Systems engineering in commercial and government organizations

by

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CHAPTER 1

GENERAL INTRODUCTION

Introduction

Systems engineers and engineering managers involved in research and development (R&D) efforts are familiar with the harsh realities of project complexities. They know that the products and services they are developing today are more complex than ever. Systems engineering (SE) has been used with varying degrees of success to combat this reality. Numerous definitions, standards, guides, methodologies, etc. have been developed over the years in an attempt to provide a common template for the use of recognized SE processes toward the mitigation of risks and successful completion of projects.

Systems engineers need greater guidance on how they might tailor, or adapt, their chosen approach to SE to better utilize limited resources. For commercial and government organizations, the relative dearth of tailoring guidance remains an unwavering and poignant issue. This research attempted to address this, with particular emphasis on commercial organizations, by developing and deploying a survey to SE practitioners and analyzing the resulting data.

Thesis Organization

This thesis is organized in a standard format. CHAPTER 1 served as a very brief general introduction to the research. CHAPTER 2 comprises the body of the research in article form including the Abstract, Introduction, Background, Methodology, Results and Discussion, and Conclusions. CHAPTER 3 provides some closing general perspective on the future of SE.

CHAPTER 2

SYSTEMS ENGINEERING IN COMMERCIAL AND GOVERNMENT ORGANIZATIONS

A paper to be submitted to the *Engineering Management Journal*

Jordan L. Hansen, Paul J. Componation, Dianne Cook, Michael Dorneich, and Guiping Hu

The graduate student, primary researcher and author of this work was Jordan L. Hansen. Paul J. Componation (principal investigator) along with Dianne Cook, Michael Dorneich, and Guiping Hu (research committee) provided reviews and development support.

Abstract

Systems engineering (SE) practitioners in research and development (R&D) projects have much general but little specific guidance to manage them. Previous research in SE has contributed to growing advice on tailoring SE efforts given particular project characteristics. This study bolsters this effort by comparing, contrasting, and exploring interactions between commercial and government project risks, success, and SE processes. Demographic company and project information provide insight into commercial and government populations of interest. Coupled with distributed team member interactions, a clearer context for discussing results and conclusions is achieved. Commercial and government projects prove to be principally similar, yet appreciably unique.

Introduction

Commercial and government organizations have similar intentions, yet a fundamental difference of their respective operating environments is of critical importance in appreciating how systems engineering (SE) is performed and judged as a success or failure in research and development (R&D). Both work to meet customer demands on time and within budget, but the robustness, or lackthereof, of the business case leads to an intuitive notion that commercial and government SE practitioners represent two different mindsets, or populations, in the completion of SE efforts.

Commercial endeavors presumably require a very strong fiscal case as well as much clearer identification and understanding of risks to ensure their mitigation or removal from the outset, and realization of a sustainable profit margin. As evidenced by increasing pressure and oversight of government programs, for example large-scale National Aeronautics and Space Administration (NASA) projects (United States Government Accountability Office, 2013), government efforts require a sound business case also. But, by the nature of their financial support structures (public tax dollars) and historical tendency to work on arguably riskier projects that in many cases simply could not realistically be approached in the commercial sector, this difference is further exemplified.

They share an increasing reliance on more holistic approaches to accomplish their technical and programmatic objectives. However, the different standards on SE are not meant to be exhaustive and it is not the case that following them to the letter guarantees successful projects. It quickly becomes evident that SE tailoring guidance required of commercial and government organizations might be different.

It is in this 'interface of practice' between identified best SE activities or processes and commercial and government organizations' utilization of them that this study finds its potential impact. The problem is that overuse of SE processes can waste time, money, and other resources while their underuse could result in added project risks. Either of these conditions could lead to project failure. SE practitioners need a more informed perspective on how to tailor their SE processes to match the scope of a given project to better maximize limited resources.

One organization that has been at the forefront of SE adoption and use is NASA. What is particularly of interest with respect to this research is NASA's coming to the understanding that large, complex projects simply were not handled well by traditional project management approaches, thus resulting in the push towards the formalization and standardization of SE. As a direct result of NASA's support and in light of today's more convoluted, larger project milieu, SE has become more and more prevalent as a method of discovery, program SE, and methodology or approach (Sheard, 2000).

To gain a greater understanding of their own SE approach and processes, Componation et al. (2009) led a study at NASA's Marshall Space Flight Center (MSFC). The details are shared in Exhibit 1, alongside the current research**.**

Exhibit 1. Motivational Componation et al. (2009) study characteristics vs. current research

Characteristic	**Componation et al. (2009)**	**Current Research**
Research Objective	Assess the relationships between project success and SE processes in NASA	Assess the relationship between project risks, success, and SE processes in commercial and government organizations
Sample Population	NASA senior managers (SE&I Skill Board) and space flight hardware projects' lead systems engineers, integrators, and/or managers	R&D/new product SE practitioners (commercial and government)
SE Methodology (as basis)	NASA NPR 7123.1A	NASA NPR 7123.1A / NASA SE Handbook (primary), and other standards
Data Collection Ease	High proximity, high fidelity, intimately involved	Convenience, snowball sampling
Data Collection Method	Phases I-IV Mixed-method	Email campaigns, relationships developed from first contact through deployment Mixed-method
Data Collection Tools	Consultations, documentation reviews, interviews	Survey (primarily online: SurveyGizmo, but some paper responses)

The differences noted are due to the 1) environment in which data was to be collected and 2) relationships between the researchers and the proprietors of the data. Projects in the 2009 reported study were chosen by NASA MSFC managers and consisted primarily of successful flight hardware projects. In the current research, there was no intent to control for success or failure of the product types. The research team in the previous work had direct access to data (SE&I Skill Board, project team members, documentation, etc.); this was not the case while trying to petition the help and support of professional societies and organizations via a survey. The survey (see the Methodology section for more) was conceptualized, developed, tested, and finally deployed for this study. The phased document reviews and interviews of the previous study were more direct.

The survey intended to garner demographic company and project descriptions, ratings for perceived overall success and performance on SE processes, and also information pertaining to how the project team interacted with emphasis on distributed, or remote, team members. The data was subject to the biases inherent to all humans in that it came from SE practitioners' recollection of a project. In other words, one data point was one completed project. In the NASA research this bias potential only arose in interview-affirmations of the data collected from actual documentation.

Despite the differences, there were items similar to both studies. A mixed-method approach was utilized in both. In the current research it was a point to appreciate and consider various standards in the development of the survey. This was particularly the case with the questions on SE processes. However, the primary sources for the survey remained NASA NPR 7123.1A (2007) and NASA's Systems Engineering Handbook (NASA PPMI, 1995).

While the motivation behind this study did find its roots in NASA, there is evidence of its potential impact in addressing some of the future research recommendations from previous SE research. Kludze (2003) and Bruff (2008) called for more private/civilian sector SE project data. A greater focus on organizational issues was also highlighted by Kludze. Bruff and Honour (2013) suggested the pursuit of a more diverse range of SE practitioners with different perspectives (e.g. industries, domains). To help guide SE efforts more effectively, Honour (2013) expressed the need to correlate best practices with program success while Elm & Goldenson (2012) spoke more generally to guidance for system developments in addition to acquisitions. Following Elm & Goldenson (2013) and others, this study aims to continue promoting SE and its application and motivating future study. These studies are not purported to be all-inclusive, but they do represent a substantial contribution of the more relevant material.

Honour and Valerdi (2006) provided an ontological framework that illustrates the plausibility of drawing parallels and interpretations across studies. Exhibit 2 shares an adapted and abbreviated form of the ontology which now incorporates elements of NASA's SE approach – the "SE Engine" (NASA, 2007, pg. 18). Capability Maturity Model Integration® (CMMI®) was included in this work as it appeared in their ontology as 1) an example of one of the five included SE standards and 2) it has been used in a number of recent studies on SE impact or effectiveness including Bruff (2008), Elm et al. (2008), and Elm & Goldenson (2012).

The results of Componation et al. (2009), in conjunction with the above studies, led NASA to again inquire into SE effectiveness. Their curiosity stemmed from an interest in understanding SE in commercial and government organizations, with emphasis on the former.

Exhibit 2. Adapted and abbreviated version of Honour & Valerdi's (2006) SE ontology

SE Categories	CMMI	NASA NPR 7123.1A
Mission/purpose definition	▪ Develop customer requirements (Req Devlp)	▪ Stakeholder Expectations Definition
Requirements engineering	▪ Req'ments development ▪ Requirements mgmt	▪ Technical Requirements Definition
System architecting	▪ Select product-component solutions (Tech sol'n) ▪ Develop the design (Tech sol'n)	▪ Logical Decomposition ▪ Design Solution Definition
System implementation	▪ Implement the product design (Tech sol'n) ▪ Product integration	▪ Implementation ▪ Integration ▪ Transition
Technical analysis	▪ Decision analysis and resolution	▪ Technical Assessment ▪ Decision Analysis
Technical management/ leadership	▪ Project planning ▪ Project monitoring & control ▪ Measurement and analysis ▪ Process and product quality assurance ▪ Configuration mgmt ▪ Integrated project mgmt ▪ Quantitative project mgmt ▪ Risk mgmt	▪ Technical Planning ▪ Requirements Management ▪ Interface Management ▪ Technical Risk Management ▪ Configuration Management
Scope management	▪ Supplier agreement mgmt	
Verification & validation	▪ Verification ▪ Validation	▪ Verification ▪ Validation

This research expands upon Componation et al. (2013) by discussing more comprehensive results of efforts to understand the relationships between SE processes and project success in commercial and government organizations. This was done in order to develop guidance and share recommendations for SE practitioners to utilize scarce resources and tailor SE efforts in the face of specific programmatic and technical risks.

The remainder of this article includes greater background on prior research, a detailed record of the research methodology, discussion of the results, and conclusions.

Background

This section will go into greater detail regarding previous studies constituting additional inspiration and justification for this research and some of their relevant findings. It also provides further insight into the challenges encountered in completing the work.

Motivational Studies

Numerous studies over the course of the last approximately 10 years, briefly introduced above, have advanced the understanding of SE's impact. These studies had considerable influence upon the strategy employed here-in and some of their major findings in terms of benefits, implications, and guidance are summarized in Exhibit 3. While a cursory overview of some of the findings is provided and each study should be consulted for a more in-depth breakdown of the constituent conclusions and implications, most pertinent to the subject research were the associations identified in their various forms across the studies. Despite the impractical nature of directly comparing results across studies that obtained data with vastly different survey instruments or other methodologies, the following relationships remain fruitful territory for comparing and contrasting results with the current research. Because of its central role, summary findings from Componation et al. (2009) are shared in greater detail directly in the Results and Discussion section.

Kludze (2003) found that SE reduces risk and enhances technical performance of INCOSE and NASA projects. Elm et al. (2008) and Bruff (2008) were intimately related research efforts supporting Department of Defense programs. Elm et al. (2008) was a combined effort between the National Defense Industrial Association (NDIA), Carnegie Mellon University (CMU), and others, while Bruff (2008) contributed via his dissertation. They identified numerous correlations between SE best practices and Earned Value Management System (EVMS) metrics.

Exhibit 3. Benefits, implications, and guidance of a collection of recent SE studies

Study	Benefits, Implications, Guidance
Kludze (2003)	• SE adds value to projects within and outside NASA • Early introduction of SE may yield better results or value • The SE training program at NASA seemed not to have the desired effect
Elm et al. (2008) Bruff (2008)	• ID's SE best practices shown to improve program performance and the bottom line • Although limited population (defense product oriented aerospace manufacturing firms), results should remain applicable and generalizable • SE is beneficial for social systems

Componation et al. (2009)	• Results do show correlations; however not all the processes identified had the same effects on success
	• Unique characteristics of individual projects do influence which SE processes should be focused on
	• Ramifications for engineering manager:
	  ○ Success of the project was found to be influenced by the use of SE processes, albeit varied and do not influence all type of project success the same
	  ○ Not all SE processes have the same influence on project success, so tailoring of the processes should be considered based on the individual characteristics of the project
	• Method for quantifying SE effectiveness

Elm et al. (2012)	• Clear and significant relationships exist between the application of SE best practices to projects and the performance of those projects. System developers can: • Plan capability improvement efforts for SE programs • Utilize it as an industry benchmark to compare SE performance • Utilize it as justification for and in defense of their SE estimates System acquirers can: • Plan contractor evaluations during request for proposal developments and source selection • Utilize the survey or similar methods to get data from suppliers as a means of identifying supplier deficiencies throughout the project
Honour (2013)	• Quantifiable relationship between SE effort levels and program success • There is an optimum amount of SE • Programs use less SE effort than is optimum • Optimal SE effort method • Some program characterization parameters are more important • SE has a significant, quantifiable ROI • It is possible to effectively quantify SE effort • No correlation found between SE and system technical quality • There is a commonly held ontology of SE sufficient to be meaningful • One can get data about SE and success through proprietary boundaries

In both, project planning was significantly correlated with schedule performance. Elm et al. (2008) found requirements management and systems architecture correlate with schedule performance. Among the many correlations from Bruff (2008), project planning, requirements management, systems architecture, trade studies, and validation improved cost (or budget) performance. An ‘overall’ (combination of three metrics on cost, schedule, and scope) performance metric was benefitted significantly by better project planning, requirements management, and configuration management. Neither study was able to illustrate significant correlations between verification and any of their metrics. Verification is generally perceived within the SE practitioner community as a critical component of SE.

Elm et al (2012) built upon the previous NDIA/CMU work and Bruff’s dissertation from 2008 and highlighted updated correlations between similarly defined SE best practices. Very strong positive relationships existed, among others, between project performance and project planning, requirements development and management, and verification. Configuration management, trade studies, product integration, and validation correlated strongly while risk management did so moderately.

Honour (2013) structured correlations in terms of commonly held SE activities with respect to cost and schedule compliance, overall success, and technical quality. Parallels with the current research can be drawn with all but technical quality. Likewise, parallels can be drawn with the defined SE activities except total systems engineering and scope management. His tests of these correlations found all SE activities correlated significantly with cost compliance and all but scope management correlated significantly with schedule compliance. Overall success significantly correlated with all but mission/purpose definition, verification, and validation.

The above studies examined more than associations and other descriptive or inferential research aims of interest, and the current research is no different. Kludze (2003) elaborated on cultural and political effects on complex endeavors, most notably the criticality of communication in very diverse and dynamic groups involved in SE work. For a more recent look at culture in the development of complex systems or systems of systems development, see Hodgson et al. (2012). Bruff (2008) argued SE's position as an agent of change with respect to prevalent social issues. Honour (2013) recommended future research in terms of how different cultures perform SE. Elm et al. (2012) and to a certain extent every other study called for global SE promotion and participation. All of these items imply a need for greater understanding of the SE team environment and other nontechnical factors, and the current research hopes to help buoy that effort with the study of SE distributed team member interactions.

Challenges

SE: The enigma

Complications arise from the very nature of the complex systems attempting to be built. SE attempts to handle the most challenging management and engineering problems and the human element as well (Valerdi & Davidz, 2009). Despite NASA proffering a more verbose description, one concise and straightforward definition of SE is: "an interdisciplinary approach and means to enable the realization of successful systems (INCOSE, 2014)." The contrasting approach by NASA and INCOSE to describe and/or define SE is but one example of the array of existing views. While SE practitioners may not agree on a definition or description verbatim, there are consistencies among them, including but not limited to: 1) satisfy customer and/or user needs, 2) interdisciplinary, 3) iterative, 4) integrated, 5) life cycle. With SE's broad international purview and ubiquitous message to tailor to the needs of the subject organization, it only makes sense to have such variability in definition and understanding. Within the Department of Defense it seems efforts to standardize around ISO 15288 have already occurred (Redshaw, 2010), but the consistency of this agenda throughout the SE community is unclear. The consistencies among the descriptions/definitions and the ontology shared above do engender confidence that the work may mean something to more practitioners, but to attempt to generalize overall with even this minor appreciation for problems associated with what SE is would seem futile.

SE: An art and science

At odds within the SE community is not simply in its definition, but perhaps more importantly the appreciation of SE as both a science and art. Dr. Robert Frosch (2008) methodically defended the ‘art’ of SE in remediating the “bad systems engineering” brought about in part from the ‘science’ of “procedures, systems, milestone charts, PERT diagrams, reliability systems, configuration management, maintainability groups and the other minor paper tools.” Further, “we have forgotten that someone must be in control and must exercise personal management, knowledge and understanding to create a system. As a result, we have developments that follow all the rules, but fail.” It is important to note that Dr. Frosch’s comments occurred during the heart of the Apollo missions, one of the most exciting and productive collection of systems development efforts in human history.

The push of science in SE has, in most respects for the last 50 years, centered on its standardization and qualification/quantification. However, any proficient systems engineer or candid observer would note the fundamental role art plays. NASA (2007) helps qualify this role: “The systems engineer must develop the skill and instinct for identifying and focusing efforts on assessments to optimize the overall design and not favor one system/subsystem at the expense of another. The art is in knowing when and where to probe” (pg. 3).

Much additional literature has been dedicated to this. Michael Griffin, in *System Engineering and the "Two Cultures" of Engineering* (2007), re-purposed the message of C.P. Snow (1959, 1963) being that of a "breakdown in communication between the humanities and the sciences" to mirror Frosch's (2008) emphasis in declaring that "system engineering is the link which has evolved between the art and science of engineering." Newbern & Nolte (1999) and Cook (2000) spoke to the necessity of the art as opposed to simply the science and its 'artistic' lessons learned in engineering complex systems. Ryschkewitsch et al (2009) interpreted SE as technical leadership (art) and systems management (science). Jansma (2012) also spoke to this need in terms of brain-hemisphere, leadership-management, process-based, and behavior-skills dichotomies. How does one begin to measure, let alone assess art?

How SE is defined and the palpable understanding of it as both science and art set the stage for discussing the methodology.

Methodology

A descriptive (Nebeker, n.d.) research design - more specifically a correlational (Price & Oswald, 2006), cross-sectional, mixed-method research design - was employed. This section develops the research design by introducing the objectives/hypotheses this work attempted to address, highlighting the challenges with researching SE, describing the survey and its contents, and concluding with discussion of the analysis and its methods.

Research Design

Research question, themes, objectives, and hypotheses

The motivational and primary research question was:

I. *What advice can be gleaned from the study of SE projects to help SE practitioners tailor their SE approach to maximize limited resources?*

In support of this primary research question was the exploration of objectives related to Level I and Level II themes (Exhibit 4). Level I objectives help describe the SE domain, providing more context surrounding the sample population. Level II objectives dig deeper into potential relationships, representing the majority of the analysis and providing inferential potential, or greater opportunities to advance the practice of SE as it is known today as opposed to simply qualifying it.

Exhibit 2. Research themes and objectives

THEME: Level I
A. Describe the organizations B. Describe the projects C. Describe the interactions of distributed team members
THEME: Level II
D. Determine if differences and similarities exist on average between commercial and government organizations' project risk, success, and SE processes E. Investigate associations within and between risk, project success, and SE processes F. Unravel the internal structure of the SE processes data… i. …with particular regard to sector a. Identify which of the 17 SE processes might best differentiate commercial and government classes ii. …with particular regard to the projects (all of the cases) a. Identify which of the 17 SE processes that are more responsible than others for the variability on all the projects b. Identify whether or not NASA's SE framework, or model (i.e. the NASA "SE Engine"), is an accurate reflection of reality presented by the projects

Research objectives A-C offer no a priori hypotheses. The hypothesis sets for research objectives D, E, and F are shared in Exhibit 5. Only objective D involves tests of significance. Of the vast number of hypotheses that could have been formulated, this list helped narrow the scope of the research.

Exhibit 3. Specific hypotheses related to the research objectives

Obj.	Hypothesis Set
D	1. Commercial respondents perceive their projects to have been more in line with what their organization typically completes (PD1) relative to the perceptions of government respondents. 2. Government respondents perceive their projects to have had greater technical (PD2) risk relative to the perceptions of commercial respondents. 3. Commercial respondents perceive their projects to have had greater budget (PD3) risk relative to the perceptions of government respondents. 4. Commercial respondents perceive their projects to have had greater schedule (PD4) risk relative to the perceptions of government respondents. 5. Perception of success will be equivalent between original and other similar projects metrics for both commercial and government projects. 6. Overall project success from the viewpoint of the organization (PSM8) as compared to stakeholders (PSM9) is equivalent for both government and commercial projects. 7. Commercial projects have a higher perceived rating on system design SE processes (SE1-4) relative to government projects. 8. There is no significant difference in the perceived agreeableness with respect to the system realization SE processes (SE5-9) between the two groups. 9. There is no significant difference in the perceived agreeableness with respect to the technical management SE processes (SE10-17) between the two groups.
E	1. Project risks will be negatively correlated with all project success metrics and SE processes. 2. PD1 will not correlate as strongly with PD2-4 as PD2-4 do with each other. 3. Project success metrics will all correlate positively with each other. 4. Project success metrics for technical success (PSM1, 2) and overall success from the viewpoints of both the organization and stakeholders (PSM8, 9) will be positively correlated with all SE processes. 5. Project success metrics for technical success (PSM1, 2) will be at least moderately (.3-.7) positively correlated with system realization processes. 6. SE technical management processes SE10-11 and 13 will be moderately positively correlated with the system design processes. 7. SE technical management processes SE12, 14-17 will be moderately positively correlated with the system realization processes.
Fi.	1. Technical management processes will be more responsible for the separation of commercial and government projects.
Fii.	1. There will be maximum variance within SE10-17, or the technical management processes, which will largely comprise the first principal component. 2. There will be a strong case for three principle components that translate roughly to an equivalent representation set forth by NASA's "SE Engine."

Researching SE: challenges

Relative to the long-evolving standards of how to go about performing SE, how to go about researching SE is a fledgling pursuit. Disciplines with similar intentions as SE that also emerged from other disciplines, e.g. industrial engineering and project management, have established research backgrounds and methods (Valerdi & Davidz, 2008). SE does not benefit from such a convenience and so must borrow from a wide variety of fields. Valerdi and Davidz appreciated the role of theory and philosophy with respect to science in general and SE, but chose to “rebalance the current theory bias in the systems engineering field” (pg. 171) by emphasizing the role of empirical methods moving forward in researching SE. They also discussed the critical role of professional organizations, which were paramount in aiding the data collection efforts in this research.

SE’s socio-technical pressures increasingly place greater importance on the social sciences’ perspectives on research as they might apply to SE. Ferris (2009) stated that “systems engineering is a branch of engineering which addresses a wide diversity of matters including technical, management and product appropriateness issues…that need to provide service in diverse application including both technical and human contexts” (pg. 5). Valerdi, Brown, and Muller (2010) echoed this by sharing: “Systems engineering as a discipline stretches from physical science at one extreme to social science at the other…as a consequence, systems engineering research faces an equally diverse range of possibilities regarding an appropriate research methodology” (pg. 554).

Valerdi and co. attempted to address the issue of “how to perform a study…by exploring specific questions related to research methodology choices in systems engineering” (pg. 552). They reference McGrath’s (1981) eight distinguishable research strategies from the social sciences, which include: (1) laboratory experiments (2) experimental simulations (3) field experiments (4) field studies (5) computer simulations (6) format theory (7) sample surveys and (8) judgment tasks. Also in reference to McGrath (1981), Diesing (1991) points out that "these eight strategies vary in their ability to achieve the three conflicting goals of behavioral research: precision, generality, and concreteness or faithfulness of a real situation" (pg. 89). Researchers can choose to maximize one of these goals to the hilt and sacrifice the other two, or compromise on two and hurt their efforts badly on one. By progressively recognizing the social, political, and cultural aspects of SE, behaviors and attitudes cannot be forgotten in terms of proposing a research methodology for this study.

The research methodology chosen must align with the problem of tailoring commercial and government SE efforts to match project characteristics. This necessitates the collection of data on a sample of projects on relevant factors, or variables, from an appropriate population. Muller (2013) proposed a research model to potentially alleviate some of the problems associated with researchers figuring out how they should approach studying topics like SE where "the expertise and the application happen in the field" (pg. 1092). Within this model, the sample survey was identified as a strong candidate to act as the vehicle for the research because of its ability to support analysis, comparison, and aggregation in light of the possibility of restricting inputs and affecting observation.

Researching SE is difficult not only due to the aforementioned challenges, but furthermore the SE community is no longer restricted to the largest of government projects nor to only a few traditional SE-laden industries for traditional requirements-driven projects. In all of this literature, it is clear that no singular and preferred approach to researching SE exists. As a result, the sample survey was chosen and became the heart of the research design.

Survey Instrument

Participants

The target population was SE practitioners involved in commercial and government product R&D efforts (see Results and Discussion for more). Each data point in the study was therefore an individual response to the survey, representing a completed project. Sampling was by convenience and permission was granted to 'snowball' the sample, or send on the survey to those the respondent felt might fit the target population that was defined for them. Both paper and online survey modes were used in this research; however, the bulk of the data was collected via the online web-based software as a service, SurveyGizmo (2013).

Structure and content

Information collected encompassed 50 questions and five sections shared in Exhibit 6. Both the survey and a table with more information on the variables can be found in the appendix.

Exhibit 6: Survey structure and description of each section's purpose

Section	Category	Purpose
1 (Q1-6)	Company Description	Basic demographics of the respondent's organization
2 (Q7-14)	Project Description	Descriptive information on a specific project the respondent worked on
3 (Q15-24)	Project Success Metrics	How successful the project was
4 (Q25-42)	SE Processes	What and how well SE processes were used
5 (Q43-50)	Distributed Team Member Interactions	Information on respondent and/or organization's interactions with distributed team members

The core of the survey consisted of 30 Likert items (Likert, 1932). A 4-point Likert response format (Strongly Disagree, Disagree, Agree, and Strongly Agree) was used in conjunction with a Not Applicable option. The neutral response was omitted in favor of the Not Applicable option to a) encourage directionality in the responses and b) better gauge what the diverse set of respondents felt was suitable for their projects and sectors/industries. Each section ended with an open-ended question where the respondent could share any additional thoughts, comments, or information regarding the items in that section. This left only 15 questions, the majority of which were closed-ended, multiple-choice questions; in some cases only one selection could be made while in others, multiple.

Company description questions identified the respondent's sector and industry, the formality of the organization's SE skills and responsibilities, and to what extent if at all SE effectiveness was tracked. Product description questions first identified how representative the project was in terms of projects their organization typically completes and then the project's technical, budget, and schedule risks. The remaining three project description inquiries spoke to the use of standards, whether or not they took a tailored approach via the standards, and the primary customer of the project. The respondent was then asked to score questions assessing the level of success of the project; these project success metrics questions were derived from the original study (Componation et al., 2009). The 17 SE questions, predominantly mirroring the framework of SE processes that NASA supports, were the core of the research. However, they were written in a general manner such that any SE practitioner stood a better chance at recognizing each statement's purpose and responding accordingly.

The final section on distributed team member interactions characterized a) the project team's composition with respect to number of groups at remote locations involved on a day-to-day basis, b) the average percentage of the total team that participated in meetings remotely, c) the formality of all team meetings, not just with remote members, d) what technologies were used in meetings with virtual participants, e) a free response of their position on three differences between face-to-face and virtual meetings, and finally f) two questions related to how often the respondent interacted with co-located and remote team members.

Analysis

This section provides an overview of the steps involved in preparing the data for analysis and shares the analysis methods utilized in trying to investigate it.

Data preparation

To prepare the 30 Likert items at the heart of the study for analysis purposes, the data from the 4-point Likert response format plus the Not Applicable option needed to be reduced to 4-point Likert data solely. There were also missing values (NA) that needed greater appreciation. A critical factor in treating missing data is whether or not it can be looked at as missing at random (MAR) or missing not at random (MNAR) (White et al., 2010). MAR data implies the probability that a value is missing depends only on the observed variables. MNAR suggests the reason for missing values depends on some unseen or unobserved information. MAR data significantly improves the outlook for analysis.

This necessitated investigating the 30 Likert variables' Not Applicable and NA data independence. In a step-wise manner, frequency tables were constructed for each variable pair and, if necessary, chi-squared independence testing was completed. This was first done for the Not Applicable and then for the NA data. No variable pairs were fit for chi-squared testing in terms of their Not Applicable data, so all Not Applicable data was transformed to NA's. Ultimately, this process resulted in the rejection of one pair's [verification (SE7) vs. validation (SE8)] null hypothesis that their missing values differed due to random variation, or that they were independent. This result is quite readily explained by SE theory because these two processes are extremely tightly coupled such that if someone's response was Not Applicable or missing on one, it would be completely reasonable to find a similar response on the other. From all the missing data in general (see Results and Discussion for more) and in spite of the above discussion on the one confirmed non-random (MNAR) relationship, the data was assumed MAR. These results set the stage to impute the data using multiple imputation by chained equations (van Buuren & Groothuis-Oudshoorn, 2011), a common imputation technique (Azur, Stuart, Frangakis, & Leaf, 2011) that provided the dataset used for all of the analyses.

Methods

Descriptive and inferential statistics were used for exploratory and confirmatory ends, but also to result in laying a foundation for more innovative future statistical work in researching SE Analyses used in this study include parametric techniques; measures of central tendency, Pearson correlation coefficient, equal variance student's t-test of means, linear discriminant analysis (LDA), and principal component analyses (PCA). It is believed that the utilization of LDA and PCA on this dataset in the manner in which it was represents a unique approach not yet attempted in researching SE. The other techniques have been used previously in SE research. The open-source, collaborative software project R v3.0.1 was used for all analyses (R Core Team, 2013).

The summary statistics of means, standard deviations, and correlations assessed the research objective hypothesis sets D and E. Because the Likert data is assumed to approximate scale data, these techniques are deemed fitting (Boone & Boone, 2012). More support for Pearson's r is provided by Havlicek & Peterson (1977) in that researchers can be confident in its application on data that is non-interval, normal or non-normal, and/or have skewed distributions.

The student's t-test method was chosen in lieu of the Mann-Whitney-Wilcoxon (MWW) test to consistently utilize parametric methods and so that a single statistic could be used for all tests. Based on evidence provided by de Winter & Dodou (2010), the regular unequal sample size yet assumed equal variances t-test was used in favor of the unequal variances t-test. The assumption of equal variances was observed to be acceptable by and large for the data. Also important for this test is the assumption of "a strongly homogenous interpretation of the statement[s] in the population (Clason & Dormody, 1994)."

LDA and PCA reduce the set of SE process variables to emphasize the more relevant contributors. The relevance of the contributors is determined by how well they best separate the two sectors (classes) via linear discriminant analysis, or how similar they are across the projects (sample cases) and combine to form linearly uncorrelated variables, or principal components (PC), via principal component analysis.

LDA is analogous to ANOVA with a categorical dependent variable in place of a numerical one in trying to define one dependent variable (sector) in terms of numerous continuous independent variables (SE processes). For hypothesis Fi., LDA emphasizes what SE processes most distinguish commercial and government entities. In other words, where do commercial and government organizations contrast the most in assessing their SE performance?

Lastly, hypothesis Fii. was fruitful territory for PCA, a variable reduction technique that accounts "for a maximal amount of variance of observed variables" (Suhr, 2005) via its computed principal components. SE project performance has been shown in many studies to involve similar processes. These processes or process families comprise different frameworks or models often depending on factors including sector and industry. While the survey instrument for this research utilized NASA's NPR 7123.1A as primary inspiration, the as-written 17 SE process

Likert items could have been derived from most any SE standard. Knowing that these 17 processes contribute to project success (see Results and Discussion) and they are in large part correlated (SE processes and their intra-correlations are not explicitly discussed in the next section), it is worth investigating by further examining those correlations to see if a simpler representation of the underlying structure exists.

Results and Discussion

The results are separated into three sections, one providing an overview of the data and study population, with the remaining two pertaining to the previously defined research themes, objectives, and hypotheses: (1) data overview and study population (2) Level I descriptions of the a) companies b) projects and c) distributed team member interactions (3) Level II summaries of e) comparing and contrasting 'on the average' f) associations: correlation and g) sector differences and project similarities.

Data Overview and Study Population

The responses to the survey proved to be largely complete. Overall, only ~3.41% of the possible responses associated with the 30 Likert items of interest was missing (NA). This was a promising finding given the research design and online survey contribution. While 29 out of the 30 variables had at least one NA, many of the variables had very few. The majority of the cases - 71 (~85.5%) of commercial and 40 (87.0%) of government - had two or fewer.

A total of 11 groups provided participants for the study and are shared in Exhibit 7 with their approximate size, or potential contribution to the survey.

Exhibit 7. Survey sample organizations

Group	Size
ASEM	450
INCOSE Heartland	60
INCOSE Huntsville	140
IEEE Iowa-Illinois	213
IEEE Huntsville	1100
NDIA Iowa-Illinois	846
SAE Mississippi Valley	741
Student Professionals*	24
Huntsville Training*	23
Center for eDesign	30
Subject Matter Experts	10
Total	3637

*Paper responses only

There were 207 entries into the SurveyGizmo software online. Of those, ultimately only 82 were deemed fit for analysis. Those removed from consideration were blank, insufficiently completed, or something was shared in the open-text response questions disqualifying them from further consideration (e.g. blatant reference to the project in question being ongoing). All 47 completed paper surveys from the student professionals and Huntsville trainees were included. A rough estimate of the effective response rate would therefore be: (82 + 47) / 3637 = 3.55%. This response rate is low relative to the few SE survey research response rates of Kludze (2003) and Elm & Goldenson (2012), but certainly not unexpected (Fan & Yan, 2010). Invariably, this increases the potential for non-response bias. However, this was an unavoidable consequence of this research design.

Level I Descriptions

Companies

This section addresses research objective A from Exhibit 4. Question 1 asked the respondent to identify their sector. Through a reconciliation process using answers to numerous questions, particularly the open-ended text responses if provided, all 129 participants and the completed projects they were recalling involved in this study were categorized as either commercial (83) or government (46). The results of Question 2, or what industry they feel best describes their organization, suggest they were primarily derived from the aerospace, agriculture, defense & security, and energy industries although every other industry category except for health & welfare had at least one representative. There were 19 cases identifying their industry as something other than was provided in the question list. SE skills and responsibilities were found to be largely distributed (Question 3) throughout the organization with 50 commercial and 24 government selections. A fair number, 10 and 9 respectively, of commercial and government organizations manage them by a single department with execution being done at the project level. However, ~23% of the respondents, or 18 commercial and 12 government respondents, claim their organization does not formally recognize SE, although they clearly perform traditional SE activities as their selections would indicate.

Finally, in terms of Question 4 and how their organization tracks SE effectiveness, of all 129 respondents, 51 (39.5%) identified their organization as not tracking SE effectiveness. Of the remaining responses, 31 (24.0%) say they track at the overall project level, 11 (8.5%) at the organizational level, 9 (7.0%) at the project task level, and 4 (3.0%) at the individual level. Because this question allowed a respondent to select multiple options, Exhibit 8 summarizes the other combinatorial possibilities that were present in the responses.

Exhibit 8. Summary of other SE Tracking categories (Question 4)

SE Tracking	Count	Percent
At the organization, overall project, task, and individual level	9	7.0%
At the organization and overall project level	7	5.5%
At the organization, overall project, and project task level	4	3.0%
At the overall project and project task level	2	1.5%
At the project task level and We do not track*	1	1.0%

* A misunderstanding or selection error occurred in this case

<u>Projects</u>

Question 11 inquired about the use of an SE standard or multiple standards. 36 respondents, 29 commercial and 7 government, said no standard was used. If one was used, it was likely developed internal to the subject organization with 50 commercial and 20 government responses in support of that selection. More popular choices included the Defense Acquisition Guidebook (not a standard in its own right) which saw 7 commercial and 8 government respondents select it and the CMMI, represented by 12 and 5, respectively. Only 2 commercial projects and 1 government project used ISO/IEC 15288. Multiple selections were also allowed with this question to accommodate those projects that might have used more than one and this did occur in 27 commercial and 8 government projects.

The highest percentages of respondents, 37% commercial and 61% government, indicate some tailoring of the standard or standards (Question 12). Commercially, no tailoring was quite similar with some tailoring at 36%, while the government projects fell to 19%. Extensive tailoring was more prevalent in commercial (18%) as opposed to government (11%) projects. Because in some projects no standard was followed, inherently no tailoring would have occurred. Commercially, 5% of the respondents claimed no tailoring occurred because no standard was followed, with 9% of government respondents choosing equivalently. Some (4%) commercial respondents did not make any selection. The clear distinguishing features are the relative differences between each category, with commercial organizations being more balanced between some and no tailoring.

Lastly in describing the projects in this study (Question 13), the majority of commercial projects involved primary customers of an industrial/commercial (40, 48%) or private (23, 28%) nature. As expected, the bulk of the government projects dealt with government projects, defense- (26, 57%) and not defense-related (12, 26%). Only 9 and 3 commercial projects were associated with defense- and not defense government customers, respectively.

Distributed team member interactions

Research objective C considered Questions 43-46, 48 and 49 near the end of the survey. Exhibit 9 shares summary information from Question 43, which includes the effects of removing one commercial and three government outliers. They were removed because they had numbers of groups of team members at remote locations that were two to three orders of magnitude larger than the other projects. Again discarding those same outliers, the overall average number of groups of team members at remote locations was 5.1 with a standard deviation of 5.3.

Exhibit 9. Summary of the number of groups of team members at remote locations involved in projects' day-to-day work (Question 43)

	Min	Q_1	Median	Mean	Q_3	Max	NA Count	SD
Commercial	0	2	3.50	29.81	5	2000	5	225.99
-outlier	0	2	3.00	4.22	5	25	5	3.61
Government	0	2	5.25	15.85	10	150	4	33.92
-outliers	0	2	5.00	6.81	8	30	4	7.27

Despite the similarity in the first quartile (Q_1) from Exhibit 9, they proved to have clear differences. For example, commercial projects do not involve as many remote groups. Also, commercial variation in the number of remote groups is smaller than government projects. One might conclude that commercial projects are more consistently internal efforts.

In looking at Exhibit 10 with respect to the average percentage of the total team that took part remotely (Question 44), an interesting result arises when considering the previous question: While there were fewer remote teams involved day-to-day in commercial projects on average, when there were they tended to be a bigger part of the overall team. An interpretation of this might be that when commercial organizations have to opt for external help or consultation, they do so in a committed manner in terms of the volume.

Exhibit 10. Summary of average percentage of total team taking part remotely (Question 44)

	Min	Q_1	Median	Mean	Q_3	Max	NA Count
Commercial	0	15	50	45.05	75	100	4
Government	0	10	25	26.40	35	95	3

Question 45 and the results in Exhibit 11 supplied some perspective on the formality of team meetings in terms of formal (e.g. design reviews) vs. informal (e.g. brainstorming) gatherings. In general, the percentages are largely consistent; however, there is a more distinct separation in favor of informal meetings in terms of government projects.

Exhibit 11. Summary of percentage of team meetings - formal vs. informal (Question 45)

	Min	1st. Qu.	Median	Mean	3rd Qu.	Max	NA %
Overall							
Formal	0	23.75	50	48.08	75.00	100	3.88
Informal	0	25.00	50	50.49	76.25	100	3.88
Commercial							
Formal	0	25.00	50	50.22	75.00	95	2.41
Informal	5	20.00	45	49.07	75.00	100	2.41
Government							
Formal	2	20.00	40	44.05	65.00	100	6.52
Informal	0	30.00	50	53.16	77.50	100	6.52

Questions 48 and 49 provided a glimpse into how often co-located and remote team members interact from more common, daily meetings to just once per year. Exhibit 12 clearly illustrates that co-located team members are on average meeting quite regularly, with more diversity in remote team member meeting frequency.

Exhibit 42. Summary of how often on average co-located and remote team members interact (Questions 48, 49)

	Daily	Several times a week	Weekly	Several times a month	Monthly	Several times a year	Yearly	NA %
Overall								
Co-located	67.44	21.71	5.43	-	-	-	-	5.42
Remote	17.05	33.33	23.26	9.30	7.75	2.33	0.78	6.20
Commercial								
Co-located	72.29	21.69	2.41	-	-	-	-	3.61
Remote	19.28	34.94	24.10	6.02	7.23	3.61	-	4.82
Government								
Co-located	58.70	21.74	10.87	-	-	-	-	8.69
Remote	13.04	30.43	21.74	15.22	8.70	-	2.17	8.70

Question 46 addressed the technological aspect of meeting when virtual participants are involved. As one might expect for both types of organizations, Exhibit 13 shows that technology use is dominated by telephone conferencing systems, shared desktop software, and electronic distribution of documents.

Exhibit 13. Summary of technology use in meetings with virtual participants (Question 46)

Technology	Commercial	Government
Telephone conferencing system	82	37
Shared desktop software	74	22
Low fidelity video conferencing	13	0
High fidelity video conferencing systems	17	13
Electronic distribution of documents	76	33
Shared drawing surfaces	13	7
Text-based communication software	48	12
Other	3	5

To a lesser extent, text-based communication software contributes in commercial organizations. Low/high fidelity video conferencing, shared drawing surfaces, and other technology while perhaps fewer in number, play a part all the same.

Level II Summaries

Comparing and contrasting 'on the average'

Research objective D focused the investigation on the averages of the 30 Likert items. For the remainder of the paper, equivalent notation (appendix) for survey questions 7-10 (PD1-4), 15-23 (PSM1-9), and 25-41 (SE1-17) help direct the discussion. Also, system design (SE1-4), realization (SE5-9), and technical management (SE10-17) terminology will be used. Exhibits 14 and 15 summarize all the averages and standard deviations associated with these items.

Exhibit 14. Averages of risk (PD1-4), success (PSM1-9), and SE process (SE1-17) variables

RISK	PD1	PD2	PD3	PD4
Overall	3.36	3.29	3.39	3.49
Commercial	3.36	3.43	3.55	3.59
Government	3.35	3.04	3.09	3.30

SUCCESS	PSM1	PSM2	PSM3	PSM4	PSM5	PSM6	PSM7	PSM8	PSM9
Overall	3.17	3.23	2.57	2.83	2.57	2.98	2.84	3.26	3.23
Commercial	3.08	3.16	2.48	2.77	2.42	2.94	2.86	3.27	3.22
Government	3.33	3.37	2.74	2.93	2.85	3.04	2.80	3.24	3.26

SE PROCESS	SE1	SE2	SE3	SE4	SE5	SE6	SE7	SE8	SE9
Overall	3.06	2.98	2.75	3.15	3.23	3.17	3.40	3.29	3.22
Commercial	3.06	3.04	2.70	3.06	3.22	3.22	3.46	3.40	3.25
Government	3.07	2.89	2.85	3.30	3.26	3.09	3.28	3.11	3.17

SE PROCESS	SE10	SE11	SE12	SE13	SE14	SE15	SE16	SE17
Overall	2.81	3.04	3.07	3.03	3.16	3.18	2.92	2.81
Commercial	2.80	3.01	3.02	3.11	3.16	3.17	2.89	2.78
Government	2.85	3.09	3.15	2.89	3.17	3.20	2.98	2.85

On average, there was an almost identical belief among commercial and government respondents that their respective project was representative of projects their organization typically completes (PD1). This provides confidence in the processes and procedures used to complete them in that they are also likely representative. This belief varied more for commercial respondents. Both groups are somewhere on the continuum between agree and strongly agree in

Exhibit 55. Standard deviations of risk (PD1-4), success (PSM1-9), and SE process (SE1-17) variables

RISK	PD1	PD2	PD3	PD4
Overall	.671	.722	.743	.663
Commercial	.708	.666	.610	.645
Government	.604	.759	.865	.662

SUCCESS	PSM1	PSM2	PSM3	PSM4	PSM5	PSM6	PSM7	PSM8	PSM9
Overall	.651	.667	.864	.719	.958	.775	.758	.732	.656
Commercial	.684	.707	.861	.704	.964	.802	.783	.782	.716
Government	.560	.572	.855	.742	.894	.729	.719	.639	.535

SE PROCESS	SE1	SE2	SE3	SE4	SE5	SE6	SE7	SE8	SE9
Overall	.715	.770	.829	.626	.690	.741	.754	.712	.721
Commercial	.705	.706	.852	.612	.682	.716	.754	.697	.778
Government	.742	.875	.788	.628	.713	.784	.750	.706	.608

SE PROCESS	SE10	SE11	SE12	SE13	SE14	SE15	SE16	SE17
Overall	.778	.733	.687	.749	.682	.678	.714	.781
Commercial	.728	.741	.680	.733	.653	.678	.716	.716
Government	.868	.725	.698	.767	.739	.687	.715	.894

assessing technical, budget, and schedule project risks (PD2-4); commercial projects trend much higher for all three and they vary less than government projects.

For all but two project success metrics, government respondents believe their projects are more successful. Both groups do agree their projects were successful, but schedule and budget success both in relation to the original project outlook (PSM3, 5) and other previous similar projects (PSM4, 6) are not as high as technical success (PSM1,2). Original budget (PSM3) and schedule (PSM5) success were less consistent. Neither group felt extremely confident in how much they agreed that their overall management approach was effective (PSM7), but both were quite similar in how they felt their organization (PSM8) and stakeholders (PSM9) positively viewed the project result.

Most SE processes were assessed favorably (> 3.0), but some were below that threshold indicating poorer performance including logical decomposition (SE3), technical planning

(SE10), technical assessment (SE16), and decision analysis (SE17). These same processes also exhibited some of the largest variance. System realization processes (SE5-9) were consistently thought to achieve their intended goals, to a greater degree for commercial respondents. Commercial and government technical management processes (SE10-17) proved to be fairly similar on average, but government projects exhibited less consistent application. This effect could be due to a smaller sample of government projects.

While these summaries can provide a brief overview of the risks, success metrics, and SE processes, there was an interest in investigating some select, formal hypotheses regarding the means. Exhibit 16 shares the statistically significant ($\alpha = .05$) results of the tests of differences in means from Exhibit 5's hypothesis set D.

Exhibit 16. Significant t-tests of differences in means from hypothesis set D

Hypothesis	Variable	Null/Alternative Hypotheses	p-value
D3: Greater commercial budget risk	PD3	H_0: $\mu_C - \mu_{G.P} = 0$ H_a: $\mu_C - \mu_{G.P} > 0$	0.0002468
D4: Greater commercial schedule risk	PD4	H_0: $\mu_C - \mu_{G.P} = 0$ H_a: $\mu_C - \mu_{G.P} > 0$	0.0091490
D5: Equal original vs. other similar schedule and budget project success metric assessments for commercial projects	PSM3 PSM4	H_0: $\mu_{CPSM3} - \mu_{CPSM4} = 0$ H_a: $\mu_{CPSM3} - \mu_{CPSM4} \neq 0$	0.0189900
	PSM5 PSM6	H_0: $\mu_{CPSM5} - \mu_{CPSM6} = 0$ H_a: $\mu_{CPSM5} - \mu_{CPSM6} \neq 0$	0.0002326
D7: Greater commercial assessment of system design processes (design solution definition)	SE4	H_0: $\mu_C - \mu_{G.P} = 0$ H_a: $\mu_C - \mu_{G.P} \neq 0$	0.0334200
D8: Equal commercial and government assessment of system realization process (validation)	SE8	H_0: $\mu_C - \mu_{G.P} = 0$ H_a: $\mu_C - \mu_{G.P} \neq 0$	0.0266100

It is clear that commercial organizations perceive their projects to have greater budget and schedule risks. While the explanation for this is unknown, it could be speculated that government organizations have been utilizing SE processes and principles longer so the complexities involved with budget and schedule risks do not seem as intimidating. Given a risky venture, it would not be surprising to see budget and schedule risks rated higher from the commercial perspective due to the greater impetus on an attractive business case. Government organizations have more leeway in this regard.

Hypotheses D5 and D6 were different in that they tested within-group means. D5 postulated that perception of success will be equivalent between original and other similar projects metrics (PSM 1vs2, 3vs4, 5vs6) for both commercial and government projects. The logic behind this was that in SE efforts the original technical requirements, schedule, and budget for a given project would largely be based on the experiences gained from other similar projects and as such, they would be equal. Similar thinking applied to D6, or that the overall project success from the viewpoint of the organization (PSM8) as compared to stakeholders (PSM9) would be equivalent for both commercial and government projects. In this case it was thought that success from the perspective of the organization would be largely tied to how the stakeholders perceived the project.

In the case of D5 where two significant results were found with respect to the commercial projects, this might suggest that when it comes to schedule (PSM3,4) and budget (PSM5, 6) metrics, the above thinking would not apply. In other words, budget success with respect to the original project's budget does not appear to coincide with budget success relative to other similar project budgets. Intuitively, it would make sense that more often more hard and fast, technical components would be more reliable from project to other similar project than programmatic details.

Of the remaining tests, only design solution definition (SE4) and validation (SE8) resulted in statistically significant findings that commercial and government organizations were not equivalent in terms of their perceived performance on those two aspects of the project. Ultimately, all of these test results could simply be attributed to testing and/or sampling error.

Associations: correlation

When relating SE processes vs. project success, SE processes vs. risks, and project success metrics vs. risks, there was interest in investigating SE processes vs. project success to provide some mode of comparison with Componation et al (2009). Providing depth/breadth to the appreciation of these complex development projects are risks vs. SE processes and project success metrics. While different values and ranges of Pearson's r have been used to judge the relative strength of relationships, the 2009 NASA study cutoff of $r \geq .4$ was mirrored. With this criterion in mind, first the overall dataset's correlations are examined, and then the segmented commercial and government relationships are compared and contrasted.

SE processes vs. project success

Exhibit 17 shares the 25 correlations that met that cutoff from this study with those (shaded) from an adapted version of a similar figure in Componation et al (2009). Technical planning and technical risk management appear to be more critical for successful projects. Technical planning, interestingly enough, correlates with schedule and budget success more than technical success. It is within these technical planning correlations where the first commonality between this and the NASA study is noted. For this study, the singular overall project success metric of the NASA study was broken down into the respondent's perspective of how the organization and stakeholders saw the success of the project. With this in mind, technical risk management provides the second commonality in its correlation with overall project success from the organization's viewpoint.

Technical success is correlated with logical decomposition, integration, verification, transition (both metrics), and decision analysis. It is in this context two more similar findings between the two studies arise in integration and verification. What may be regarded as perhaps

Exhibit 6. Comparison of overall dataset correlations (r ≥ .4) with Componation et al. (2009)

Original NASA Study and New Study Overall dataset Correlation ≥ 0.4 Project Success and Systems Engineering Processes	1. Stakeholders Expectations Definition	2. Technical Requirements Definition	3. Logical Decomposition	4. Design Solution Definition	5. Product Implementation	6. Product Integration	7. Product Verification	8. Product Validation	9. Product Transition	10. Technical Planning	11. Requirements Management	12. Interface Management	13. Technical Risk Management	14. Configuration Management	15. Technical Data Management	16. Technical Assessment	17. Decision Analysis
Technical success relative to original requirements			.44						.43								.42
Technical success relative to similar projects						.55	.50		.49								
Schedule success relative to original project plan			.41							.51							
Schedule success relative to similar projects										.43							
Budget success relative to original project plan										.50		.46	.41			.41	
Budget success relative to similar projects										.46			.41				
Effective project management process	.41	.48		.41						.54			.41			.45	.45
Overall project success (organization view)						.55			.47								
Overall project success (stakeholder view)													.45				

the most surprising initial indication these correlations provide is the relative lack of association of system design (SE1-4) and realization (SE5-SE9) processes with project success. It is generally accepted that the processes involved in design and realization are critical components of successful SE efforts. This result does not mean they are not critical, but for these variables in terms of this measure of linear association, this data does not appear to bear that convention out.

For system realization processes, beyond integration's and verification's correlation with technical success relative to other similar projects shared above, there are only four other correlations of note. The correlation relationship between integration and overall project success from the perspective of the organization was also found in the NASA study. Surprisingly, not one project success metric stands out positively with respect to validation. In fact, the correlations with respect to validation are lower in general across the PSM-suite of metrics than the other SE processes. The weaker associations bring to the forefront a good point of emphasis and a temporary shift in direction in that the correlations that are near zero should not be so easily dismissed. This is due to the fact that near zero or negatively correlated items provide potential interpretive value as well. Only three correlations are near zero or negative and they all involve validation, which is not surprising in theory. In validating products or systems, issues are identified and returned for fixes or further development. This should have a negative or weak positive effect on project schedules or budgets. Validation's higher correlation with technical success metrics (PSM1, 2), effective project management process (PSM7), and overall project success (PSM8, 9) would seem to support the contrasting point-of-view, or the value validation has with getting the right system.

While similar thinking may be tempting with respect to validation's counter-part, verification, this data might suggest that verification is more important in the positive direction than validation. In trying to get the system right, ongoing verifications end up helping the schedule and budget more because they prevent more errors from reaching validation where errors of a pre-defined nature meet those that are more likely to have not been defined. In other words, there are errors with respect to getting the system right (errors arising from the defined) that appear to be more positively associated with successful projects. On the other hand, errors involved with accomplishing the right system (i.e. validation's end-game involving errors of often times the undefined) generally seem to hurt the projects, or perhaps not have a linear but instead a different relationship.

Finally, overall effectiveness of the project management (PSM7) involved on the project was correlated with the most SE processes (7), supporting the commonsense presumption that projects likely trend towards greater results when SE processes and the overarching project management approach are successful in tandem.

Assessment of correlation hypotheses

Exhibit 18 reports on the specific a priori hypotheses of interest from the previously defined hypothesis set E. These hypotheses provided a quick and easy way to informally evaluate mostly expected and intuitive results. In some hypotheses, for example E6 and E7, these were largely 'best guesses' as opposed to more advanced literature-based reasoning.

For all of the hypotheses that were expected and readily intuitive (E1-E5), it is clear that e1) project risk measures do indicate negative impact with these project success measures, e2) there is a noticeable difference between the intra-correlations of PD1 with PD2-4 as opposed to PD2-4, e3) in general if one project success measure is high every other success measure should be as well, e4) all SE processes sans validation (SE8) vs. success relative to the original schedule (PSM3) positively impact success, and finally e5) technical success with respect to the original project (PSM1) or others that were similar (PSM2) is positively impacted by the realization processes, sans validation. The near zero and negative correlations between validation and success have already been discussed, but it bears repeating that this was unexpected.

Exhibit 18. Results of the informal hypothesized correlations of hypothesis set E

Hypothesis	Finding
E1: Risks will be negatively correlated w/project success metrics and SE processes	Confirmed/Denied. 33 out of 36 risk-project success metric pairs and 57 out of 68 risk-systems engineering process pairs were negatively correlated
E2: How representative a project was with what that respondent's organization typically faces will not correlate as well with technical, budget, and schedule risks as they do with each other	Confirmed. Correlations of PD1 with PD2-4 (-.088/.013/-.045) were much smaller than PD2/3 (528), PD2/4 (.431), and PD3/4 (.485)
E3: Project success metrics will correlate positively w/each other	Confirmed. All within-PSM correlations were .322 or higher.
E4: Technical (PSM1,2) and overall (PSM8,9) success will be positively correlated with all SE processes (SE1-17)	Confirmed. All (17x4) 68 pairs of PSM1-2, 8-9 with SE1-17 were positive. Also, all but one PSM1-9 with SE1-17, or (17x9) 153, variable pairs were positive
E5: Technical success will be at least moderately (.3-.7) correlated with system realization processes (SE5-9)	Confirmed/Denied. Validation (SE8) fails for both PSM1 (.295) and PSM2 (.101)
E6: SE technical management processes technical planning (SE10), requirements mgmt. (SE11), and technical risk mgmt. (SE13) will moderately correlate with system design processes (SE1-4)	Confirmed/Denied. SE1/SE11 falls short (.263); SE1-3/SE13 fall short (.288/.231/.151)
E7: SE technical management processes interface mgmt. (SE12), configuration mgmt. (SE14), technical data mgmt. (SE15), technical assessment (SE16), and decision analysis (SE17) will moderately correlate with system realization processes	Confirmed/Denied. SE5/SE12, SE5,6,9/SE14, SE5/SE15, SE5/SE16, SE5,7,9/SE17 confirmed. Remaining 16 pairs denied.

Hypothesis E6 was derived from the idea that technical planning, requirements management, and technical risk management would be more positively correlated with system design due to their technical aspects coupled with SE's emphasis on eliminating risks earlier. Similar thinking applied in developing E7 in that the remaining technical management processes would be more positively associated with realization processes later in the project life cycle. These two hypotheses were, of course, weakly intuited appreciating the intertwined, integrated, repeated nature of SE processes occurring throughout the development process.

Exhibit 19 shares the overall (o) correlation relationships of Exhibit 17, but also considers commercial (c) and government (g) subsets of the data. While numerous consistencies exist when looking at the overall vs. commercial and government datasets (e.g. technical requirements definition vs. technical success relative to original technical requirements), only three relationships are similar across both studies. These similar relationships involve product integration vs. the organization's view of overall project success, verification vs. technical success relative to other similar projects, and technical planning vs. schedule success relative to other similar projects. Across both study populations, this might elicit confidence in terms of integration's positive impact on overall project success, verification's impact on technical

Exhibit 79. Overall, commercial, and government dataset correlations (r ≥ .4) compared with Componation et al. (2009)

Original NASA Study and New Study All datasets Correlation ≥ 0.4 Project Success and Systems Engineering Processes	1. Stakeholders Expectations Definition	2. Technical Requirements Definition	3. Logical Decomposition	4. Design Solution Definition	5. Product Implementation	6. Product Integration	7. Product Verification	8. Product Validation	9. Product Transition	10. Technical Planning	11. Requirements Management	12. Interface Management	13. Technical Risk Management	14. Configuration Management	15. Technical Data Management	16. Technical Assessment	17. Decision Analysis
Technical success relative to original requirements	g		og				g		oc g	c	g	g	g			g	oc g
Technical success relative to similar projects	g		g	g	g	oc	oc g		oc	g	g					g	g
Schedule success relative to original project plan	g	g	oc							oc g		c				g	
Schedule success relative to similar projects	g	g			g					oc g		c	g			g	g
Budget success relative to original project plan	g						g			oc g		oc	oc			og	g
Budget success relative to similar projects	g	g					g			oc g			oc			g	
Effective project management process	og	oc g		oc	g		g			oc g			og			og	o g
Overall project success (organization view)	g					oc g	c	g	oc g								
Overall project success (stakeholder view)	g				g	c				g			○c			g	g

success, and technical planning's impact on schedule success. One more palpable observation is the sheer amount of government correlations of note relative to commercial. Hazarding an interpretation of this, it might be simply due to government respondents' familiarity, expectations, etc. with respect to SE efforts because of SE's greater presence and promotion in the government ranks for longer periods of time.

SE processes vs. risk and project success vs. risk

The primary interest in investigating the correlations between project risks and both SE processes and project success metrics was to investigate whether project risks would be negatively associated with both (E1). The overall dataset did bear this out as seen in Exhibit 20 which summarizes these correlations.

Exhibit 20. Correlations between project risks (PD1-4) and SE processes (SE1-17) and project success metrics (PSM1-9) on the overall dataset

	PD1	PD2	PD3	PD4
SE1	-.328	-.066	-.193	-.048
SE2	-.132	-.048	-.003	-.016
SE3	-.062	-.007	-.008	.037
SE4	-.134	-.010	-.073	-.118
SE5	-.224	-.060	-.055	-.079
SE6	.013	.008	-.107	-.075
SE7	-.013	-.129	-.108	-.186
SE8	-.024	.149	.004	-.009
SE9	-.124	-.023	-.076	-.052
SE10	-.143	-.041	-.158	-.080
SE11	-.210	-.007	.058	.041
SE12	-.183	-.010	-.099	-.007
SE13	-.320	-.046	-.232	-.141
SE14	-.145	.045	-.064	.065
SE15	-.117	.067	.048	-.074
SE16	-.189	-.137	-.179	-.051
SE17	-.207	-.092	-.152	-.012

	PD1	PD2	PD3	PD4
PSM1	-.021	-.041	-.154	-.068
PSM2	-.093	-.078	-.136	-.047
PSM3	-.183	-.110	-.215	-.166
PSM4	-.030	.022	-.197	-.070
PSM5	-.178	-.246	-.403	-.235
PSM6	-.076	-.113	-.228	-.175
PSM7	-.161	.060	-.081	-.058
PSM8	-.004	.004	-.213	-.115
PSM9	-.147	-.047	-.219	-.138

The only major deviation from this was between technical risk (PD2) and validation (SE8) with r = .149. It is not surprising to see this result theoretically as technically riskier projects will often be characterized by more technical errors of the undefined which could lead respondents to rate validation efforts more extremely depending on how technical risk evolved in their projects. In the case of the projects for this study, this relationship was positive in direction.

It was apparent that when a project is not something an organization typically completes (PD1), stakeholder expectations definition (SE1) and technical risk management (SE13) were more negatively impacted. Also, not only is original budget success (PSM5) most negatively related to budget risk (PD3), it appears as though in general budgeting success as a pair (PSM5-6) is most negatively impacted by all four risks (PD1-4).

As with the overall dataset, it also holds when looking at data from either commercial or government classes of projects independently that the correlations with respect to budgeting success (PSM5,6) are more negative across the risks. A similar, but not entirely, consistently negative relationship across the commercial and government datasets for all the risks occurs for scheduling success relative to the original schedule (PSM3). The associations between how representative a project was (PD1) and all project success metrics with the exception of schedule success relative to the original schedule (PSM3) for government projects were more negative by quite a large margin than for the overall data. Government SE process assessments (SE1-17) were also more negatively impacted by a project not being representative of what an organization typically does (PD1). With this being the case for success metrics and SE processes, it provides some evidence that there is less flexibility within government SE efforts. Commercial projects perform better than government projects during system design with increasing technical, budgetary, and schedule risks, but they trend lower with respect to most system realization processes. With increasing technical and programmatic risks, commercial projects fair decidedly better in terms of technical planning, configuration management, technical assessment, and decision analysis.

Sector (class) differences and project (sample) similarities

LDA and PCA attempt to provide a clearer picture of the data that an individual cannot manually decipher. These two techniques were used to identify such relationships with respect to the SE processes. LDA focuses on identifying the factors or variables that best indicate where classes are different. This has potential value for a few reasons, but predominantly because at a glance it can share how SE process performance is being perceived differently between commercial and government sectors. PCA focuses on identifying new variables, or principal components, that best indicate where the cases are similar. The value with this relates back to how projects are approached in terms of the frameworks or models that the various standards and methodologies promote. Are the SE processes organized in a way that accurately reflects reality?

Class separation

Exhibit 21 shares the resulting LDA loadings, or coefficients. LDA coefficients comprise a single discriminant function that differentiates commercial from government sectors. This discriminant function is often used in classification, and to that end it would be commonplace to entertain all the variables. But, the goal herein is to identify those most responsible for the difference in sector. Choosing which variables to focus on can become a purely subjective exercise if the coefficients are trivially separated in magnitude.

Since the value for design solution definition (SE4) is very high relative to the other coefficients, unless the sectors were separated on that variable alone, caution must be exhibited in terms of what other variables are included. In addition to SE4, the linear discriminant function

(LD1) - for the purpose of identifying the most important variables separating commercial and government SE efforts - becomes a linear combination of the other largest loadings including validation (SE8), interface management (SE12), and technical risk management (SE13).

Exhibit 8. LDA list of component coefficients

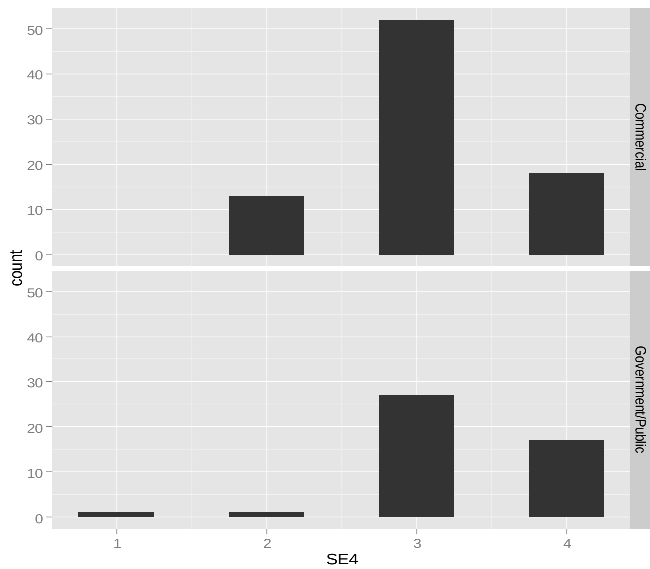
Var.	LD1
SE1	-0.081
SE2	-0.305
SE3	-0.175
SE4	1.869
SE5	-0.672
SE6	-0.266
SE7	-0.313
SE8	-0.825
SE9	0.586
SE10	0.343
SE11	-0.486
SE12	0.733
SE13	-0.892
SE14	-0.196
SE15	-0.292
SE16	0.184
SE17	0.548

$$LD1 = 1.8690*SE4 - .8251*SE8 + .733*SE12 - .8917*SE13$$

Implementation (SE5), transition (SE9), and decision analysis (SE17) could be included in this discussion as well, but again this is largely a subjective practice. Because the intent was simply to identify as opposed to use the function to classify, the criticality of the function LD1 above is arguably trivial. It does, however, help illustrate a use-case of LDA. The function, with its coefficients and their signs, indicate contrasts - the direction either toward or away from classifying a project into a given sector. LD1 might be thought of as the contrast between the defined design solution and interface management with the validation and technical risk management effort that is involved for each class of project.

Briefly, then, how are these coefficients larger for some variables than others? Each respective variable's distributions, partitioned by class, were investigated in a step-wise fashion. Explanatory differences were evident in the counts' ratios. Exhibit 22 illustrates this with SE4's marginal distribution; it is clear commercial's (top) higher ratios of 3:4 and 3:2 (1 to 4 from left to right) play a key role in this variable's distinguishing influence in LD1.

Exhibit 22. Distribution of SE4 by class



Assessment of linear discriminant hypothesis

It was hypothesized (Exhibit 5's Fi.) that the technical management processes (SE10-17) would be more responsible for the separation of commercial and government projects. This did not prove to be the case for the four highlighted SE process variables, and even if you were to include some of the other suggested variables it would not balance in their favor. However, if you ranked the absolute values of the 17 coefficients, the average rank of the technical management processes (8.875) would be lower than the rest (9.111), indicating more impact on average in terms of their contribution to quantifying a difference between the two classes. Also, the standard deviation of their ranks ($\sigma_{SE10-17}$ =4.61) show less deviation than the rest (σ_{SE1-9} =5.69), indicating more consistent impact.

Sample similarities

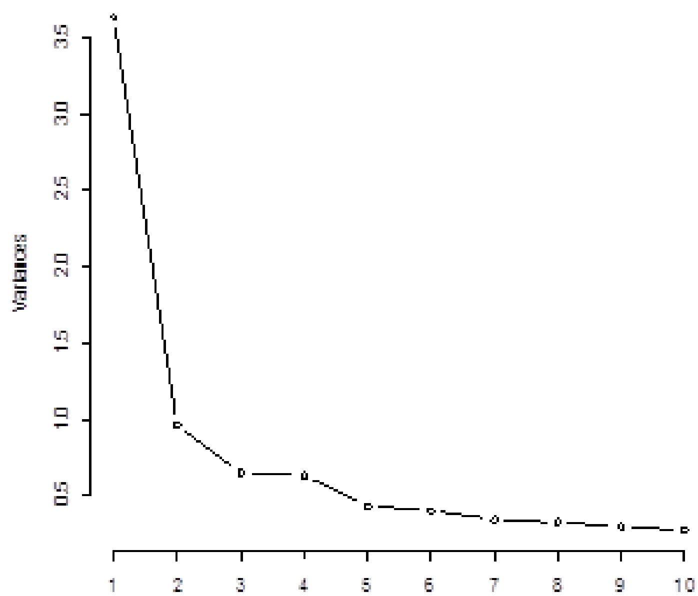
Principal component analysis was the second dimension-reduction technique used in this research. PCA results in principal components (PC) that are linear combinations of all or some of the original variables. It does this by analyzing the variance between the sample data; for this analysis, the overall dataset is used in favor of partitioning by commercial and government sectors. Exhibit 23 shares the resulting principal components and their standard deviations and variances. It is evident that the first PC accounts for a large amount of the explained variance, which is by PCA design.

Exhibit 93. Principal component summary statistics

PC	Standard Deviation	Proportion of Variance	Cumulative Proportion
PC1	1.9060	.4020	.4020
PC2	.9790	.1060	.5090
PC3	.8049	.0718	.5804
PC4	.7955	.0701	.6505
PC5	.6550	.0475	.6980
PC6	.6317	.0442	.7422
PC7	.5846	.0379	.7801
PC8	.5693	.0359	.8160
PC9	.5447	.0329	.8488
PC10	.5210	.0300	.8790
PC11	.5078	.0286	.9074
PC12	.4482	.0222	.9297
PC13	.4338	.0208	.9505
PC14	.3855	.0165	.9670
PC15	.3547	.0139	.9809
PC16	.3131	.0101	.9918
PC17	.2725	.0082	1.0000

The scree-plot of Exhibit 24 is helpful in understanding the results. By virtue of the changes in slope from one component to the next, it is straightforward to see that at three or five PCs there is much less value-add in terms of cumulative proportion of variance explained in the data with more additional components. This implies that the new variables or PC's, consisting of the original variables with a few of the original variables being more important than others in a given PC (more on this below), would suggest that a fair amount of reduction could occur.

Exhibit 104. Scree-plot of the first 10 principal components



If the SE processes were looked at from the perspective of these PC's, after investigating both the individual/cumulative proportions of variance and scree-plot, one could argue in support of the reduction of 17 individual constructs into three or five constructs (PC's). Kaiser's criterion (Kaiser, 1960) cannot be used because the variables were not standardized. Standardizing is common practice when the input variables have very different variance. For this data, the input variables, or the SE processes, were not standardized because their variance was deemed to be similar. If the decision of three PC's was made, 58.04% of the variance would be explained, jumping to 69.80% if extended to five components. A third possible way to determine the number of principal components to retain involves a predetermined minimum amount of the explained variance; no relevant guidelines could be identified. All of the first 5 PC's and their loadings are considered in Exhibit 25. It is critical to note that the signs of the loadings are arbitrary. If PCA was completed in different software of even different builds of R, they could be different. However, if they were different they would be so in kind (i.e. it would be as if the columns were multiplied by -1). Contrasting variables in one analysis would remain contrasting in another.

Exhibit 115. First five principal components and their loadings

	PC1	PC2	PC3	PC4	PC5
SE1	0.2353	-0.0506	0.3653	-0.2109	0.4050
SE2	0.2403	-0.1184	0.1913	-0.5167	-0.0819
SE3	0.2997	-0.3033	-0.2033	-0.3104	-0.4152
SE4	0.2264	-0.1516	-0.1457	0.0308	0.2860
SE5	0.2618	-0.0659	-0.1445	-0.0845	0.4694
SE6	0.1998	0.3735	-0.2733	-0.0400	0.2353
SE7	0.2147	0.5386	-0.1788	0.1074	-0.0928
SE8	0.1616	0.2945	0.0455	-0.3174	-0.0584
SE9	0.2037	0.4338	-0.1069	-0.2320	-0.1545
SE10	0.3094	-0.1246	0.2148	0.0863	-0.1910
SE11	0.2635	-0.2105	-0.2777	0.1804	-0.2751
SE12	0.2147	-0.1653	-0.4057	0.1514	-0.0540
SE13	0.2292	0.1742	0.2558	0.4558	-0.0953
SE14	0.2485	-0.1264	-0.0287	-0.0226	0.0891
SE15	0.2027	-0.1403	-0.2006	0.2496	0.2970
SE16	0.2517	-0.0511	0.3362	0.1105	0.0696
SE17	0.3060	0.0618	0.3449	0.2658	-0.1958

With respect to the first PC, all the loadings for the SE variables are of the same sign. While no variable loading stands out markedly from the others, logical decomposition (SE3), implementation (SE5), technical planning (SE10), requirements management (SE11), technical assessment (SE16), and decision analysis (SE17) are the largest - all being greater than an arbitrary .25. Of these six variables' loadings, logical decomposition, technical planning, and decision analysis are the greatest and might distinguish themselves enough from the rest to merit particular attention. When looking at all of the loadings, however, a conservative interpretation of this PC might suggest that each SE process contributes in a similar direction to the project, none separating themselves tremendously in terms of magnitude.

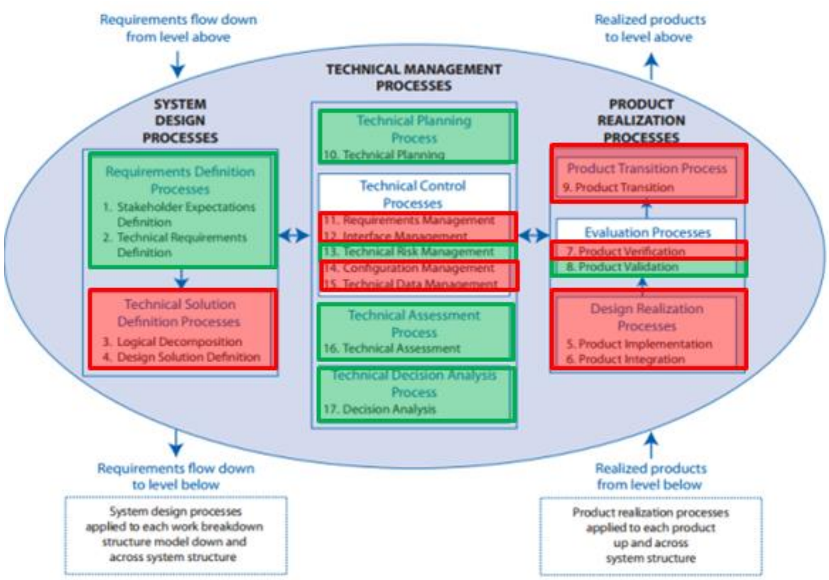
The second PC possibly illustrates some stronger and more diverse relationships. Strictly in terms of the largest coefficients, it appears to be a linear combination of logical decomposition, integration (SE6), verification (SE7), validation (SE8), and transition (SE9). This PC could be interpreted as a contrast, or contributing in opposite directions, between the design-related logical decomposition of requirements with the realization processes of integration through transition. Overall, if one temporarily disregarded magnitude, this PC may be alternatively interpreted as design-related processes plus implementation and most of the SE technical management processes contrasted with the realization-related processes (sans implementation) and technical risk management/decision analysis.

The third PC proves to be interesting in its own right. In simply looking at the loadings' absolute magnitude, stakeholder expectations definition (SE1), interface management (SE12), technical assessment, and decision analysis are of highest relevance. When taking into consideration the directions of these four processes, this PC may be interpreted as the contrast between managing interface development with the definition of technical requirements, assessing the technical progress, and employing established decision analysis processes.

As with the first and second PCs, if one simply looks at the contrasts in terms of all the variables, the interpretation could be drastically different. It could be a contrast of processes within and between the design, realization, and technical management groups of processes.

Exhibit 26 shares a visualization of this PC as it pertains to an adapted version of NASA's "SE Engine." The colors have no meaning other than illustrating similarity in direction. Stakeholder expectations definition and technical requirements definition (SE2) are contrasted with logical decomposition and design solution definition (SE4) within the design-related processes. Similarly, within realization processes, validation is contrasted with implementation, integration, verification, and transition. The 'technical_' (sans technical data management) management processes of SE10, 13, 16, and 17 are contrasted with the '_Mgmt' (sans technical risk mgmt.) management processes SE11, 12, 14, and 15.

Exhibit 126. Third PC contrasts relative to NASA's "SE Engine"



The fourth and fifth PC's were more straightforward. PC4 is a contrast between technical requirements definition and technical risk management. This relationship highlights a well-known aspect of SE in terms of the oft-contrasting effects of defining technical requirements and managing technical risk. PC5 represents a contrast of stakeholder expectations definition and implementation with logical decomposition. This contrast might suggest a complementary relationship between defining stakeholder expectations and implementing the system that has been defined regardless of logical decomposition's ability to flow the requirements down to subsequent levels.

Assessment of principal component hypotheses

It does not appear the technical management processes are the primary source of variance (hypothesis set Fii.1.). The second hypothesis (Fii.2.) regarding NASA's "SE Engine" does not gain support from this work either. There could be three or five components suggested depending upon the importance of variance explained and/or any other a priori restriction. If three PC's were chosen, they do not mirror NASA's model; this does not preclude, however, that NASA's model reflects reality in terms of the SE processes.

Conclusions

In concluding this article, important findings are summarized and related to studies in Exhibit 3 and discussed in the Background section. Next, some of the limitations of the research design are highlighted. Finally, brief commentary on future research recommendations as a result of this and previous related research is shared. These conclusions extend those from the preliminary report in Componation et al. (2013) with a more complete and comprehensive dataset and analysis framework.

Summary of Findings

Investigating research objectives A and B yielded numerous independent yet in some cases complementary company and project factors that provided a more comprehensive understanding of where and how SE is being used. Distributed team member interactions (research objective C) can help researchers begin to address cultural [Kludze (2003) and Honour (2013)], social/ political (Bruff, 2008), and other nontechnical factors impacting SE with communication being at the center.

The projects, deemed representative of work the respondents' organizations typically face, clearly had significant technical, budget, and schedule risks. Other 'on the average' features were made evident considering research objective D. Commercial projects were perceived to have statistically significant higher programmatic risk scores than government projects. While certainly not the only study to have come to a similar conclusion, this study would reinforce Kludze's and others' statement of SE adding value to projects. Increasing the likelihood of success is certainly a value-add, and from the sampled population of a broad swath of SE practitioners it is evident the commercial and government projects were successful. There is no guarantee success is the result of good SE, but this adds to the growing preponderance of evidence that it is not merely a correlation event, but causal. For all but two success metrics - effective project management and overall project success from the organization's view – government organizations scored higher than commercial projects. For both groups, technical success was rated higher than programmatic budget and schedule metrics. Only design solution definition and validation processes were shown to be significantly different in terms of their perceived performance between commercial and government organizations.

Researching objective E started with the overall dataset, which exhibited positive associations between SE processes and project success metrics. There were just 11 correlations of note ($r \geq .4$) out of a possible 81 between success and system design or system realization processes. This is surprising in that traditionally these processes are what make or break SE efforts. In agreement with Elm et al. (2012) and Honour, project planning and technical risk management proved to be positively correlated with numerous metrics. Technical success was best associated with logical decomposition, integration, verification, transition, and decision analysis. Integration, transition, and technical risk management were the only SE processes that correlated well with overall project success. In agreement with Kludze's finding that SE enhances technical performance, all but one of the 153 SE-PSM variable pairs had a positive relationship; only validation with respect to the original project schedule was negative, and that was likely due to random noise because the magnitude was effectively zero. Effective project management was associated with numerous SE processes which supports the commonsense notion that better SE and project management go hand in hand. In general for the overall dataset, higher scoring SE processes do reduce risks as Kludze found, and success was largely impacted in an opposing manner by project risks.

Five similar findings in terms of positive association were found between Componation et al. (2009) and this study, namely: 1) integration and 2) verification with technical success relative to other similar projects, 3) technical planning with schedule success relative to other similar projects, 4) integration with overall project success from the organization's view, and finally 5) technical risk management with overall project success from the stakeholder view. Of those five, 2), 3), and 4) were also found when considering commercial and government data independently.

The final research objective, F, inquired into the most critical differences and similarities between commercial and government SE process assessments. LDA showed how separation by class was best determined by performance on design solution definition, validation, technical risk management, and interface management. This might suggest that these processes are where commercial and government SE efforts are most distinguishable from each other. PCA resulted in three or five principal components, depending on the degree to which the set of variables might need to be reduced or how much the explanation of variance is desired. Some principal component interpretations, particularly for the third PC, might prove extremely interesting and insightful to veteran and novice SE practitioners alike in the context of NASA's SE framework. This is because it could provide initial support that the framework/model by which the SE processes are related may not best represent how they interact and ultimately contribute. Some processes traditionally viewed as complimentary may have contrasting impacts.

Limitations

The major limitations in this study revolve around the survey development, survey deployment, and the analysis of the collected data. After subject matter expert (SME) feedback and suggested improvements was incorporated, the limitations of the instrument were noted. The vast majority of the problems encountered can be traced back to three major themes: 1) Inherent and classical survey considerations 2) Likert item use and construction, and 3) familiar aspects of reliability and validity (particularly as applied to Likert items).

Admittedly, by virtue of the target population, the set of practitioners could vary widely. This could weaken the homogeneity and ultimately interpretability and/or validity of findings. Alternatively, it could be viewed as an advantage in diversifying the responses, which was a documented research recommendation from previous studies. There was considerable effort taken to obtain appropriate responses by engaging specific groups. By the very nature of sampling by convenience, the issue of whether or not a representative sample of SE practitioners was obtained is raised. Beyond the identification of candidate sample groups, ideally the contacting and facilitating of the distribution of the survey would be handled consistently, but once a group agreed to do so it was out of the research team's control. The consideration of the correlation results between success and SE processes must be appreciated cautiously simply because of the sheer number of related SE processes and the likelihood of spurious, or indirect, relationships which were not controlled for.

Future Research

Many critical aspects of a given SE effort were not included in the scope of this research. Projects often re-baseline items throughout their life in response to design changes, priority or schedule changes, etc., that impact an individual's perspective and judgment of project success. Costs are key drivers of decisions, and no financial information was collected to assess their impact. Neither project length information nor respondent experience was requested; this would have been yet more drilldown opportunities for analysis consideration. Continued research taking into account these and other factors and trying to obtain a better handle on understanding their relationships are crucial for the future of SE.

In 2008 and 2009, NASA tried to "identify the characteristics or behaviors frequently observed in highly regarded systems engineers (Williams & Derro, 2008, pg. 4)." Across all of NASA's Centers, there were consistent behaviors identified with those that had proven to be the best at utilizing SE. This is but one example of many non-technical, or soft, factors that impact success in projects.

A major component and enabler of SE research is the sample survey. Data has been shown in the referenced studies, in particular by Honour (2013), to be accessible despite organizational and other boundaries. Surveys exist in various lengths and in different mediums (paper versus online), and are comprised of many different question types. A major problem with SE survey research that stems from its "identity crisis" (Emes et al., 2005) and the innumerable directions SE research can seemingly go is the re-invention of the survey every time different objectives and inquiries want to be explored. To a certain extent this is always going to remain the case, but with numerous surveys now having been developed and deployed, the SE community at large could benefit greatly from a culling together of SE survey "best practices" or something more tangibly supportive that could be used in tandem with guidance on the process to put one together (e.g. Smartt and Ferreira (2013), Etchegaray and Fischer (2010)) and obtain higher quality responses in greater numbers (Fan & Yan (2010), Sauermann & Roach (2012)).

In this study, an attempt was made to reduce the dimensionality of the data by way of LDA and PCA. Not only would it be interesting to see others utilize these methods more often to explore their potential in this field, but to extend the statistical methods toolbox to include factor analysis. Factor analysis is an inferential technique as opposed to PCA's descriptive nature. It could further investigate the internal structure of the data by way of identifying latent variables that more adeptly speak to the structure of the variability versus maximizing the cumulative proportion of the variability a model can explain.

CHAPTER 3

GENERAL CONCLUSIONS

The Future of SE?

In 2007, Dr. Dale Thomas reported on the deficient SE processes preceding seven NASA system failures. His paper supports the art side of the art and science paradigm in that despite all the resources on SE approaches, it is not the case of different yet similar SE methodologies being responsible for the failures, rather the way in which they were implemented. Perhaps something should be said for a little philosophy (Brown, 2009).

Increasingly so, rhetoric within NASA is at a crossroads between the development of greater levels of guidance on implementing standards and policies, the impetus of this research, and "an overhaul from the ground up [that] can move large system design from uncertainly avoidance and denial to uncertainty management (Collopy, 2012)." This "shift from a focus on process to a focus on product" (pg. 1) was highlighted in a three-part workshop series in 2010 and 2011 through a partnership between NASA and the National Science Foundation (NSF). Furthermore, as document-based SE models become more obsolete, the advent of alternative SE models that engage and are enabled by better technology will add challenges in its research and application (Murphy & Collopy, 2012).

Due to resource constraints and a widening and deepening dependence upon the commercial sector for mission critical R&D and more, the potential and need for the collaborative evolution of SE has never been greater. Continued empirical and theoretical research into SE – and the 'systems thinkers' that comprise the field (Valerdi & Rouse, 2010) - with regard to both technical and nontechnical factors, is needed.

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APPENDIX

Systems Engineering Survey

Survey on Systems Engineering (SE) Processes and Project Success

Welcome

Welcome to the Survey on Systems Engineering (SE) Processes and Project Success! Your answers are anonymous and will be kept confidential. The only information released will be in aggregate.

While there are numerous representative definitions of systems, projects, etc. - and subsequently Systems Engineering as a practice - based on *your* experiences we would like to gather:

1. Basic demographics of your organization
2. Descriptive information on a specific project you worked on
3. How successful the project was
4. What systems engineering processes were used
5. Information on how you interacted with your distributed team members

The following items highlight some additional information and instructions:

1. From the next page onward, you can save your progress and return at your convenience.
2. After completing this survey for ***one*** specific completed project, you can complete this survey for different projects (one survey submission per project).
    1. You will have to return to the original link sent to you should you want to complete the survey more than once.
    2. If possible, please consider doing so for projects of varying success, from above the expected or anticipated to project failure.
3. Your accurate and thorough responses help contribute to the best representation of system development projects across numerous domains of commercial and government work.

Company Description

1. My organization is part of the:

- ○ Public sector
- ○ Private sector (publicly traded)
- ○ Other (please specify):

2. My organization's industry or service is *best* described by (select the most representative category):

- ○ Aerospace
- ○ Agriculture
- ○ Communications
- ○ Defense & Security
- ○ Electronics & Electrical
- ○ Energy
- ○ Environmental
- ○ Health & Welfare
- ○ Infrastructure
- ○ Transportation
- ○ Other (please specify):

3. Within my organization, SE skills and responsibilities are:

- ○ contained in a single department
- ○ distributed throughout the organization
- ○ managed by a single department, but execution is done at the project level
- ○ not formally recognized in the organization

4. We track SE effectiveness (select all that apply):

- ☐ At the organization level
- ☐ At the overall project level
- ☐ At the project task level
- ☐ At the individual level
- ☐ We do not track SE effectiveness

5. Please share your organization's name (optional):

6. Additional thoughts, comments, information regarding your *company description* (optional)?

Project Description

7. This project was representative of the scope of work my organization typically completes.

Strongly Disagree	Disagree	Agree	Strongly Agree	Not Applicable
○	○	○	○	○

8. This project had significant technical risk.

Strongly Disagree	Disagree	Agree	Strongly Agree	Not Applicable
○	○	○	○	○

9. This project had significant budgetary risk.

Strongly Disagree	Disagree	Agree	Strongly Agree	Not Applicable
○	○	○	○	○

10. This project had significant schedule risk.

Strongly Disagree	Disagree	Agree	Strongly Agree	Not Applicable
○	○	○	○	○

11. Which SE standard(s) was (were) used on this project (select all that apply):

- ☐ No standard was used
- ☐ Internally developed standard
- ☐ Defense Acquisition Guidebook
- ☐ ANSI/GEIA EIA-632
- ☐ EIA/IS 731.1
- ☐ IEEE 1220-2005
- ☐ ISO/IEC 15288
- ☐ ISO/IEC 15504: 2004
- ☐ ISO 10303-AP233
- ☐ CMMI
- ☐ NASA NPR 7123
- ☐ Other (please specify):

12. This project used a tailored approach based on the above SE standard(s):

- ○ Followed the standard(s) with *no tailoring*
- ○ *Some* tailoring of the standard(s)
- ○ *Extensive* tailoring of the standard(s)
- ○ No standard was followed - no tailoring

13. This project's primary customer is *best* described by:

- ○ Government - defense related
- ○ Government - not defense related
- ○ Academia
- ○ Industrial / Commercial
- ○ Private customer
- ○ Other (please specify):

14. Additional thoughts, comments, information regarding your *project description* (optional)?

Project Success Metrics

15. This project was a success when compared to the original technical requirements.

Strongly Disagree	Disagree	Agree	Strongly Agree	Not Applicable
○	○	○	○	○

16. This project was a technical success when compared to *other similar projects* .

Strongly Disagree	Disagree	Agree	Strongly Agree	Not Applicable
○	○	○	○	○

17. This project was a success when compared to the original project schedule.

Strongly Disagree	Disagree	Agree	Strongly Agree	Not Applicable
○	○	○	○	○

18. This project was a scheduling success when compared to *other similar projects* .

Strongly Disagree	Disagree	Agree	Strongly Agree	Not Applicable
○	○	○	○	○

19. This project was a success when compared to the original project budget.

Strongly Disagree	Disagree	Agree	Strongly Agree	Not Applicable
○	○	○	○	○

20. This project was a budgeting success when compared to *other similar projects* .

Strongly Disagree	Disagree	Agree	Strongly Agree	Not Applicable
○	○	○	○	○

21. The project management process used was effective.

Strongly Disagree	Disagree	Agree	Strongly Agree	Not Applicable
○	○	○	○	○

22. Overall this project was viewed by our *organization* as a success.

Strongly Disagree	Disagree	Agree	Strongly Agree	Not Applicable
○	○	○	○	○

23. Overall this project was viewed by our *stakeholders* as a success.

Strongly Disagree	Disagree	Agree	Strongly Agree	Not Applicable
○	○	○	○	○

24. Additional thoughts, comments, information regarding your *project success metrics* (optional)?

Systems Engineering Processes

25. This project identified all the stakeholders and their expectations for the system under development.

Strongly Disagree	Disagree	Agree	Strongly Agree	Not Applicable
○	○	○	○	○

26. The project transformed stakeholder expectations into unique, quantitative, and measurable technical requirements that can be used for defining a design solution.

Strongly Disagree	Disagree	Agree	Strongly Agree	Not Applicable
○	○	○	○	○

27. This project decomposed and allocated requirements to the lowest possible level of the system.

Strongly Disagree	Disagree	Agree	Strongly Agree	Not Applicable
○	○	○	○	○

28. This project translated the requirements into a design solution.

Strongly Disagree	Disagree	Agree	Strongly Agree	Not Applicable
○	○	○	○	○

29. This project translated the design solution into the actual system.

Strongly Disagree	Disagree	Agree	Strongly Agree	Not Applicable
○	○	○	○	○

30. This project integrated lower level products into higher level products and ensured proper functionality of the system.

Strongly Disagree	Disagree	Agree	Strongly Agree	Not Applicable
○	○	○	○	○

31. The project conducted a verification program to ensure the end product conforms to design requirements and specifications (the system was completed right).

Strongly Disagree	Disagree	Agree	Strongly Agree	Not Applicable
○	○	○	○	○

32. This project conducted a validation program to ensure the end product satisfied stakeholder expectations and would perform its intended use or function (the right system was completed).

Strongly Disagree	Disagree	Agree	Strongly Agree	Not Applicable
○	○	○	○	○

33. This project transitioned a verified and validated realized system to a customer at the next level of integration or the end-user.

Strongly Disagree	Disagree	Agree	Strongly Agree	Not Applicable
○	○	○	○	○

34. This project established a plan to apply and manage the technical processes within all technical and programmatic constraints.

Strongly Disagree	Disagree	Agree	Strongly Agree	Not Applicable
○	○	○	○	○

35. The project managed the product requirements providing traceability and changes to established requirements.

Strongly Disagree	Disagree	Agree	Strongly Agree	Not Applicable
○	○	○	○	○

36. This project managed interface development, maintaining definition and compliance.

Strongly Disagree	Disagree	Agree	Strongly Agree	Not Applicable
○	○	○	○	○

37. This project measured, assessed, and managed risk.

Strongly Disagree	Disagree	Agree	Strongly Agree	Not Applicable
○	○	○	○	○

38. This project identified, controlled, and preserved (recorded) the system configuration.

Strongly Disagree	Disagree	Agree	Strongly Agree	Not Applicable
○	○	○	○	○

39. This project managed the identification, acquisition, access, protection, and distribution of technical data.

Strongly Disagree	Disagree	Agree	Strongly Agree	Not Applicable
○	○	○	○	○

40. This project monitored technical progress and provided status updates in support of the systems engineering process.

Strongly Disagree	Disagree	Agree	Strongly Agree	Not Applicable
○	○	○	○	○

41. This project employed established decision analysis processes regarding technical decisions, alternatives, and uncertainties impacting cost, schedule, and risk.

Strongly Disagree	Disagree	Agree	Strongly Agree	Not Applicable
○	○	○	○	○

42. Additional thoughts, comments, information regarding your *systems engineering processes* (optional)?

Distributed Team Member Interactions

43. How many *groups* of team members at remote locations (i.e. you can't easily walk over to talk with them) were involved in your project's day-to-day work?

[ ]

44. For your project, what is the *average* percentage of your total team that typically participated in meetings from remote locations (i.e. not face-to-face)?

(%) ______

45. Please indicate what percentage of your team meetings were formal (e.g. design reviews) versus informal (e.g. brainstorming).

Formal team meetings (%) ______

Informal team meetings (%) ______

46. If some of your meetings involved virtual participants, what technologies did you use (select all that apply)?

- ☐ Telephone conferencing system
- ☐ Shared desktop software (e.g. WebEx, Lync, Connect, Sametime, etc.)
- ☐ Low fidelity video conferencing (e.g. Skype, webcam)
- ☐ High fidelity video conferencing systems (e.g. point-to-point video conferencing)
- ☐ Electronic distribution of documents (e.g. email)
- ☐ Shared drawing surfaces (e.g. electronic whiteboards)
- ☐ Text-based communication software (e.g. chat, instant messaging)
- ☐ Other (please specify): ______

47. List three differences between virtual meetings and face-to-face meetings:

1. ______
2. ______
3. ______

48. On average, how often do you interact with your *co-located* team members?

- ◯ Daily
- ◯ Several times a week
- ◯ Weekly
- ◯ Several times a month
- ◯ Monthly
- ◯ Several times a year
- ◯ Yearly

49. On average, how often do you interact with your *remote* team members?

- ○ Daily
- ○ Several times a week
- ○ Weekly
- ○ Several times a month
- ○ Monthly
- ○ Several times a year
- ○ Yearly

50. Additional thoughts, comments, information regarding your *team dynamics* (optional)?

Variable Information

Company Description (CD)
Project Description (PD)
Project Success Metrics (PSM)
Systems Engineering Processes (SE)
Distributed Team Member Interactions (DTMI)

Survey Question #	Variable by area	Variable descriptor	Survey Question #	Variable by area	Variable descriptor
1	CD1	Org. Type	26	SE2	Technical Reqs. Definition
2	CD2	Org. Industry	27	SE3	Logical Decomposition
3	CD3	Org. Distribution of SE Skills & Responsibilities	28	SE4	Design Solution Definition
4	CD4	Org. Tracking of SE Effectiveness	29	SE5	Implementation
5	CD5	Org. Name	30	SE6	Integration
6	CD6	Org. Supplementary	31	SE7	Verification
7	PD1	Representative Project Risk	32	SE8	Validation
8	PD2	Technical Risk	33	SE9	Transition
9	PD3	Budget Risk	34	SE10	Technical Planning
10	PD4	Schedule Risk	35	SE11	Requirements Mgmt.
11	PD5	Standards	36	SE12	Interface Mgmt.
12	PD6	Tailored Standards	37	SE13	Technical Risk Mgmt.
13	PD7	Primary Customer	38	SE14	Configuration Mgmt.
14	PD8	Project Supplementary	39	SE15	Technical Data Mgmt.
15	PSM1	Technical Success: Original Tech. Reqs.	40	SE16	Technical Assessment
16	PSM2	Technical Success: Other Similar Projects	41	SE17	Decision Analysis
17	PSM3	Schedule Success: Original Schedule	42	SE18	Processes Supplementary
18	PSM4	Schedule Success: Other Similar Projects	43	DTMI1	Number of groups that are remote
19	PSM5	Budget Success: Original Budget	44	DTMI2	Percent of total team that is remote
20	PSM6	Budget Success: Other Similar Projects	45	DTMI3	Percent Meetings Formal Percent Meetings Informal
21	PSM7	Success: Effective Project Management	46	DTMI4	Remote Meeting Technology
22	PSM8	Success: Overall Org.	47	DTMI5	Differences in meeting virtually vs. face-to-face
23	PSM9	Success: Overall Stakeholders	48	DTMI6	Average number of interactions of co-located team members
24	PSM10	Success Supplementary	49	DTMI7	Average number of interactions of remote team members
25	SE1	Stakeholder Expectations Definition	50	DTMI8	Distributed Team Supplementary