through feedback sessions encouraged in each of these actions, leaders can assess if an engineer is embracing the DE transition or struggling/feeling lost. Based on this feedback, leaders can revisit the implementation of the intervention actions and make appropriate changes to encourage DE within the engineers' culture. These proposed intervention actions can empower engineers in a DE transition with an increase in positive attitudes and demonstrated behavior changes associated with increased organizational commitment and decreased stress, resistance, and threat.

## **Conclusion**

An organization is implementing an organizational change as it transitions from TDSE to DE. This organizational change impacts the engineers who are critical in accepting and implementing this DE transition. However, the engineers have expressed the negative influence of resistance, stress, uncertainty, and threat in their attitudes. Engineers have yet to demonstrate productive behaviors associated with enabling the DE transition such as participation in selecting new tools, creating new processes, collecting metrics, and integrating DE into competitive bids. Based on a review of organizational psychology articles and application of systems thinking tools, proposed intervention actions – knowledge transfer, training, communication - have been developed to increase positive attitudes towards this organizational change, enabling the desired productive behaviors and empowering engineers to accept this organizational change of DE transition.

## References

- [55] Erwin, D & Garman, A 2010, 'Resistance to organizational change: Linking research and practice', *Leadership & Organization Development Journal*, vol. 31, no. 1, pp. 39-56.
- [56] Kotter, J 1995, 'Why transformation efforts fail', *Harvard Business Review*, vol. March-April, pp. 59- 67.
- [57] Kram, K & Hall, D 1991, 'Mentoring as an antidote to stress during corporate trauma', *Human Resource Management*, vol. 28, no.4, pp. 493-510.
- [58] Meadows, D 2008, *Thinking in Systems*, London: Sustainability Institute Earthscan.
- [59] Oreg, S 2006, 'Personality, context, and resistance to organizational change', *European Journal of Work and Organizational Psychology*, vol.15, no.1, pp. 73-101.
- [60] Reed, J & Vakola, M 2006, 'What role can a training needs analysis play in organizational change?', *Journal of Organizational Change Management*, vol. 19, no. 3, pp. 393-407.
- [61] Vakola, M & Nikolaou, I 2005, 'Attitudes towards organizational change: What is the role of employees' stress and commitment?', *Employee Relations*, vol. 27, no. 2, pp. 160-174.
- [66] Van den Heuvel, S, Freese, C, Schalk, R & van Assen, M 2017, 'How change information influences attitudes toward change and turnover intention', *Leadership & Organization Development Journal*, vol. 38, no. 3, pp. 398-418.
- [67] Yousef, D 2017, 'Organizational commitment, job satisfaction and attitudes toward organizational change: A study in the local government', *International Journal of Public Administration*, vol. 40, no. 1, pp. 77-88.

## Appendix (peer reviewed paper appendix)

The third systems thinking tool used is Causal Loop Diagrams (CLD) covering the three proposed intervention actions. CLD for each recommended action and the engineers' culture is summarized with Appendix Figures 1A– 4A. Reinforcing (R) feedback loops and changed culture impact the SOI, ES and SC systems and their interfaces result in balanced (B) loop for engineers' culture enabling DE transition as shown in Figure 4A.

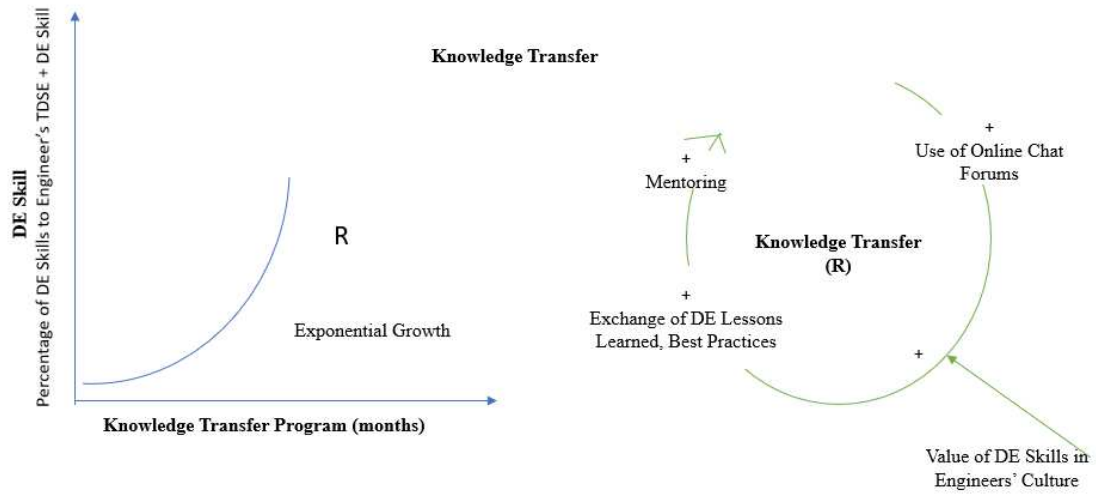


Figure 1A. Knowledge Transfer Action's Pattern of Behavior and CLD

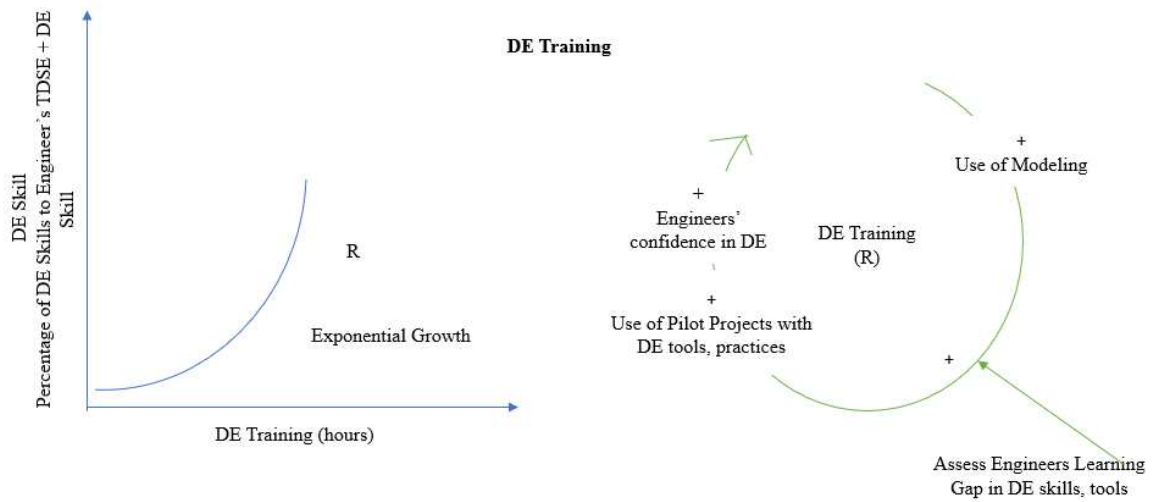


Figure 2A. DE Training Action's Pattern of Behavior and CLD

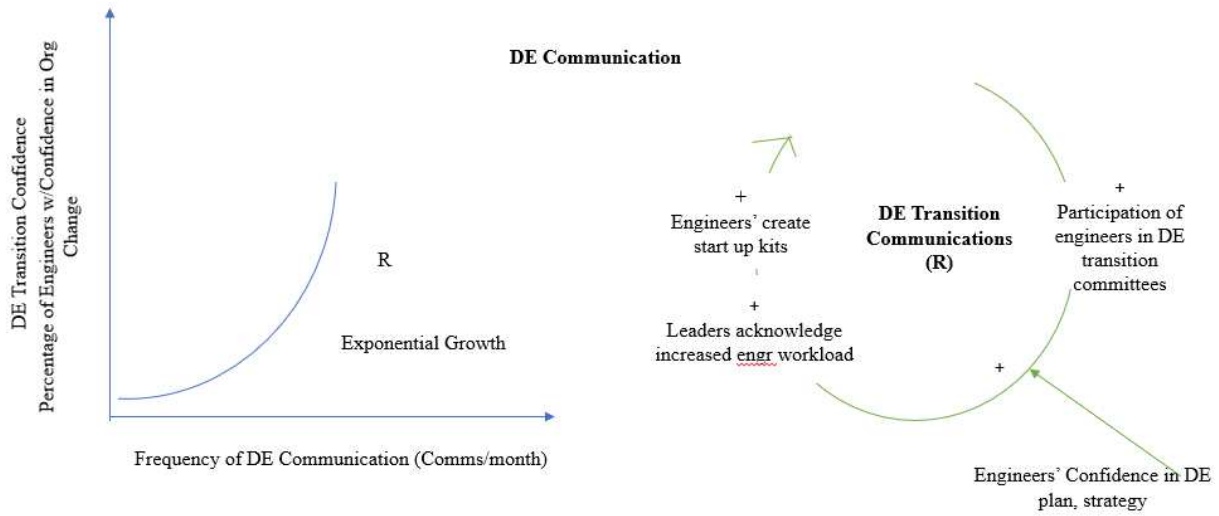


Figure 3A. DE Communication Action's Pattern of Behavior and CLD

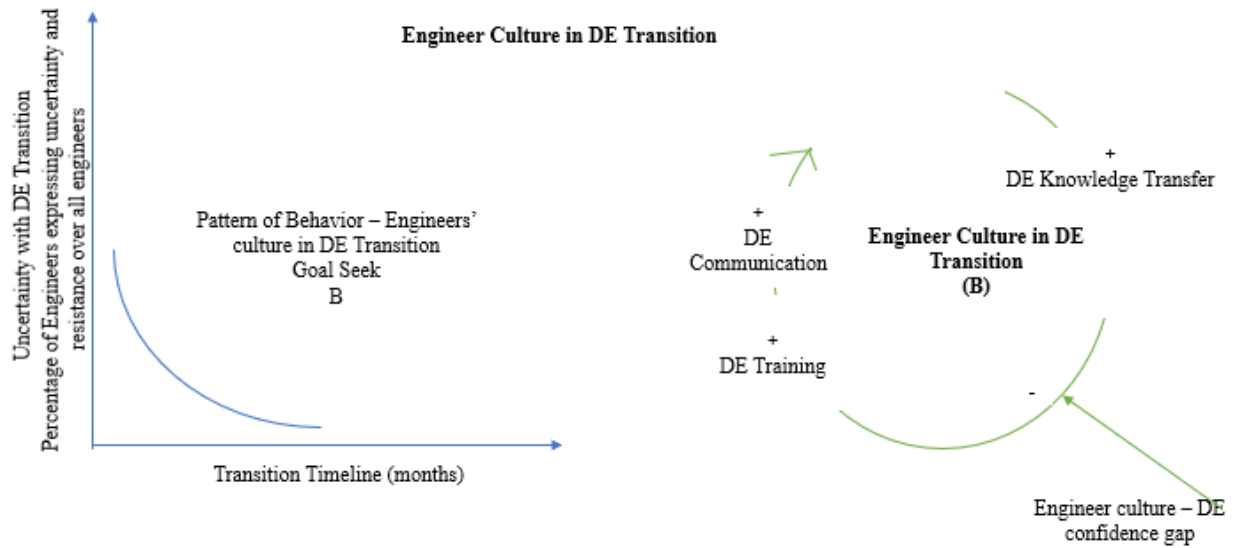


Figure 4A. Engineer Culture in DE Transition's Pattern of Behavior and CLD

## List of Acronyms

AESS – IEEE Aerospace and Electronic Systems Society

CDR – Critical Design Review

COCOMO – Constructive Cost Model

COSYSMO – Constructive Systems Engineering Cost Model

CPI – Cost Performance Index (EVM term)

CSER – Conference on Systems Engineering Research

CT – Change Task

CV – Contract Value

DD – Defect Density

DE – Digital Engineering

DFR – Design for Reuse

DWR – Design with Reuse

DoD – Department of Defense

ECP – Engineering Change Proposal

ERS – Engineered Resilient Systems

EVM – Earned Value Measurement

HW – Hardware

ICE – Independent Cost Evaluation

IEEE – Institute of Electrical and Electronics Engineers

INCOSE – International Council on Systems Engineering

KPP – Key Performance Parameters

KPI – Key Performance Indices

KSLOC – 1000 (k) Source Lines of Code

LCV – Lifecycle Value

MBCM – Model-Based Capabilities Matrix

MBSE – Model-Based Systems Engineering

MOE – Measures of Effectiveness

MOSA – Modular Open Systems Approach

MOTW – Missed Opportunity to Win

MR – Management Reserve

NC – Non-Conformance

NDIA – National Defense Industrial Association

NFR – Net Factored Risk

NRE – Non-Recurring Engineering

OBS – Organizational Breakdown Structure

ORR – Operational Readiness Review

OT – Overtime

PDR – Preliminary Design Review

PM – Project Management

POC – Point of Contact

PRA – Probabilistic Risk Analysis

QN – Quality Note

RE – Recurring Engineering

RFP – Request for Proposal

RQ – Research Question

ROI – Return on Investment

SE – Systems Engineering

SEaaS – SE as a Service

SEE – Systems Engineering Efficiency

SEI – Software Engineering Institute (of Carnegie Mellon University)

SERC – Systems Engineering Research Center

SME – Subject Matter Expert

SoS – System of Systems

SOW – Statement of Work

SPI – Schedule Performance Index (EVM term)

SST – Single Source of Truth

SRR – System Requirements Review

SW – Software

TBD – To Be Determined or To Be Decided

TDSE – Traditional Document-based Systems Engineering

TR – Technical Reserve

UI – User Interface

VAC – Variance at Completion (EVM term)

WAUP – Won at Unfavorable Price

WBS – Work Breakdown Structure

WSRC – Western States Regional Conference (INCOSE)