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Development of a new instrument to assess the performance of systems engineers

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Submitted to the Faculty of
Mississippi State University
in Partial Fulfillment of the Requirements
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in Industrial & Systems Engineering
in the Department of Industrial & Systems Engineering

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2020

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System engineering (SE) is a structured systematized methodology that deals with designing, managing, and optimizing systems performance. System engineers use the perspective of system thinking to make the successful use and retirement of engineering systems. Since the role of system engineers ranges widely from technical support to customer interaction, system design to management, there is a demand to develop a cadre of effective systems engineers. However, two critical questions are not well-defined in the extant body of SE literature: *(1) What are the fundamental attributes of systems engineering that would influence the performance/effectiveness of individual systems engineer? (2) What are the corresponding leading indicators for appraising the performance of an individual systems engineer?* To respond to these questions, this study proposes a new instrument to evaluate the system engineers' performance and subsequently identify their strengths and weaknesses within the complex system domain. The instrument is based on the set of performance indicators examining six fundamental system engineering attributes. The implication of this study would assist systems engineers in strengthening their system skills and reflects a state that can be improved through training, workshops, and education to prepare them to face the complex situations originating from the problem domain.

DEDICATION

This dissertation is dedicated to:

Apple of my eye, my adorable son, my world: *Arham N. Hossain.*

My pillar of support, my dear and lovely wife: *Dr. Farjana Nur*, who relentlessly supports and motivates me throughout my PhD journey while pursuing her doctoral study.

My respected parents, my source of energy: *Md. Liaquat Hossain* & *Hasina Kaniz Fatema,* and my sweet sibling: *Mahmud Ullah,* for their continuous prayer, love, and affection at every step of my PhD journey and wishes me to achieve a doctoral degree. Without them, I am nothing.

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CHAPTER I

INTRODUCTION

Modern systems are designed and develop to fulfill needs or provide solutions for bettering organizations and overcoming persistent challenges stemming from increasing complexity. However, systems and their derivative problems are not likely to be settled in the near future rather, they are more likely to intensify in complexity. Perhaps, revolutions in technologies and proliferation of information are indicative of the future, which must be dealt with by systems engineers. Thus, there is a need to employ a "systemic approach" to better manage and navigate these complex system problems (Alfaqiri et al., 2019; Hossain & Jaradat, 2018). In response, *Systems Engineering (SE)* has developed as a distinctive discipline to address these challenges and concerns by using a systemic approach to ensure that individual elements, sub-elements, and associated phenomena are functioning harmoniously in a given operational environment to achieve an effective performance of the overall system.

Dated back to World War II, there was a fundamental operational transformation in industrial and construction sectors around the world. During the war, a new engineering discipline is known as "Systems Engineering (SE)" evolved as a major new paradigm to countervail the complexities associated with newly emerging processes and systems(Gorod et al., 2008). Systems engineering has continued and developed as a distinctive specialized discipline since its inception. There have been rapid and continuing advances in this area in the last two decades ultimately targeted to address the intricacies stemming from increasingly sophisticated and diversified complex systems permeating every aspect of society. Unlike traditional engineering, systems engineering is not grounded by a set of rigidly defined basic theorems anchored in science related to physical properties. Instead, SE has evolved as a set of best techniques for managing the ill-structured complex problems based on circumstances (Hallam, 2001; Hossain and Jaradat, 2018). At the most basic level, SE is the implementation of systematized methodologies to guide the design, analysis, execution, and development of systems that addresses needs and resolve problems (Hossain and Jaradat, 2018). Systems engineering addresses the life cycle of product systems from conception to disposal, and it operates to trace and satisfy customer requirements within constraints of the system. In other words, from a fundamental perspective, systems engineering is an iterative process to ensure that the embedded elements and subsystems constituting the system are designed, balanced, and function in the most effective manner while integrating appropriate "ilities" (i.e., maintainability, sustainability, reliability, maintainability, supportability) and other attributes into the total engineering effort (Blanchard et al., 1990; Buede & Miller, 2016; Hossain & Jaradat, 2018; Shishko & Aster, 1995).

System Engineering offers unique approaches to solve complex engineering problems where the traditional engineering approach fails to perform. As a result, system engineer performs different process, tools, and technologies at an organization to make the system efficient and the organization better. There are different role areas of the system engineers, and the role of system engineering must be understood at the commercial level to uplift the organization (Sheard, 1996). The different roles of the system engineer may include system designer, system analyst, technical manager, process engineer, and much more. As the different positions and roles can be critical, it becomes necessary to analyze the deficiencies of performances of the individual systems engineers. In this research, *we develop a new instrument based on the text mining approach called* *"grounded theory" coding.* Sociologists Barney G. Glaser and Anslem L. Staruss's in 1967 had initially developed Grounded theory. In "The Discovery of Grounded Theory" book, authors characterized the approaches related to the grounded theory and described a significant way to derive a hypothesis using qualitative data analysis.

This chapter demonstrates an overview of the research by describing the objective of the study. Afterwards, the research questions and hypotheses are presented to address the existing gap in the literature. Finally, this chapter ended up with discussing the implication of the study from different standpoints to fully appreciate the research.

1.1 Research Purpose

In years past, each engineering discipline was seen as a self-contained domain. As systems and technologies increase in complexity, the need for interdisciplinary teams and engineers who can consider the system in a holistic way have become a standard requirement for any systems development activity. Systems engineers fill this role to lead interdisciplinary teams and consider the entire life cycle of the system during the development, operation, and disposition of a system (Hossain & Jaradat, 2018; Hossain et al., 2020). The International Council for Systems Engineering (INCOSE) developed a vision of system engineering for 2025 (INCOSE, 2014), in which an imperative includes "Enhancing education and training to grow a system engineering workforce that meets the increasing demand." Education can either cover the breadth of systems engineering knowledge or be targeted based on the needs of the individual or organization. Building an effective workforce is not just attaining the quantity to meet the demand, but the quality of these engineers is even more important. INCOSE also publishes a Systems Engineering Handbook (INCOSE, 2015) and Systems Engineering Body of Knowledge (SEBoK) (SEBoK contributors, 2020)outlining the processes and core competencies of systems engineers.

Besides the processes and technical knowledge, what differentiates a great or successful systems engineer needs to be addressed. A study by Davidz & Rhodes (2005) looked at how to accelerate the development of senior or highly skilled systems engineers. It was posited that systems engineers would need to be quickly developed in order to handle the increasing complexity in the field of engineering. Frank & Carlo (2007) studied the characteristics of successful systems engineers. This study resulted in a list of 38 characteristics of a successful systems engineer. In 2008 the National Aeronautics and Space Administration (NASA) launched the Systems Engineering Behaviors Study to determine what qualities are shared by highly regarded systems engineers. The study involved interviewing and shadowing 38 highly regarded systems engineers in order to find common attributes. The researchers concluded that among the three axes of the Systems Engineering competency model – process knowledge, technical knowledge, and personal behaviors – the latter component was the most important determinant for the highly regarded systems engineers (Derro & Williams, 2009).

While identifying the characteristics of a successful systems engineer is critical, training is one way to develop these skills. Systems engineering is a mix of art and science (Ryschkewitsch, Schaible, & Larson, 2009). The art of systems engineering involves creativity, leadership, communication, and engineering instinct referred to as technical leadership. In contrast, the science is implementing a disciplined, systematic engineering approach, process definition and control, and a clear understanding of the system and its interconnectivity.

The studies discussed the need for highly skilled systems engineers and the characteristics of these engineers. While this is a start to building a highly-skilled systems engineering workforce, there is a gap in assessing the current workforce's ability to perform the systems engineering work. For example, NASA has documented the capabilities that a systems engineer at NASA must have at each performance level (Ryschkewitsch et al., 2009), but they have not developed a tool for assessing the capabilities of the systems engineers. Additionally, Frank & Carlo (2007) recommended the use of the identified characteristics of the successful systems engineer to develop a "test for assessing the Capacity for Engineering Systems Thinking" that could be used for "selection, filtering, screening, placement, and classification of candidates for a systems engineering position."

To address the current gap in the literature**,** *this study will provide an overview of performance measurement tools, the development of an instrument for assessing a systems engineer's performance, review the assessment and interpretation of the results, and then finally provide implications and conclusions. The outcome of this instrument would provide a unique profile for individual systems engineers and help the systems engineers to understand their weaknesses and strengths.* Figure 1.1 illustrates the structure of the research inquiry. The research purpose is anchored by research questions and supports the research significance.

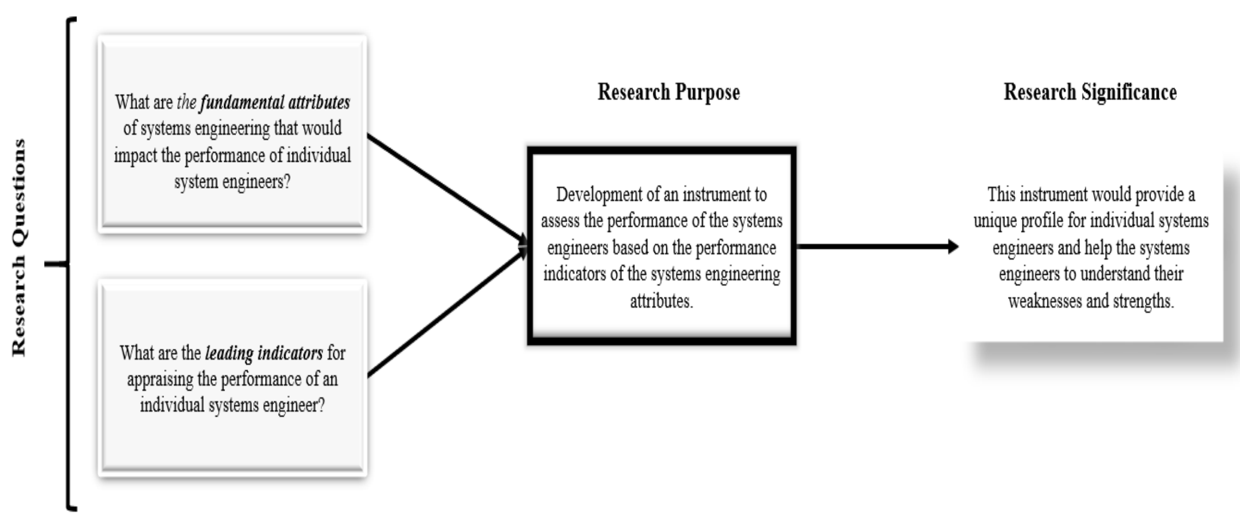


Figure 1.1 Structure of the Research Inquiry

1.2 Research Questions

Over the years, many issues have complicated the tasks of systems engineers. These include evolving legacy and off-the-shelf components, contextual specificity, extensively large structures, and lack of clarity in multiple expectations and outcomes (Sousa-Poza et al., 2014). Thus, there is a need to develop an effective system engineering workforce that can efficiently work in complex system problem domains. Mark Schaeffer, the former Principal Defense Systems and Director, Systems Engineering for the Office affiliated with Secretary of Defense (ATandL) made a statement to emphasize the importance of developing qualified systems engineers. He stated that "degreed workforce is a shrinking pool" and that we "need new ways to attract and develop system engineers (Schaeffer, 2005)." He also added, "An experienced, trained workforce is in short supply (Schaeffer, 2005)." This again stresses the importance of organizations developing a cadre of skillful systems engineers. This also suggests two important questions that are not well defined in the existing body of literature:

(1) What are the fundamental attributes of systems engineering that would impact the performance of individual system engineers?

To answer this question, the researcher applied Grounded Theory Coding (GTC), which is a qualitative data analysis methodology with the help of Nvivo 12 (QSR International) software in organizing, analyzing, and synthesizing the qualitative data. This leads to derive the six fundamental attributes of systems engineering. Based on these six attributes, the performance of the systems engineers can be assessed.

(2) What are the leading indicators for appraising the performance of an individual systems engineer?

To answer this question, we conducted an extensive review (qualitative approach) on systems engineering literature to identify the corresponding performance indicators for each fundamental attribute. This review supports the development of a novel systems engineering performance measurement tool that captures and assesses the performance of individual systems engineers. This performance is based on assessing the leading indicators of the fundamental systems engineering attributes

To summarize, the aforementioned two underlying themes were investigated with systems engineers, stemming from the questions that were phrased along the following sentence: *how to develop an effective systems engineer?* The in-depth analysis and justified response to these questions will provide a set of systems engineering attributes and corresponding performance measures, which can provide a strong ground to support the rationale of this instrument. In other words, there is no established empirical evidence that demonstrates to assess the performance of systems engineers, or at least it is not prevalent research discussed in the existing SE literature. This research investigates only the systems engineering population.

1.3 Research Hypotheses

The hypotheses have developed an attempt to explore the relationship of the systems engineering attributes to the level of performance for an individual system engineer. Following two hypotheses were developed to pursue the objective of the research:

***H_1*:** *There is a statistically significant relationship between the proposed systems engineering attributes and the state of performance of the individual systems engineer while engaging in systems engineering activities.*

Which is tested against the null hypothesis:

***H_0*:** *There is no statistically significant relationship between the proposed systems engineering attributes and the state of performance of the individual systems engineer while engage in systems engineering activities*.

1.4 Research Significance

1.4.1 Theoretical

- The study addresses a critical gap in the existing academic literature. There is no instrument that is available in the current literature that could assess the performance of the systems engineers. This study provides a framework for how to develop an instrument to measure the performance of systems engineers. Therefore, the purpose of the framework is to lessen the confusion with respect to the fundamental attributes of systems engineering.

- Although there is a wide gamut of theoretical and empirical studies focused on the analysis and characterization of performance measurement systems tools, there is scant research that has attempted to quantify the performance of individual systems engineers based on a unique set of determinants. To address this gap, this instrument assesses the skill of systems engineering based on the set of performance measurement indicators of six fundamental SE attributes.

1.4.2 Methodological

- Served as a 'baseline snapshot" to assess the performance of systems engineers measuring in complex systems and their symptomatic problems.
- This research offers a starting point to better understand what the skills are required to be effective systems engineers.

- Another contribution the research added from a methodological dimension is that the proposed instrument provided a set of different profiles that determine the state of performance for systems engineers. Each profile gives a clear description of how an individual would perform systems engineering activities. Although there are several methods**,** techniques, and tools attempted to talk about the performance of system engineering; however, these methods have not been able to measure the performance of individual system engineers.

1.4.3 Practical

- Appreciation of this framework will also serve as a benchmark to trace out the weakness of individual systems engineers. Once ‘weak’ areas are identified, they can serve to:
  - Support developmental areas for system engineers,
  - Identify potential vulnerabilities in performance of work assigned to systems engineers that may be performing ‘systems’ engineering activities for which they are not sufficiently prepared, and
  - Identify where additional/different skill sets might need to be added to supplement systems engineering activities.
- The systems engineering instrument can be applied at multiple levels: individuals, organizations, teams, and others. It helps individuals/ cadre of systems engineers to strengthen their weak area and fit themselves to face the complexities stemming from the problem domain in where they are anticipated to be deployed.

- Further, this instrument could serve as “a point of comparison “to inform the development of individual and organizational development programs and training programs to increase systems skills in systems engineering.

CHAPTER II

LITERATURE REVIEW

Traditional Systems Engineering (TSE) deals with single complex system problems in order to optimize the performance of the system. Currently, the representation of SE consists of different interpretations, including life-cycle based approaches, management technology paradigms, process-problem archetypes, discipline-oriented paradigms, and systems thinking and non-systems thinking approaches (Kasser & Hitchins, 2011). While this suggests a somewhat fragmented discipline, more rigorous development of the historical roots and evolution of development might serve to better understand two central issues. First, how this discipline arrived at its present state. Second, what this historical basis portends for future development of the discipline.

Although SE has been introduced in the defense and space industries, efforts are being made to extend the application of the discipline to different fields as well (Shenhar and Bonen, 1997). However, regardless of having diversified applications of SE, many scholars and practitioners continue to publish their research under the domain of the SE discipline. The state of art of SE literature is a somewhat fragmented compilation of apparently modified perceptions of related domains. The main purpose of this chapter is to trace the chronological development of SE from 1926-2017. To achieve this purpose, the chapter will explore the evolution of the SE field by segmenting the discipline development timeline into three different intervals and examining the significant developments within those intervals. It is anticipated that this view will offer the reader a comprehensive map of the development of SE and highlight the involvement of past contributors to the progression of SE. The objectives of this chapter are as follows:

- Trace the historical development of SE from 1926-2017 based on insights derived from a histogram analysis. This would provide a comprehensive overview of SE domain.

- Discuss the roles of systems engineers prevalent in SE literature. This would serve as a baseline snapshot to invoke a dialogue that possibly contributes to fruitful to the future advancement of SE field and unified the roles and responsibilities of the systems engineers in order to derive common language about roles, which might aid prevalence of discussion about the context and nature of systems engineering.

- Lessen the confusion pertaining to SE and its derivative terms. This would allow the practitioners to understand the applicability of SE terminology and how these nomenclatures are embedded in SE definition.

- Discusses the limitations and challenges of the systems engineering.

To achieve the objectives of the chapter, more than one hundred and fifty different resources have been coded and analyzed. The spectrum of sources includes scholarly journal articles, conference proceedings, letters, technical papers, special features, books, and book chapters. Since it is difficult to trace all works pertaining to SE, related works that contributed most significantly to the field of SE (based on the frequency of citations) are used as a primary criterion for the selection of publications for inclusion in the analysis. To trace the progression history of SE, we considered Ferris (2007 a,b,c), Gorod et al., (2008), Brill (1998) as grounded references where Ferris (2007 a,b,c) explored the early history of SE during pre and post-world war era. Gorod et al. (2008) and Brill (1998) traced the history of SE from 1950-1995. This research provides a comprehensive review of SE history from 1926-2017 and traces the development of SE discipline over the years.

Although not all SE works are included, the underlying overview originating from this synthesis will provide a good understanding of the field as a whole. Even though there is not a detailed discussion of all the references, all 150+ sources are incorporated into the analysis. Grounded Theory Coding (Charmaz & Belgrave, 2012) techniques were employed with the use of Nvivo 12 (QSR International, 2018) software that helped in structuring the large dataset.

The construction of the histogram analysis, consisting of three main intervals, is presented below. The examination of the intervals is followed by the progression history of SE pertaining to those three intervals. From the results of the analysis, this section concludes with a discussion of the implications of the analysis for the SE discipline along with the avenue of future research.

2.1 Progression Trajectory of SE Discipline and Relevant Analysis

2.1.1 Historical Perspective on the Development of Systems Engineering Discipline

In this section, the design and execution of the histogram analysis are developed (results summarized in Figure 2.6). The following topical areas were selected to guide examination of the literature to comprehend the histogram analysis: (1) definitions of SE, (2) characteristics for SE, (3) principles and axioms for SE, and (4) different perspectives and methodologies supporting SE. The histogram analysis provides a comprehensive discussion of different aspects of SE on a chronological development scale, rather than other potential organizing constructs (e.g. sector, geography, theme, etc.). Chronological tracing of the SE discipline development is offered as a path to potentially different insights and future implications based on the time-based development of the SE discipline. To create a histogram analysis, a time range of 91 years was used, the difference between the highest value (2017) and the lowest value (1926). This range would cover the historical context of SE from its inception to 2017 through three intervals, namely, (SE introductory, SE development, and SE revolutionary periods). Figure 2.1 provides the interval classifications for the histogram.

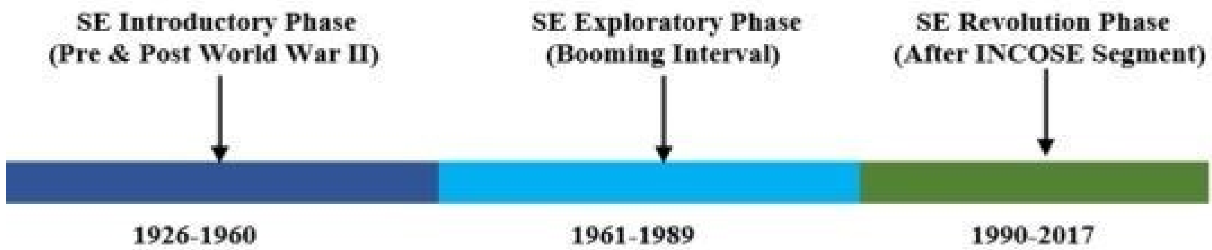


Figure 2.1 Classification of SE Interval for Histogram Analysis

The purpose of the histogram plot is (1) to provide quantitative information about the underlying frequency distribution of literature spanning the SE discipline history from 1926-2017 and (2) to discuss the main themes and challenges for the SE discipline that are derived from each interval. The horizontal axis in the histogram signifies the timeline of the study (classes), whereas the vertical axis embodies the relative frequency of contribution activity for each class (see Figure 6). This organization offers one of many possible ways in which the literature might be organized and examined. However, although not absolute, the inclusion of both frequency and content themes provides a clearer picture of the discipline development from the perspective sought in this paper.

2.1.2 Intervals

Based on the histogram analysis and the grounded theory coding, three main intervals were derived. Each interval reflects the development of SE history during that period of time. The first interval, labeled as the '*SE Introductory' interval*, is from 1926-1960, the second from 1961-

1989 labeled as '*SE Exploratory*' interval, and the third labeled as '*SE Revolutionary*' interval is from 1990-2017. For each of the intervals, an interpretation of the major contributions to the body of SE is identified and discussed.

2.1.2.1 Interval I (1926-1960): Introduction of SE

SE is entrenched in older management archetypes that were used during the construction of numerous ancient projects. Among these projects were the pyramids in Egypt, the water distribution and irrigation systems in Mesopotamia, and the infrastructure expansion in Greece and Rome, as well as the more modern 19th-century canals and railroads (Kasser, 2002). The construction of John Ericsson's iron-clad battleship from the Civil War era presented another example of historical evidence of the use of SE (Engstrom, 1957). The earliest foundations of SE can be traced to Smuts (1926), who first coined the term "holon" to describe the "wholeness or the integration of the elements of a system." The concept of holism, which developed from this term, is still considered to be one of the fundamental attributes of SE.

Prior to World War II, military weapons and equipment were not as complex as those in use and development today; thus the reliability of equipment was not as central of a concern. However, during World War II, electronic equipment became so sophisticated that reliability became a serious concern. For instance, due to poor radar reliability, numerous battleships were sunk at the beginning of the war in the Pacific. Along the same line, during the Korean War, bombing missions were halted due to the inability to effectively operate the complex electronic weapon systems (Brown, 1953). The complexity of the equipment exceeded the capabilities of service operators to maneuver the apparatus properly during operation, resulting in reliability becoming a prime concern of military applications (Romig, 1956). In order to address this issue, the American military sought help from large numbers of engineers and scientists to develop a technique to deal with these increasingly complex problems. This joint military-civilian endeavor was named *Operation Research*. The accumulated knowledge and experience that resulted from World War II stimulated the application of the systems approach in different domains. A noteworthy example of the invention during World War II were "black boxes" used on aircraft. Demand for multiple types of electronic gear essential for airborne operations triggered the development of widespread types of elemental devices, commonly known as "black boxes" (Engstrom, 1957). These inventive avionic architectures included multiple systems that were synchronized with the aircraft system to perform individual functions (Tolk et al., 2011).

During the 1930s and 1940s, a rapid advancement took place in the field of technology, especially in space and control engineering, power distribution, and communication systems. Reflections of these technological advances led to thinking about building structures that could be made even more robust by combining different interdisciplinary engineering approaches. This interdisciplinary systematic approach was actively incorporated in radio, telephone, and television industries during the late 1930s and ushered in the evolution of modern telecommunications networks. For instance, the Radio Corporation of America (RCA) and Bell Telephone Company aimed to expand the television transmission domain and long-distance telephone network using new broadband technologies. However, these experimental projects failed to progress due to the interruption caused by World War II. Consequently, in place of the telecommunications industry leading the SE discipline development, the Department of Defense (DoD) was placed 'front and center" in leading SE development.

World War II was arguably the first-time practitioners realized the importance of managing and synchronizing various complex systems to achieve long-term objectives. As an outcome, "quantitative management" techniques were developed out of World War II. In the post-war era, many perceived that the techniques developed during the war could be extrapolated and applied to other fields as well. For instance, after World War II, the scientists and researchers from RAND (research and development) corporation, Bell Telephone Laboratories, and RCA capitalized on the war-time experiences in advancement and expanded the technology of modern telecom and electrical power systems (Tolk et al., 2011). The RAND Corporation, which originated in 1946 by the United States Air Force, developed a "systems analysis" methodology, which is still considered to be one of the fundamental concepts of SE. RCA also deployed the "systems approach" for the advancement of electronically scanned, black, and white television (Engstrom, 1957). In 1943, to further advance the Aircraft Warning Communication Service, the National Defense Research Committee (NDRC) formed a systems committee in conjunction with Bell Laboratories to conduct a project named C-79 (Buede and Miller, 2016). Bell Laboratories was comprised of three different groups; systems engineering, design and development, and pure research (Keller, 1950). Bell Telephone Laboratories was perhaps the first organization to coin the phrase "systems engineering" (Schlarger, 1956).

The first operational intercontinental ballistic missile (ICBM) program, known as the Atlas ICBM program, also bears significance to the inception of SE. Before the Atlas ICBM program, the prime airframe manufacturers were only contractors accountable for designing military aircraft and supervising all the subcontractors under the authority of the U.S. Air Force. As a result, there was a scarcity of resources to produce the military weapons for the U.S. Air Force. In the early 1950's, when further development of an ICBM capability became necessary, the Air Force again looked to enlist the services of the airframe manufacturers. Subsequently, the Strategic Missile Evaluation Committee (codenamed Teapot Committee) was formed to assess various missile development projects all over the U.S (Hallam, 2001). The primary charge of this committee was to track the duplication of the implementation strategy and to appraise the competence of airframe prime contractors in order to develop a system requiring substantial electronic and computational capabilities. Several thousand skilled engineers, scientists, contractors, subcontractors and specialists were involved in the Atlas program. The Teapot committee (lead by Simon Ramo) contributed to the establishment of SE as a discipline by developing an administration responsible for monitoring and coordinating all the necessary activities for subcontractor design, development test, integration, verification, and validations (Hallam, 2001). Following the success of the Atlas program, scholars from different disciplines extrapolated the technique followed in the military program to management science, and SE evolved as a budding discipline at that time.

After World War II, MIT Radiation Laboratory, known as Rad Lab, published a series of books, which discussed the application and evolution of radar systems during the war. Although the series did not cite the term “systems engineering”, they did highlight how a holistic approach could be applied to an engineering system (Ferris, 2007c). In 1950, the first formal endeavor to teach SE was made by G. W. Gilman, who was the Director of systems engineering at Bell Laboratories at Massachusetts Institute of Technology (MIT) (Hall, 1962). In 1955, the biologist Ludwig Von Bertalanffy along with economist K.E. Boulding, physiologist R.W. Gerard, and the mathematician A. Rappoport developed the idea of generalizing ‘Systems Thinking’ or ‘Holistic Thinking’ to any kind of system; their ideas became known as “General Systems Theory (GST)” (Bertalanffy, 1968). This theory emerged due to the inadequacies of science alone to offset the challenges of complexity and confronted the effectiveness of reductionist based approaches for increasingly complex systems.

They presented the applicability of general system theory for any kind of system and suggested a universal language and laws that could be used in different areas with the objective of global acceptance. GST also engender the concept of systems thinking (ST) that facilitated higher levels of cognitive skills to better understand the context of complex problems. Some of the GST objectives included:

- To formulate a theory that represents underlying principles for all systems, irrespective of the context of the system.
- To explore the identical principles, laws, and models in many disparate fields, and to aid the successful transformation of these axioms from one field to another, and assimilate these understandings to avoid unnecessary duplication and ambiguities between fields.
- To encourage the harmony of science through enhancing communication among the practitioners (Checkland & Howell, 1993:93)

There are some other theories, such as Game Theory and Information Theory (Shannon and Weaver, 1949) that somewhat resemble or are related to the themes of general system theory, and these theories were widely adopted during this period of time. During and after World War II, a number of projects were undertaken in the U.S. to defend its people and protect its borders, such as the Analyze air defense system (1937) and Nike-line-of-sight -anti-aircraft missile system (1945-1953). The complexity and stochastic nature of the projects necessitated a systemic, holistic approach to successfully accomplish the project goals.

Schlarger (1956) was the first person to formalize a brief outline of the SE process encompassing planning, analysis, optimization, integration, and testing. He also suggested the adaptation of different types of systems analysis methods such as game theory, decision theory, linear and dynamic programming, probability and statistics, information theory, symbolic logic in system analysis and optimization process. Ramo, Engstrom, and Schlager portrayed SE as a significant method to deal with challenges in identifying and satisfying customer needs. The principle behind their proposition was that the integration of satisfactory components does not always produce a satisfactory system to achieve the desired goal. Engstrom (1957, p. 1) provided a basic definition of SE writing that "This method is best described by stating the two major requirements for its success: first, a determination of the objective that is to be reached; and second, a thorough consideration of all factors that bear upon the possibility of reaching the objective, and the relationships among these factors." Although Engstrom first introduced the concept of "interdisciplinary approach" in the SE process, he did not explicitly use the phrase "interdisciplinary approach" but rather coined the term "collaborative work." He amplified the idea of "interdisciplinary approach" by mentioning that a system project needs a wide range of expertise from disparate fields so that the system can be adequately assessed from different perspectives.

Olthuis (1954) probably was one of the early advocates who introduced the idea of a holistic perspective of top-down approach to design, emphasizing the need to draft the conceptual design of the entire system prior to explicit details or knowledge of the constituent elements. For instance, most of the communications missile subsystems of military systems were designed from a holistic perspective (Spanke, 1954). Likewise, in the area of acoustics, the necessity for a holistic approach was recognized for the proper dissemination of acoustic energy in the audible space to have a better performance of audio reproduction. By the same token, a holistic view of acoustic communication was also identified in the development of voice communication devices for incorporating in an aircraft system, where all the necessary components and communication channels were integrated together (Hawley, 1956). In another case, the invention of jet aircraft challenging air traffic control systems emerged in response to the need for complex system versatility (Krishner, 1956). This versatility created a need for a holistic approach to integrating ground to ground, ground to air, and air to air communication systems to enable a trouble-free air traffic channel. In this SE development interval, a number of articles (Speaks 1956, Okress et al. 1957) were published that illustrate the necessity of considering the engineering work in a holistic technical manner (i.e., consider the technical environment of the operating system as a whole instead of focusing on particulars). Steiner (1959) described the need for a systemic, holistic approach to elicit the design requirement and necessary solutions for Boeing commercial aircraft.

The first book on SE was written by Goode and Machol in 1957 and was titled *Systems Engineering – An Introduction to the Design of Large-Scale Systems*. This book follows a theme that shows how systems thinking and approaches facilitate the design of equipment. The overlap between management and engineering was also acknowledged by Goode and Machol in early 1959 when they wrote: "Management has a design and operation function, as does engineering (Goode and Machol 1959, p. 514)." The commonality and dissimilarity between the roles of SE and project management have also been discussed in various publications, which will be discussed in the third interval (SE Revolution).

A survey of the literature from (1926-1960) shows that: (1) World War II and several pre-war government projects had a significant impact on the inception of SE, (2) late in the 1950s, the focus toward holistic approaches to deal with increasingly complex systems and their fundamental problems became apparent and (3) several pervasive concepts pertaining to SE such as "system analysis" techniques, "systems engineering process" and "system thinking" were introduced. Figure 2.2 highlights the main themes in the interval I.

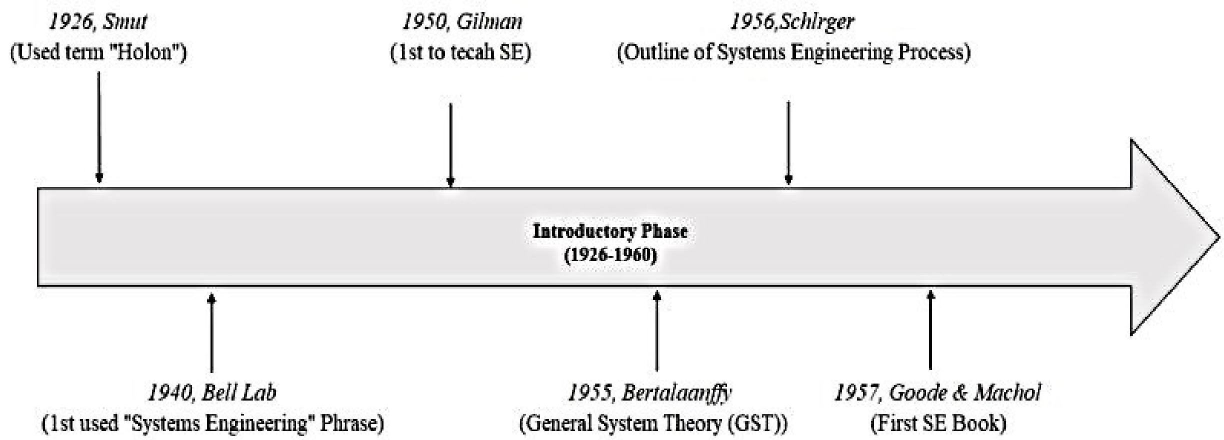


Figure 2.2 Main Themes for the 1926-1960 SE Development Timeline

2.1.2.2 Interval II (1961-1989): Exploration of SE

In the 1960s-1990s, SE had significant growth along with the widespread application. During this interval, the diversified characteristics of this discipline encountered some successes as well as failures and gave rise to debates based on the subjective application of the discipline. Various aspects of SE and its process can be better understood from the literature of Arthur Hall. In 1962, Hall introduced a concept of "systems engineering methodology" or "process of systems engineering" through three fundamental principles. First, SE definition is composed of diverse paradigms such as management technology, process-oriented approach, and problem-solving methodology. Second, to have a better understanding of complex system problems, a systems engineer has to appraise a system from three different perspectives: the physical or technical, the business or economic, and the social (Gorod et al., 2008; Hall, 1962). Third, SE is designed specifically to fulfill customer requirements in the most effective way based on available information. Hall's SE methodology consists of five phases: 1) system studies or program planning; 2) exploratory planning, which embodies problem definition, determining the objectives, synthesizing and analyzing the system followed by selecting the best system and communicating the output; 3) development planning, which is replications of phase 2 in a more comprehensive way; 4) studying the development, integration, and testing of the system; 5) current engineering which refers to the operational activities while the system is functioning and being refined (Buede & Miller, 2016, p. 7).

Shinners (1967) recommended that to solve a system-oriented problem, a systems engineer must grasp the fundamentals of the system problem, elicit the overall requirements and objectives of the system, and understand the comprehensive knowledge concerning the constraints inherent in the system. Shinner's problem formulation and solving methodology are somewhat aligned with the earlier advice recommended by Chestnut (1965). Chestnut emphasized that to explicate the problem, systems requirements must be derived from the user-specified need. While Shinners offered a set of seven general strategies in conjunction with the concept of a feedback loop to explore a large complex system, Chestnut proposed an optional feedback process to compare results being attained to meeting the customer's requirements.

Jenkins (1969) provided a basic definition of SE that somewhat refers to the system integration or holistic perspective of a system. He defined SE as "the science of designing complex systems in their totality to ensure that the component subsystems making up the system are designed, fitted together, checked and operated in the most efficient way." Jenkins explained that the SE approach deals with local authorities, organizational norms, whole organizations, and hardware systems to weave together. His definition served as a grounded reference for further advancement regarding all aspects of SE.

In the 1970s, several SE theories and models were introduced in the SE literature. Following Von Bertalanffy's work on GST, Ackoff in 1971 opposed the idea of analyzing systems by segregating the systems into sub-elements. Rather, he proposed that the entire system should be treated as a whole. He asserted that the interdependencies among the elements within systems should be considered aggregately. Thus, he concluded that reductionist-based approaches are not adequate for understanding these overall interactions and interdependencies. In addition, Ackoff addressed several caveats and limitations in reductionist approaches whenever they are applied to real-life complex situations. Similarly, Beer (1972) introduced the term "meta-system" to designate the integration of systems by means of a cybernetic perspective. He developed the viable system model (VSM), which consisted of five main functions, including the productive function, coordination function, operation function, development function, and identity function. Beer felt these functions were indispensable when ascertaining the viability (continued existence) of a complex system and that together they deliver a broad understanding of the mutual interdependencies among the elements of the systems. The insights drawn from Beer's concept provided a noteworthy contribution to realize the structure of a complex system.

At the beginning of 1971, a series of ten lectures titled "Systems Concepts for the Private and Public Sectors" was presented at the California Institute of Technology by several scholars, with a primary purpose to criticize the many perspectives of the reductionist approach (Ramo, 1971). Ramo articulated that the systems approach focuses on analyzing and designing a system from a holistic perspective while considering all possible parameters from both societal and technological standpoints rather than dealing with different individual elements or parts. Miles (1971) stated that system approaches work well when the objectives of the system are clearly defined, and the necessary technologies are adequately developed. The lectures were later edited and published by Miles in 1973. Miles identified the following steps needed for the systems approach: (1) goal definition or problem statement (2) objectives and criteria development

(3)systems synthesis (4) systems analysis (5) systems selection (6) systems implementation (Brown, 1953).

A year later, Chase (1974) emphasized the importance of the development of proper semantics and lexicology for the systems concept. He asserted that language difficulties might cause barriers to effectively communicate on topics pertaining to the system concept and that work was needed in this area. A remarkable contribution came from Blanchard and Fabrycky (1981), who introduced the concept of "System Development Life Cycle (SLDC)." The concept is based on Hall's (1962) methodology (problem identification; problem definition; planning and designing of a system; construction and disposal). They described the steps of the system life-cycle as "starting with the initial identification of a need and encompassing the phases (or functions) of planning; research; design; production or construction; evaluation; consumer use; field support; and ultimate product phase-out (Blanchard & Fabrycky, 1981, p. 19)." This concept is still upheld as one of the underlying principles of SE.

In 1974, The Defense Standard of the United States (Military Standard) introduced the concept of "Systems Engineering Management Plan (SEMP)." They described SE as practical use of scientific effort that incorporates all the "ilities" to meet the technical objectives of the system. This observation can be mapped into the management-oriented paradigm. According to MIL-499A (1974), SE is defined as "engineering efforts to:(1) transform an operational need into a description of system performance parameters and a system configuration through the use of an iterative process of definition, synthesis, analysis, design, test, and evaluation; (2) integrate related technical parameters and ensure compatibility of all related, functional, and program interfaces in a manner that optimizes the total system definition and design; (3) integrate reliability, maintainability, safety, survivability, human, and other such factors into the total technical engineering effort to meet cost, schedule, and technical performance objectives (MIL-499A (1974), p. 9)."

Wymore (1976) indicated that an interdisciplinary approach is an essential component of the SE discipline, which is governed by three fundamental attributes "modelling human behaviour, dealing with complexity and largeness-of-scale, and managing dynamic technology" (Wymore, 1976, p. 78]. Wymore also extended the application of SE by adding the education, health, and legislative systems to the paradigm along with the existing systems of communication and construction (Checkland, 1981). In 1984, M'Pherson (1986) brought another dimension to the SE definition by proposing the term "hybrid methodology." He stated that SE is "a hybrid methodology that combines policy analysis, design, and management. It aims to ensure that a complex man-made system, selected from the range of options on offer, is the one most likely to satisfy the owner's objectives in the context of long-term future operational or market environments" (IEEE P1220 1994, p. 130-133).

In 1984, Jackson and Keys (1984) made a notable contribution by classifying the problem-solving methodologies of SE based on *unitary* (pursuit of a definite set of objectives) and *pluralist* (pursuit of multiple, potentially diversified goals) approaches. Unitary approaches are applicable for simple systems where the context of the problem is static and can be solved by a predetermined set of techniques. For unitary problems, SE tools, hard system methodologies and operation research techniques can be applied. However, pluralistic problems are more dynamic, uncertain and complex in nature, and thus new techniques are needed. Clemson's (1991) writings in the same year underscored the importance of exploring complex system problems from different standpoints that are mutually supportive of the axioms derived from cybernetics. In 1986, Perrow

(1984) made a contribution to the SE field by exploring the stochastic nature of failure in large complex systems.

A survey of the literature within this interval (1961-1989) indicates that: (1) there was a clearly recognized need and the corresponding shift in paradigms to holistic-based thinking and approaches to address complex system problems, (2) several definitions were proposed that embodied numerous characteristics of SE, (3) some fundamental models were developed recognizing SE life-cycle and management-oriented concepts, and (4) several problem-solving methodologies were developed to address the SE problem domain. The timeline in Figure 2.3 below shows the main themes in interval II.

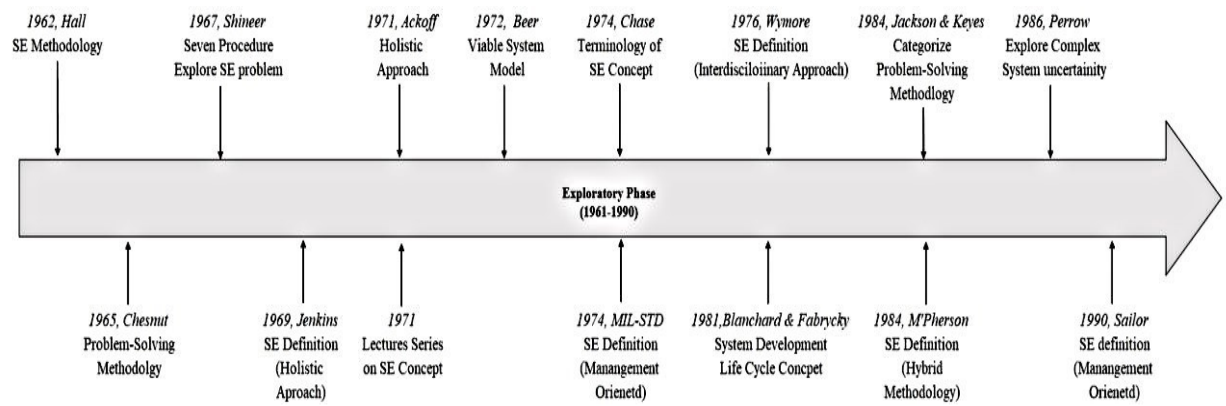


Figure 2.3 Main Themes for the 1961-1989 Timeline

2.1.2.3 Interval III (1990-2017): Revolution of SE

This interval witnessed the widespread advancement of SE. Several perspectives and concepts were articulated, and the field was in full progress during this period. Many studies and investigations were tempted to synthesize the definitions of SE from different standpoints and tried to establish the objectives of SE. Another stream of research focused on developing a SE body of knowledge encompassing different SE methodologies, unifying the systems theories, developing various models/processes, and building standardized frameworks. A significant number of presentations, conferences, articles, symposiums and journals pertaining to SE were also made available. To disseminate the SE principles and practices and provide better solutions to complex societal and technical challenges, a non-profit organization, The International Council on Systems Engineering (INCOSE), was established in 1990. In 1998, a dedicated SE journal titled "Systems Engineering" started its proceedings to cover the full spectrum of research germane to SE and System of Systems (SoS). The following themes can be derived from SE during this period:

- Management grounded technology
- Requirement driven process and SE process (life-cycle)
- Interdisciplinary approaches
- Problem-solving

2.1.2.3.1 Theme I: Management Grounded Technology

Although many works have been published that brought about a sense of management technology in SE processes, Sage (1995) was the first who explicitly incorporated the term "management technology" in the definition of SE. Based on his definition, "SE is the management technology that controls a total life-cycle process, which involves and which results in the definition, development, and deployment of a system that is of high quality, trustworthy, and cost-effective in meeting user needs" (Sage 1995, p.3). His definition was based on three fundamental levels: SE management, SE methodology, and SE methods and tools. The three fundamental levels involved three key points: *structure, objective,* and *function*.

Sailor (1990) stated that SE comprises both technical and management processes that transform the customer's need into the desired system design. In distinction, whereas technical processes involve the systemic transformation of the consumers' operational needs, management processes coordinate different design and configuration control groups and encompass handling risk, schedule, and budget associated with the task. Similar to Sage's definition of SE, the Department of Defense used the term "management" in their SE definition, but they also incorporated the concepts of "interdisciplinary approach" and "life cycle process."

2.1.2.3.2 Theme II: Requirement Driven Process and SE Process (Life Cycle)

Forzberg and Mooz (1992) described SE as "The application of the system analysis and design process and the integration and verification process to the logical sequence of the technical aspect of the project life-cycle." In 1994, Shenhar (1994) introduced the ideas of "management" and "interdisciplinary" in the definition of SE. He mentioned that SE is a technology-oriented management process that encompasses a sequential order of activities, including 1) identifying the customer need and convert it into system performance parameters and ultimate system design, 2) tracing and allocating the functional requirements, 3) selecting the appropriate system concept and design, 4) integrating and testing the system architecture and finally 5) evaluating the system's performance. Another process-oriented SE definition came from Shishko (1995), who wrote that SE is "iterative" in nature. The iterative nature assists in compensating for undesirable consequences and ensuring higher level qualities of the system (Shishko,1995; p. 4].'Iterative process' is used in many SE definition (ECSS-E-10-01, 1996). Martin (1996) called SE a system development process that works to achieve optimal system balance among all sub-elements. Skyttner (1996) defined "SE as a method by which the orderly evolution of man-made systems can be achieved." Gardy (2000) described SE as a process-oriented approach that transforms a set of intricate technical needs into feasible solutions via detailed design and manufacturing processes. In his work, Arnold (2000) mentioned that every organization must follow a standard

SE process, and SE is traditionally associated with a single process, standardized objectives and a course of development actions. A simple definition of SE came from Hitchins (2003, p. 309) "the art and science of creating systems." NASA handbook described SE as a decomposition (design), recomposition (creation/integration), and operation of a system (Kapurch, 2010).

A somewhat different SE definition came from Hallam (2001) who used the term "pull process" and mentioned that SE is a customer requirement driven "pull process" where a customer demands influence the flow of system development activities. In the updated version of the military standard handbook MIL-STD-499B, SE was defined in terms of standard processes, system analysis, and control. According to MIL 499B, systems engineering is an interdisciplinary approach including the set of technical endeavor to develop and verify an integrated set of system people, product, and process solutions in order to meet customer need" Kossiakoff et al.,(2011, p. 3) used the term "guide" in his definition: "The function of SE is to guide the engineering of complex systems," where "to guide" means direct and lead towards achieving the best solution. This definition stresses the aim of SE as a process of selecting the optimal solution out of many possible alternatives.

Wymore brought a new terminology in the definition of SE. He defined SE as a "discipline" instead of a process. Wymore (1994, p. 5) argued that SE is not only a process but also a distinctive discipline, where existing recognized SE processes are only applications of the SE discipline. His definition included "the intellectual, academic, and professional discipline, the principal concern of which is to ensure that all requirements for bioware/hardware/software systems are satisfied throughout the life-cycles of the systems." To support his argument, Wymore illustrated the definition of SE discipline provided by Kline (1995, p. 3):"a discipline possesses a specific area of study, a literature, and a working community of paid scholars and/or paid practitioners."

Hazelrigg (1996) provided a more specific definition of systems engineering and introduced the term "information-based approach." He emphasized that mathematical intensity in the systems engineering approach fostered better decisions pertaining to system design and synthesis. The general threads running through these definitions are that SE is a top-down approach that encompasses both technical and managerial efforts to integrate the diversified processes to optimize system performance. Additionally, SE is a requirement driven process where a customer's need is transferred into a requirements statement in order to develop the fundamental attributes of a functional physical design.

2.1.2.3.2.1 Theme III: Interdisciplinary Approach

Several other SE definitions developed in this interval that echo the theme of "interdisciplinary approach." IEEE P1220 (1994, p. 12) defined SE as "an interdisciplinary collaborative approach to derive, evolve, and verify a life-cycle balanced system solution that satisfies customer expectations and meets public acceptability." The Capability Maturity Model Integration (CMMI, 2001) described SE as an interdisciplinary collaborative approach that encompasses technical and managerial efforts to transfer the customer requirement into product solutions. Jerome Lake asserted that "systems engineering is an interdisciplinary, comprehensive approach to solving complex problems and satisfying stakeholder requirements (Martin, 1997, p. 244)." Abdallah et al. (2014) provided a more contemporary definition of SE, mentioning that SE integrates all the disciplines to pursue a well-structured technical effort and governs the design, development, and verification of a system to satisfy the customer need. Grasler and Yang (2014) also pointed out the attribute of an interdisciplinary approach in the SE process to fulfill the stakeholder need. Shenhar (1994) added another layer to the definition of SE by including the concept of the interdisciplinary approach, holistic perspective, and management process. SE deals with identifying the operational needs of customers, forecasting operational and technological processes, developing new concepts, and design by considering the overall system life cycle. Rechtin and Maier (2000) emphasized that there is a close link between SE and decision making, suggesting that SE is a multidisciplinary design-oriented process where decisions are made based on their impact on the system as a whole. A comprehensive definition of SE came from INCOSE (2006) as follows: "Systems Engineering is an interdisciplinary approach and means to enable the realization of successful systems. It focuses on defining customer needs and required functionality early in the development cycle, documenting requirements, then proceeding with design synthesis and system validation while considering the complete problem." The thrust of this movement was recognition of the interdisciplinary nature of the SE approach.

2.1.2.3.2.2 Theme IV: Problem Solving

Hitchins-Kasser-Massie (2007) developed a framework that clarified the reasoning behind overlapping SE and management and offered a concept for planning fundamental problem-solving to offset the challenges associated with a complex system. This framework also paved the way to having a broader understanding of the SE body of knowledge. The framework consists of three dimensions. The vertical dimension encompasses five layers: socioeconomic, industrial systems engineering, business systems engineering, project or system level, and project or system level, whereas the horizontal dimension signifies the sequential phases of the system life cycle. Activities are grouped based on the corresponding vertical layer and horizontal life cycle to represent the role of the systems engineer. The third dimension is still under development, which describes the problem-solving activity.

Literature shows that there are overlap and correlation between systems engineering processes (SEP) and the generic problem-solving processes. However, the set of activities of the

SEP and problem-solving processes are fairly distinct in nature. For instance, the steps involved in the generic problem-solving processes (OVAE, 2005; GDRC, 2009) are different in contrast to the general SEP approaches such as ANSI/EIA-632 (1994), generic V-model and SIMILAR (Bahill & Gissing, 1998). This common misunderstanding between problem-solving and SEP can be resolved by understanding the SE emphasis on the holistic perspective of generating a human-made system as a solution to a defined problem. A common meta-SEP can be developed by uniting the Hitchins (2007), and Mar (2009) approaches into the following 10-step sequence. This sequence combines the problem-solving process and the solution recognition process together. This 10-step sequence is feasible if we consider the systems engineering activity as a project (see Figure 2.4).

In 2005, Hitchins (2005) pointed out an interesting analogy between "soft system methodology (Checkland, 1981)" and the general problem-solving paradigm. For a better solution to the ill-structured problem, Hitchins, in his model, combined two different paradigms: an *exploration of the initial problem* and *development of the technological solution*. The model consists of a set of activities that address the background of the problem and develops the technological solution by considering the systems from a holistic perspective.

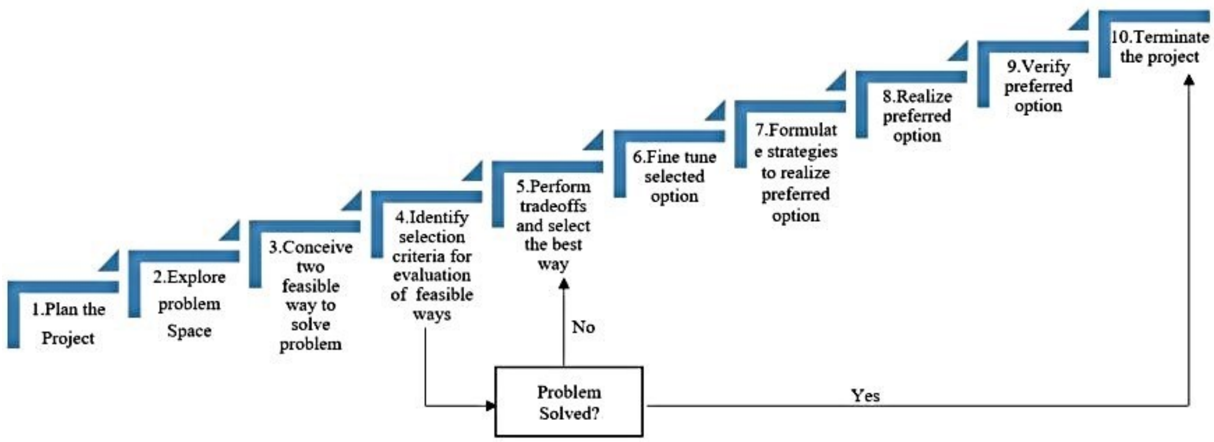


Figure 2.4 10-step Problem Solving Process

Another contribution came from Vencel and Cook, 2005. They explore the typology of complex system problems, defined the entire problem space, and categorized it based on seven-dimensional problem attributes the problem of interest, the nature of the problem, level of the problem, phase of the problem, problem complexity, structuredness, and dynamicity (Vencel and Cook, 2005, p.8). The importance of identification of the appropriate problem space also discussed in the literature by Stevens et al., (1998). Flood and Jackson (1991) also made a noteworthy contribution through the development of a systemic meta-methodology named as Total Systems Intervention (TSI). TSI directs the stakeholder through a systemic process to select the appropriate problem-solving procedure based on the context and situation of the problem, following through phases of creativity, choice, and implementation. To address the formulation of the problem, Ford (2010) proposed a framework that traces the difference between subjective and objective complexity and categorizes the problem by

- Level of difficulty of the problem. (Easy, medium, ugly, and hard)
- Structure of the problem. (well structured, ill-structured, wicked)

- Level of complexity of the problem. (Depends on the number of variables and the types of interdependency among the variables associated with the problem)

For more in-depth exploration of the problem-solving approach, interested readers are referred to study the nine-system model by Kasser et al. (2014), seven principles for systems engineering solution system developed by NASA and summarized by Hitchins (2007, p.85). Another stream of research during this period focused on investigating the similarities and dissimilarities between systems engineering and project management. In many cases, *systems engineering* and *project management* are considered to be different disciplines. Mooz and Forsburg (1997) recognized some significant reasons for this distinction:

- INCOSE expertise is concerned with technical solutions, whereas PMI consultants are oriented towards schedule and cost management. As a consequence, project managers are more concerned about managing cost and schedule without taking into account the technical aspect, while system specialists, who always pursue the superior feasible solutions, rarely address budget and schedule.
- The nomenclature and terminology of INCOSE and PMI are different.
- INCOSE and PMI work autonomously and rarely participate in each other's conferences. PMI members are seldom affiliated with INCOSE and vice versa.

Further discussion of the above arguments is illustrated by Roe (1995). He indicated that tech specialists observe the systems from the inside, and they are not concerned about other systems elements unless they affect their own design task. The project managers, on the other hand, consider the system from outside with a broader viewpoint acting as the advocate for the system. Project managers deal with all systems elements that would impact overall system performance/budget/schedule. They are also concerned about how to offset the constraints of system elements to ensure that projects reach their goals in an economical way within stipulated time limits. However, in reality, project management and systems engineering are not independent disciplines.

We have identified this interval as a "revolutionary interval," acknowledging that there was a significant generation of new concepts, approaches, frameworks, and formal organizations established with a view to disseminating the knowledge of SE. Several applied fields, such as the system of systems (SoS), and MBSE, also evolved during the revolutionary interval. These fields are especially pertinent to most engineering-governed approaches. The main contributions of the 1990-2017 timeline are shown in Figure 2.5.

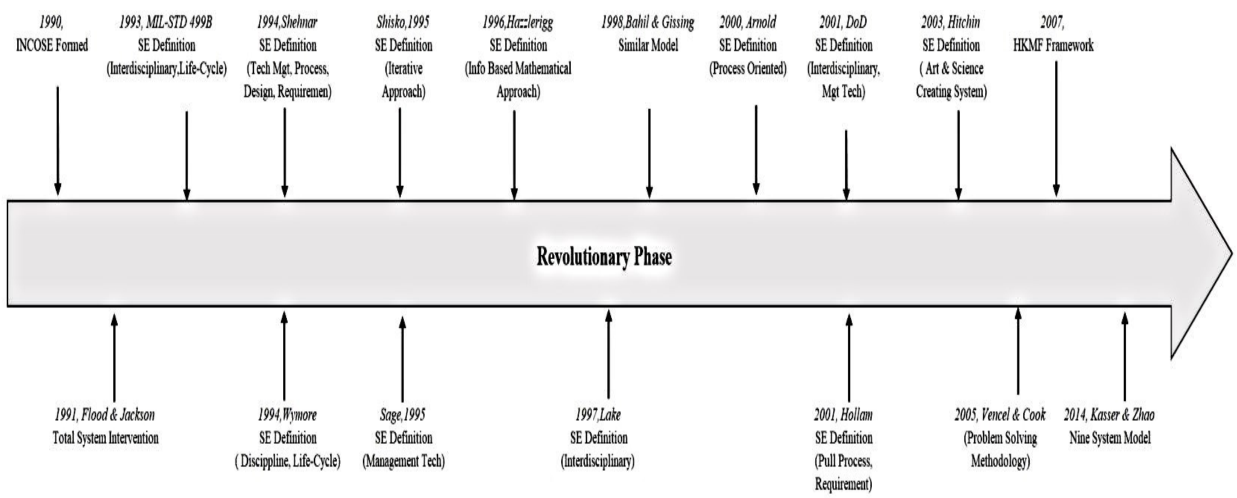


Figure 2.5 Main Contributions of 1990-2017 Timeline

The next section presents the histogram analysis of SE development through three main intervals, with each interval representing a particular stream in the development trajectory of SE. Following the histogram analysis, based on the Ground Theory Coding (GTC) approach, the main characteristics of SE are derived, which will be broadly discussed in chapter III (research and methods). The GTC application was comprised of three levels of coding: *open coding* (free form coding of ideas), *axial coding* (clustering of codes into a hierarchy of relationships), and *selective coding* (a reformulation of coding into higher-level core categories) to derive the central theme from the large unstructured dataset. It is also imperative to mention that we collected the frequency of the publication from “Scopus” database by inserting input as “systems engineering” in the search field and filtered the number of publications based on the timeline. Scopus database is more comprehensive than any other databases as others include only ISI indexed documents (Yong-Hak, 2013. The Scopus database covers almost twelve million different types of research documents from a variety of publication houses.

2.1.2.3.3 Histogram Analysis

Figure 2.6 shows the histogram analysis of SE. The horizontal axis in the histogram signifies the timeline of the study, and the vertical axis displays the frequency of publications pertaining to SE for that time period.

It is evident from the histogram analysis that the final interval (1990-2017) possesses the highest frequency and the highest cumulative value signifying that this interval experienced the peak of SE development. A larger number of presentations, conferences, journals, symposiums, and research work related to SE was published in this interval. One of the most significant events was the establishment of the International Council on Systems Engineering (INCOSE). INCOSE was founded in an effort to unite the research germane to diversified branches of SE under the same umbrella and to disseminate knowledge from the field of SE. Many universities and schools introduced systems engineering into their academic curriculum as well. There will be many future opportunities where the knowledge and information gained during this interval will be used to explore and solve various complex system challenges.

The (1961-1989) interval is identified as an exploratory interval. This interval is considered to be a transition from a discussion of fundamental theories to the development of real-world applications, tools, processes, and approaches. The advancement resulting from this interval set the foundation to support further development of systems engineering. The concept of SE became the focus of attention and achieved widespread acceptability across the world. The histogram shows that the frequency of publications increased in this interval compared to interval 1; even though there is some fluctuation, a strong growth trend is still apparent. The first interval (1926-1960) is recognized as the introductory interval of SE. In this interval, practitioners began thinking beyond the traditional engineering discipline to solve complex problems and moved towards more holistic and integrated approaches.

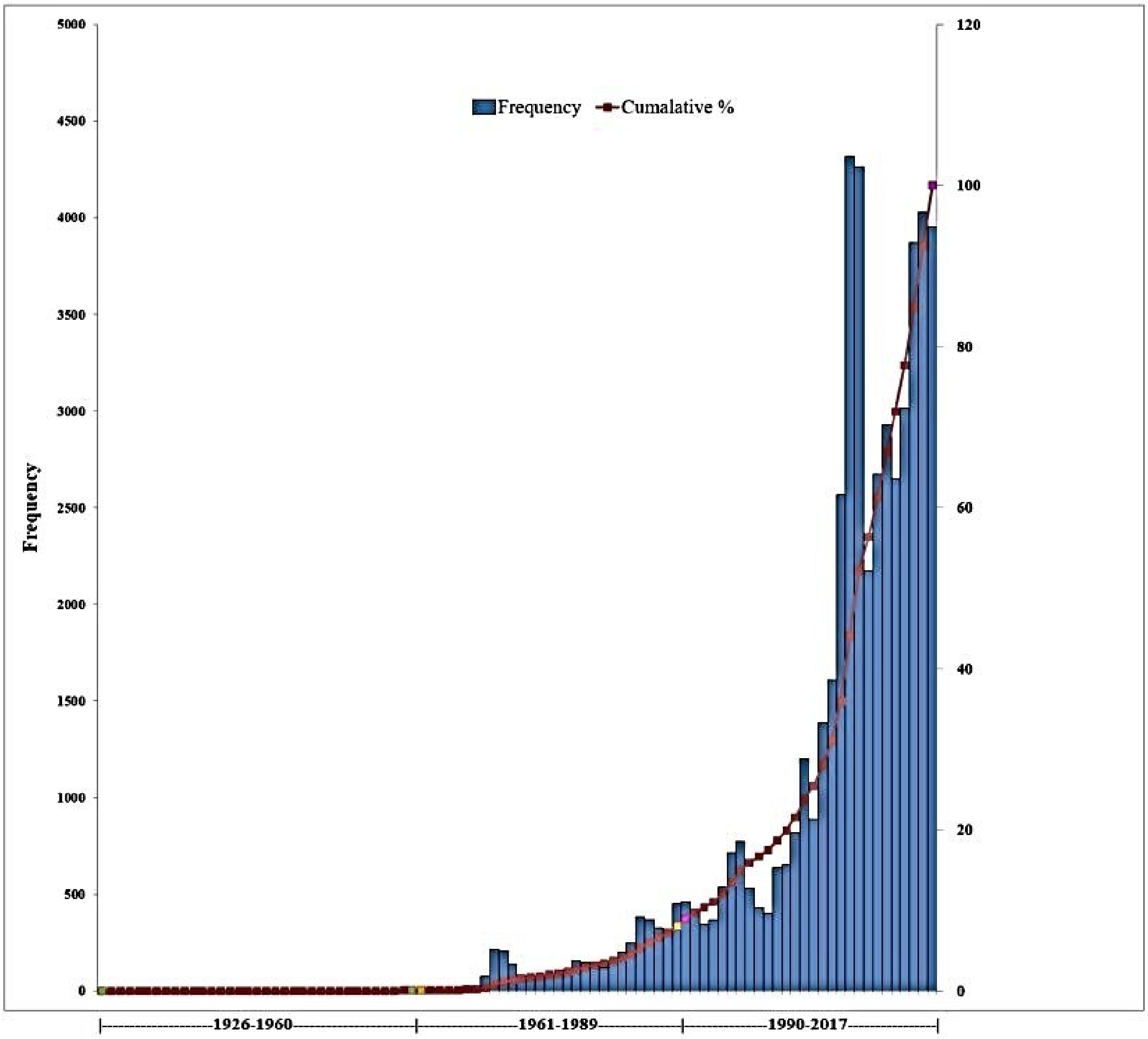


Figure 2.6 Histogram Analysis of SE (1926-2017)

2.1.2.3.4 Co-Citation Analysis

Co-citation analysis visualizes the relationships between sources/documents based on their citations (Barnett, 2004). This bibliographic coupling is conducted based on graph theory (Saukko, 2014). A co-citation map comprises of a set of nodes representing different research sources/documents (e.g., articles, conferences papers, letters, and technical reports) and a set of edges signifying the cooccurrence of nodes listed in different sources of the corresponding map

(Barnett, 2011). More precisely, co-cited sources/documents appear together in the reference lists of other documents (Fahimnia et al., 2015).

In order to perform co-citation analysis, a .NET file contained 278 sources was developed and imported into Gephi for the visual representation. The visual output didn't show any discernible pattern due to the random characteristics of the coordinate. To better represent the map, we further ran a Fort Atlas driven algorithm and adjust the values of repulsion strength, node size, gravity, speed, and other embedded graphical properties. Fort Atlas driven algorithm is well known for its clear and legible graphical output. Figure 2.7 depicts the Force Atlas layout of the co-citation map of 278 nodes. The co-cited articles are linked with each other, while the poorly connected nodes deviate from the center and move toward the periphery (Mishra et al., 2017).

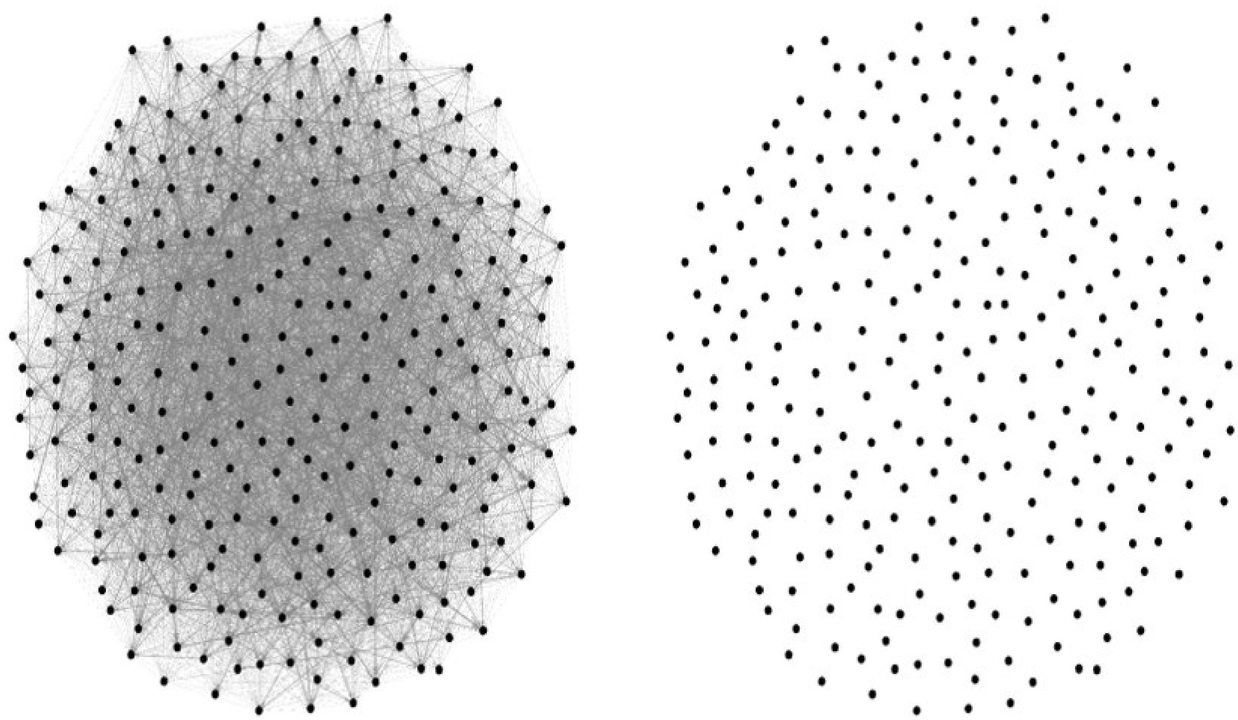


Figure 2.7 The Force Atlas Layout of the 278-node Network

2.1.2.3.5 Data Clustering: Literature Classification

The nodes in the map can be further clustered by using the data clustering technique. Data clustering technique is conducted based on modularity tool in Gephi, that groups the same kind of articles with respect to interrelation and collaboration pattern (Radicchi et al., 2004; Mishra et al., 2017). The foundation of the modularity tool is anchored in the Louvain algorithm. The modularity index of a partition ranges from -1 to +1, which illustrates the density of the links between clusters and inside the clusters (Fahimnia et al., 2015). The equation for measuring modularity index is streamlined in the following equation (Fahimnia et al., 2015).

$$Z = \frac{1}{2n}\sum\left[X_{ab} - \frac{p_a p_b}{2n}\right]\delta(r_a, r_b) \tag{2.1}$$

where X_{ab} signifies the weight of the edge between nodes a and b. p_a represents the sum of the weights of the edges attached to node a ($p_i = {}^{\mathrm{P}}{}_b\, X_{ab}$), r_a is the cluster community to where vertex a is assigned. $\delta(r_a,r_b)$ is equal to 1 if $s = t$ and 0; otherwise$n = \frac{1}{2}\sum_{ab} X_{ab}$. After running the algorithm for 278-network nodes, three major clusters were identified, as reported in Figure 8.

The description of each cluster provided in Table 2.1

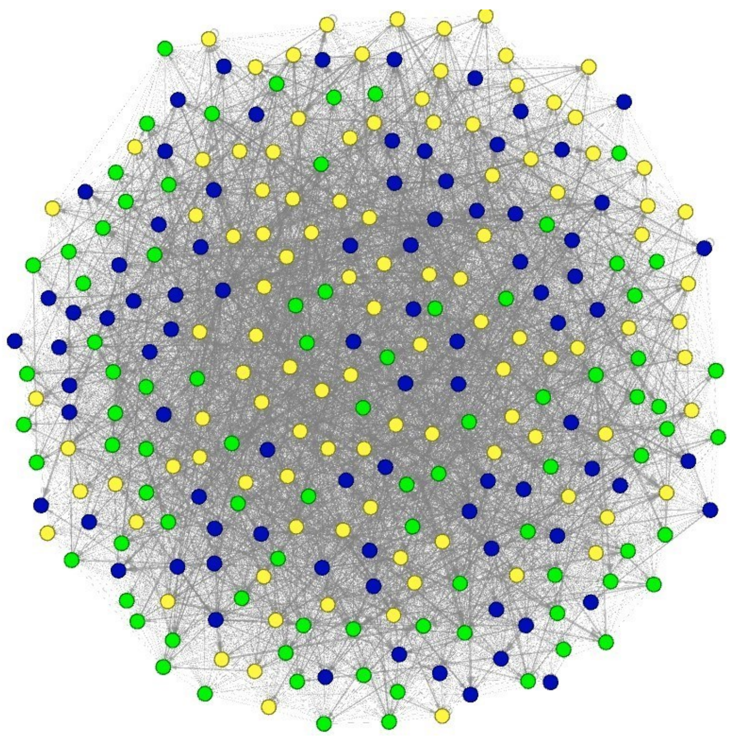


Figure 2.8 Structure of the Network with Three Clusters

Table 2.1 Three Major Clusters and their Area of Research

Cluster	Area of research
Cluster 1 (yellow circle)	SE theory, axioms, and conceptual studies
Cluster 2 (green circle)	SE methodologies, processes, and policies
Cluster 3 (blue circle)	SE application and implementation

2.1.2.3.6 Other Analysis

Scopus is a well-recognized database (Scopus, 2017). The application of SE in each discipline is depicted by the bar chart in Figure 2.9. It is apparent from the figure that SE has the widest application in the engineering discipline, followed by computer science and mathematics. The length of each bar represents the number of publications which appeared in 1926-2017. The bar chart's total percentage value is above 100 percent because, in some cases, the same publication may belong to different disciplines. The 41 definitions from 1926-2017 were also analyzed using Qiqqa (2017) – a tool to generate a fit model that connects the common themes based on the coding analysis. Figure 2.10 shows the interconnectivity between the generated eight common themes and the pertinent definitions stated by several researchers.

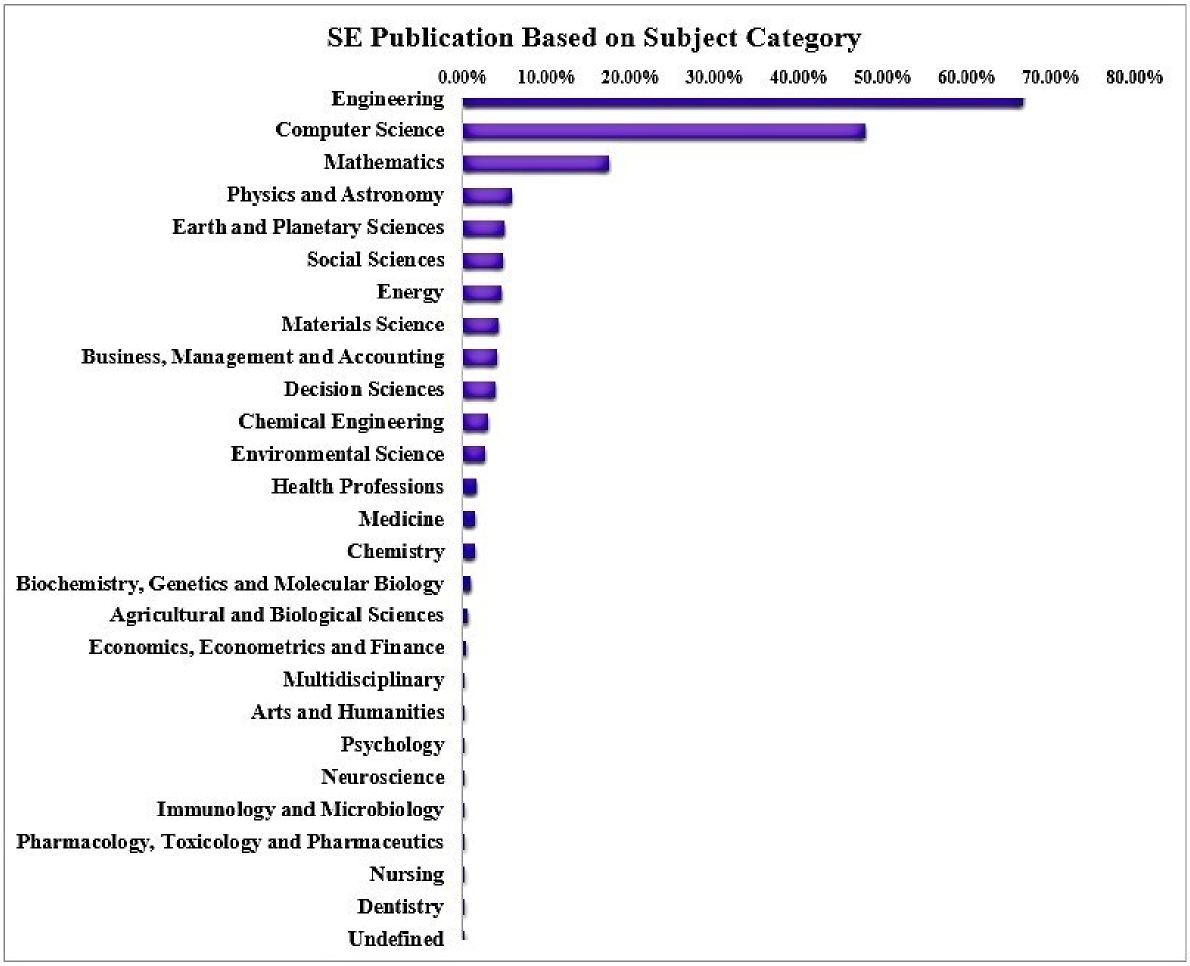


Figure 2.9 Discipline Wise SE Publications

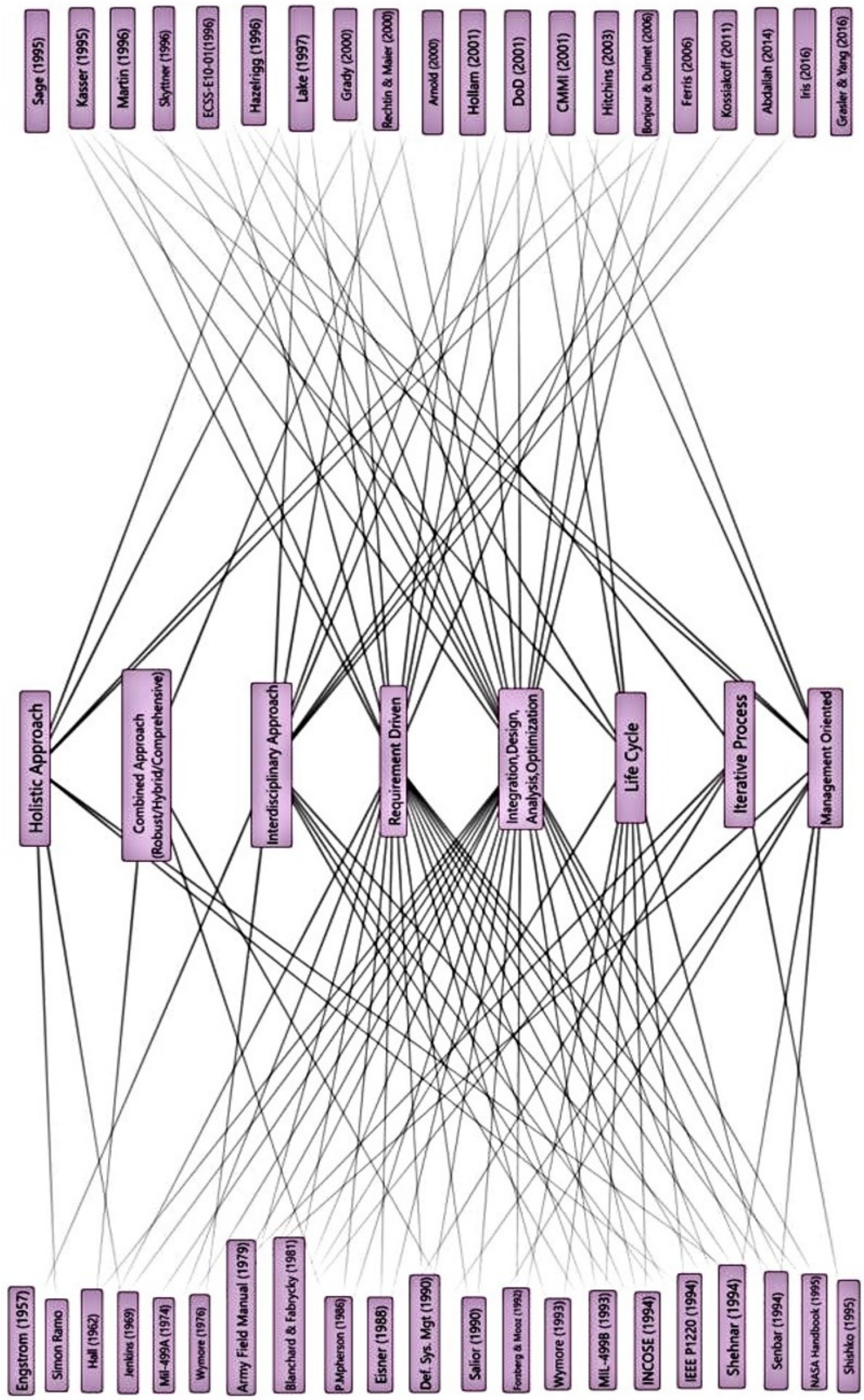


Figure 2.10 Common Themes of SE Definitions

2.2 Roles of Systems Engineer

During the Helix Project in 2013-2015, extensive interviews were conducted with systems engineers who nearly all noted that SE had only been defined as a separate discipline for the previous 15-20 years, though its functions had been performed for much longer (Pyster et al., 2014). The systems engineers participating in this study were largely members of the Department of Defense and Defense Industrial Base community, where SE has been most prevalent due to the complexity of systems involved in projects. SE functions and system engineers' roles within other organizations have generally been less clearly defined for an even shorter time, owing to the lack of consensus about what they entail. Sheard, 1996 noted that "No two authors have the same definition of what roles systems engineers have." Engineers, organizations, and researchers over the past 60 plus years have contributed to a continually evolving understanding and practice of SE (Souza et al., 2009). Because of the recognition of SE as a critical role in the future of the fast-growing hi-tech organizations, this confusion has been addressed from different perspectives in the literature by several authors.

Considering SE through the education paradigm, Shenhar, 1994 describes it as a "multidisciplinary function of design element integration." The research was conducted through interviews with project managers, experienced systems engineers, and engineering managers to aid in the design of academic curricula in SE. Common themes, such as inconsistencies in definitions and systems engineers' roles being holistic in nature, are identified and addressed. The author notes a distinction on the latter point that a holistic view is "multidisciplinary in nature, rather than disciplinary or interdisciplinary (Shenhar, 1994)".

The roles of program managers and systems engineers are discussed as being closely related to the point of being components of a single career, potentially resulting in executive positions in large laboratories and systems institutions. Acknowledging this fact leads to defining the roles of systems engineers as both technical and managerial, eventually defining SE management as the application of scientific, engineering, and managerial efforts towards the following sequence of activities: *identify operational need* > *transform into system description* > *integrate technical parameters and components* > *integrate factors into total engineering effort* > *validate with clients.*

Shenhar's analysis identified the systems engineer's need for close customer contact in operational need identification and system validation. This need is present in the systems engineer's role as *need identifier and system marketeer*. With this as the first role outlined in the paper, the second is *architect and chief conceptual designer.* This role integrates a manager's leadership component into a high-level system conceptualization combining customer and system requirements with system configuration. The third role is *integrator* in which the systems engineer coordinates the interdisciplinary input of various engineers and team members and evaluates overall system performance and feasibility. Role number four is *analyst and data processor*. This role mandates the collection of a wide variety of data to be used in decision making. *Problem-solving and decision-maker* is role number five. With complex systems comes the need for compromises and resolution of conflicts that arise from disparate interests involved in system creation (Nur et al., 2016; 2020c). The sixth and final role described by Shenhar (1994) is that of manager and administrator, in which the systems engineer must leverage excellent interpersonal skills to elicit the performance and requisite work products from system contributors.

In another study, Roe (1995) considered SE from the perspective of the project manager. This perspective arises from the counterintuitive, sometimes view that the project manager impedes the systems engineering process and is, therefore, to be avoided or overcome in pursuit of project completion. This view may be the product of the friction between the "hyper-focused" reductionist concerns of specialist engineers and the generalist systems perspective concerns of the project manager. The deep subject knowledge of the engineering specialist is needed for individual component performance; however, in the interest of delivering a balanced system, the project manager must integrate components into the whole.

Being a more ubiquitous position than systems engineers, especially outside the defense and aerospace industries, project managers may perform SE activities as they work to build cooperation and inherently have a whole-enterprise view. Roe, 1995 noted that "SE provides the technical glue that makes separate design disciplines and subsystems function together," that it bridges system development implementation and validation. The author goes on to note that while the project manager may perform SE activities in lieu of the systems engineer position being filled, the two positions often exist simultaneously. In this case, it is important to understand the distinction. Here it is noted that the two have similar technical knowledge breadth, that the systems engineer has substantially more technical knowledge depth, and the project manager has substantially more management expertise. This distinction suggests the development of an interdependent relationship where the responsibilities of the two roles overlap. Requirement engineering verification and validation engineering would fall under project management, while system design and technical management would fall under SE (see Table 2.2 for role descriptions).

Further research widened the scope of SE roles to encompass, for example, those ascribed to the project manager by Roe (1995). Six years after the founding of INCOSE, Sheard (1996) produced a paper proposing a set of SE roles based on a review of the content of *Systems Engineering*, the Journal of INCOSE inaugural issue, and the *Washington Post* newspaper's "High Tech" classified advertisement section. The author explored questions such as whether systems engineers are specialists or generalists, whether SE might be a set of life-cycle roles or a program management discipline, and even whether it is a discipline or simply an attitude. The latter question addresses the issue of whether a systems engineer must be trained and appointed as such or if any engineer performing SE activities is a system engineer.

Sheard's research produced a set of 12 roles filled by systems engineers. These roles were later adopted and supplemented by Pyster et al. (2014). The full list can be seen in Table 2.2. The twelfth role on the initial list was "classified ads" system engineer as a result of being a "catch-all" for a wide variety of computer systems-related roles listed in the aforementioned newspaper classified section. The author posits this "…May have developed from the need for programmers to adopt broader viewpoints, first as software engineers and later looking at whole computer systems" (Sheard, 1996). Regardless of the source, this further illustrates the depth of confusion surrounding the roles of systems engineers.

Table 2.2 Roles of Systems Engineers (Pyster et al., 2014)

	Role	Description
1	Requirements Owner	Individual responsible for translating customer requirements to system or sub-system requirements; or for developing the functional architecture.
2	System Designer	Individual responsible for owning or architecting the system; common titles may include chief systems engineer or systems architect.
3	System Analyst	Individual who provides modeling or analysis support to system development activities and helps to ensure that the system as designed meets the specification.
4	Verification & Validation Engineer	Individual who plans and conducts verification and validation activities such as testing, demonstration, and simulation.

Table 2.2 (continued) Roles of Systems Engineers (Pyster et al., 2014)

	Role	Description
5	Logistics/Operations Engineer	Individual who performs the 'back end' of the SE lifecycle, who may operate the system, provide support during operation, provide guidance on maintenance, or help with disposal.
6	Glue Among Subsystems	Individual who is responsible for a holistic perspective of the system; this may be the 'technical conscience' or 'seeker of issues that fall in the cracks' – particularly, someone who is concerned with interfaces.
7	Customer Interface	Individual who is responsible for coordinating with the customer, particularly for ensuring that the customer understands technical detail and that a customer's desires are, in turn, communicated to the technical team.
8	Technical Manager	Individual who is responsible for controlling cost, schedule, and resources for the technical aspects of a system; often someone who works in coordination with an overall project or program manager.
9	Information Manager	Individual who is responsible for the flow of information in a system development activity; specific activities may include configuration management, data management, or metrics.
10	Process Engineer	Individual who is responsible for the systems engineering process as a whole, who also likely has direct ties into the business.
11	Coordinator	Individual who is responsible for coordination amongst a broad set of individuals or groups who help to resolve systems related issues.
12	Systems Engineering Evangelist	Individual who promotes the value of systems engineering to individuals outside of the SE community - to project managers, other engineers, or management.
13	Detailed Designer	Individual who provides technical designs that match the system architecture; an individual contributor in any engineering discipline who provides part of the design for the overall system.

Table 2.2 (continued) Roles of Systems Engineers (Pyster et al., 2014)

	Role	Description
14	Organizational/Functional Manager	Individual who is responsible for the personnel management of systems engineers or other technical personnel in a business – not a project or program – setting.
15	Instructor/Teacher	Individual who is responsible for providing or overseeing instruction of SE discipline, practices, processes, etc.
16	Program/Project Manager	Individual who performs program or project management activities, who is not directly responsible for the technical content of a program,but works closely with technical experts and other systems engineers.

Roles 1-11 from (Sheard, 1996)

Roles 13, 14, and 16 from Helix (Pyster et al., 2014)

Roles 12 and 15 (Sheard, 2000)

As the SE roles have become more clearly defined, other research delved into abstract questions such as what sort of individual will excel in these roles and if this indicates predisposition or if such traits can be instilled through education and experience. One such research was conducted by Frank (2000). The three-stage method, because of this research's presence in two other referenced works in this literature review, is described here in detail.

1. Pilot study: 11 in-depth, open, non-structured interviews were held with key figures in the Israeli hi-tech industry
2. Observer-as-participant, on-site observations in two hi-tech companies, 17 semi-structured interviews, and content analysis of 14 SE related lectures
3. Survey—pilot questionnaire (N=31) and final questionnaire (N=276)

According to Frank (2000), "The method by which a complex problem is dismantled to components allegedly facilitates handling complex assignments and questions, but when doing so, we lose the perception of the larger whole." Engineering systems thinking is the term ascribed to the trait that enables an engineer to perceive and manage the whole; therefore, succeeding as a system engineer.

Frank's study began with no hypothesis and no definition of systems thinking, but rather the assumptions that senior systems engineers possess systems thinking capability and supervisors' opinions are a valid information source. Hypotheses as to the definition of systems thinking were built and updated based on these assumptions through content analysis (i.e. defining categories based on repeated elements and examination of frequencies).

The research resulted in eighty-three categories that break down as follows: 10 categories refer to the definition of engineering systems thinking. Four categories deal with various types of systems thinking. Fifteen categories related to the knowledge required by systems engineers. Thirty-one categories cover the skills demanded of systems engineers. Fifteen categories explore personal aptitudes demanded from systems engineers. Eight categories examine processes by which the system thinking capability is developed. These results, while significant, do little to offer a concise, clear understanding of engineering systems thinking.

To further this research, Frank (2006) combined his previous work on engineering systems thinking with two more studies to develop the idea of *capacity for engineering systems thinking* (CEST), which consists of the knowledge, abilities, cognitive characteristics, and personal traits of successful systems engineers. The second study consisted of interviews with and observations of mechanical engineering students and teachers in a "creative intro to mechanical engineering" course. The third study was a second phase of the original study in which the survey questionnaire was delivered as an interview to 46 systems engineers.

Employing triangulation in the analysis, this research resulted in a refined list of 31 interconnected and interrelated abilities, characteristics, and traits that accompany high CEST. To illustrate the relative characteristic, the author references two items from the list: “not getting stuck on details” and “ambiguity tolerance” which are related in that a lack of details may create ambiguity. Other items from the list include “understanding the whole system,” “thinking creatively,” “requirements analysis,” “using simulations and systems engineering tools,” “management skills,” and “ask good questions.”

The significance of the study lies in the conclusion that CEST may be acquired or developed through relevant SE experience (e.g. job rotation, training, systems work roles) over the long-term in the career of a systems engineer. It is, however, noted that this may not necessarily be the case in that the author found instances of veteran engineers who never attained CEST, suggesting that “talent” may be a factor. In conclusion, Frank (2006) acknowledges the lack of a quantitative tool for assessing CEST and the need for its development.

Frank (2006) was once again employed as the first study in a combined study of three works; this time in Frampton et al., (2007) where a list of cognitive characteristics, aptitudes, personality traits, and experiences of successful systems professionals operating in different organizational and national cultures was developed. The three studies are conducted in different parts of the world: USA, Australia, and Israel. This large dataset brings diversity to the study and suggests the characteristics of successful systems engineers are global constants rather than regional variables.

The second study, conducted in Australia, analyzes interviews of IT architects with a minimum of five years' experience selected for their involvement in highly regarded, sufficiently large-scope projects. The research questions in the second study were as follows: *What do IT architects think makes them and other IT architects good at their job? What do IT architects look for when choosing to train and hire other IT architects?* The third study, which serves as a contrast to the preceding two, focuses on whole brain thinking and its effects on the performance of systems professionals. The author describes the research method as "…a process of truth estimation in the face of incomplete knowledge which blends information known from experience with plausible conjecture" (Frampton et al., 2007). In other words, the relevant information is extracted from literature reviews, colloquia, and personal experience.

Triangulation was used to analyze the results of all three studies and determine the most significant characteristics. The authors note the asymmetry of some portions of the three studies as challenging, not overwhelming. Multiple passes were made through results until consensus could be reached between all three authors, generating a combined list of 38 characteristics of successful systems engineers, systems architects, and IT architects. As other authors have noted, it is unlikely that a single person will possess all 38 characteristics. Given that a systems engineer is likely to possess a portion of the identified characteristics and be employed based on such, command of a portion of the list is sufficient in being considered "successful." The list is shown in Table 2.3. The authors note that this list is not necessarily comprehensive, nor does it indicate which characteristics are "necessary" or if excess amounts of one may compensate for lacking another.

Table 2.3 38 characteristics of successful systems engineers, systems architects and IT architects (Frampton et al., 2007)

1	Understanding the whole system and seeing the big picture	20	Management skills
2	Understanding interconnections	21	Building and controlling the work plan
3	Thinking creatively	22	Defining boundaries
4	Understanding systems without getting stuck on details	23	Taking in consideration non-engineering factors
5	Understanding and seeing implications of proposed changes to the system	24	Good human relations
6	Understanding a new system/idea/concept immediately upon presentation	25	Autonomous and independent learner
7	Understanding analogies and parallelisms between systems	26	Curious, innovator, initiator, promoter, originator
8	Understanding systems synergy	27	Willing to deal with systems
9	Understanding the system from multiple perspectives	28	See failures not as "the end of the road"
10	Analyzing the need	29	Integrity
11	Analyzing and/or developing the concept of operations	30	Self confidence
12	Requirement analysis	31	Discipline
13	Generating the logical solution functional analysis	32	Analytical
14	Generating the physical solution	33	Outgoing/extrovert
15	"seeing" the future	34	Interdisciplinary knowledge
16	Using simulation and SE tools	35	Conceptualizing the solution
17	Optimizing	36	Ask good questions
18	Using systems design considerations	37	Broad experience
19	Conducting trade studies and providing several alternatives	38	Education

In 2007 NASA's Jet Propulsion Laboratory (JPL) published a paper detailing both the importance of systems engineers to NASA missions and the criteria by which they could be hired and cultivate their SE workforce (Jansma & Derro, 2007). In what the authors describe as a competency model, three axes, including Technical Knowledge, Process Knowledge, and Personal Behaviors, are presented for the measurement of systems engineer performance.

The Technical Knowledge Axis is demonstrated by engineers with an appreciation for and grasp of the technical details of systems engineering at all levels. They have a wide breadth of technical understanding with the deep knowledge of a specialist in one or two relevant product domains.

The Process Knowledge Axis encompasses ten SE functions as follows in Table 2.4.

Table 2.4 The Process Knowledge Axis of Systems Engineers

Life-Cycle Dependent Activities	**Management and Oversight Activities**
1.Develop System Architecture	1.Conduct Technical Reviews
2.Develop and Maintain Requirements	2.Manage Technical Resources
3.Develop and Maintain Interfaces	3.Participate in Risk Management
4.Analyze and Characterize the Design	4.Manage and Control the Design
5.Verify and Validate	5.Manage the SE Task

The Personal Behavior Axis was defined by a trained psychological and organizational behavior professional, observing nine highly regarded systems engineers. Information gathered during the observation was analyzed to isolate common themes. The resulting behavior list is shown below in Table 2.5.

Table 2.5 The Behavioral Axis of Systems Engineers

1. *Leadership Skills*	2. *Attitudes and Attributes*
a. Ability to influence b. Ability to work with a team c. Ability to trust others d. Communicates vision and technical steps needed to reach implementation e. Mentors and coaches less experienced systems engineers	a. Intellectual self-confidence b. Intellectual curiosity c. Ability to manage change d. Remains objective and maintains a healthy skepticism
3. Communication	**4. Problem Solving and Systems Thinking**
a. Advances ideas and fosters open two-way discussions b. Communicates through storytelling and analogies c. Listens and translates information	a. Manages risk b. Thinks critically and penetrates a topic in a methodical manner

The development of NASA missions is one of the most severely complex system environments faced by organizations today. Owing to this fact, NASA researchers have produced several papers in the pursuit of a better understanding of SE and better programs for the development of systems engineers. In another such example, Bay et al. (2009) admitting a "common understanding of systems engineering [is needed]" describes SE as being both an art and a science. The authors relate the art aspect to technical leadership or life cycle-spanning management of the system's technical aspects and integrity. This idea is elaborated to include a mix of "broad technical domain knowledge, engineering instinct, problem-solving, creativity, leadership, and communication (Bay et al., 2009)".

Systems management, related to the science of SE, is noted to be more concerned with efficient system development and operation. NASA Systems Engineering and Integration Manager Chris Hardcastle describes his job as being to "bring order from chaos." In addition to great complexity, NASA systems life cycles have the potential to span decades, thus requiring the systems engineer to appropriately manage extensive technical documentation for his or her successor.

The specific roles described by Bay et al. (2009) are divided into three system life cycle phases: concept, development, and operations. While working within each phase, the system engineer's roles change to fit the specific needs. The concept phase entails systems architecture and design as well as planning for the operation. Validation and verification are emphasized in the development phase as the systems engineer works to ensure the technical requirements are met and carried into system operation in the final phase. This is when the systems engineer's role changes to focus on mission success.

Another NASA SE study conducted by Lumpkin (2009) at Kennedy Space Center centered on five systems engineers being interviewed and observed to ascertain the behaviors and attributes that make them successful. The interview questions in three groups—context, relation to self and personal awareness, and the future of systems engineering—were asked in an initial and follow-up interview. The resulting five behaviors were validated by the interviewees and mirror the Personal Behavior Axis of the JPL results to which it adds *Technical Acumen.* This dimension of technical competence and diverse experience is accounted for in the JPL paper under the Technical Knowledge Axis.

The final NASA study addressed in this literature review builds on the previous three. In this study, Derro and Williams (2009) examine the behaviors of some of the agency's top-performing systems engineers. Each of these individuals was identified as being a "go to person." In total, 38 systems engineers were identified, interviewed, and shadowed by other NASA personnel with backgrounds in either engineering, psychology, organizational behavior, human resources, or training development.

The previously developed three-axis SE competency model is employed to guide the study. The findings are thus similar to those of Jansma and Derro (2007), emphasizing the personal behaviors axis. The authors claim this is “where maximum leverage is gained…[what] separates the merely good SEs from the highly successful SEs.” These personal behaviors are divided into the same five themes as in Lumpkin 92009). The component competencies: however, are either slightly different or unique as the list is expanded from containing 21 to 40.

Another perspective of systems engineer success is produced in a paper investigating the relationship between years of experience and proficiency in SE tasks (Souza et al., 2009). In what the authors describe as “a discipline that applies holism to understand and solve problems,” there are components, referred to as artifacts, of education and experience that contribute to the maturation of each systems engineer. The authors compile through triangulation qualitative data on the various artifacts from interviews, relevant literature, and job listings. A Fuzzy Logic model is used in the comparison of system engineer traits with years of experience and annual salaries.

This paper produces two exponential learning curves that plot three different SE skills against time. The first curve represents requirements analysis and project management skills; the second, cost management skills revealing a doubling in effectiveness with system engineers experienced from 10 to 15 years. Several other SE roles are mentioned and displayed in a SE career maturity model that places, for example, specialist skills on the low end, quality management, mentoring and simulation in the middle, and analysis, system evaluation, and cost management on the high end. It is also noteworthy that oral and written communication skills span the entire model suggesting that while they are present in the early career of the systems engineer, they are developed and strengthened over time (Souza et al., 2009).

Intentionally disregarding the time aspect of competency development, Kasser and Frank (2010) create a model that focuses instead on maturity levels. This work is noteworthy for an attempt to aggregate the skills, traits, behaviors, and knowledge identified in the preceding literature. The authors note, "…the lesson learned from behavioral psychology indicates that the production of a long list is an important and necessary intermediate stage in the process, but once developed, the list should be aggregated to some small set of common generic characteristics" (Kasser & Frank, 2010). Many of the works discussed in this literature review are included and compiled into what the authors simply describe as "knowledge," though it features knowledge, cognitive characteristics, and individual traits.

With "knowledge" in the vertical dimension and five "types" of systems engineers along the horizontal dimension, it may be seen in the model what is required for a systems engineer to exist at each suggested level of competency maturity. For each category, individual traits are binary yes/no, while knowledge and cognitive characteristics categories feature a tertiary descriptor set. These are as follows:

- Declarative – knowledge that can be told
- Procedural – knowledge that must be demonstrated
- Conditional – knowing when and why to employ declarative and/or procedural knowledge

As with many other SE inquiries, (Kasser & Frank, 2010) consider how a systems engineer behaves, thinks, and acts. The authors say little directly about what a systems engineer *does* in terms of roles within an organization. Inferences about these roles may be made by considering what the authors write about pairs of knowledge, traits, and characteristics. Noting system engineers have a SE knowledge commensurate to their level of domain-specific engineering knowledge combined with a management trait, and it is, therefore, reasonable to conclude the role of technical manager would be appropriate.

In some instances, systems engineers may perform roles that require opposing paradigms. This is described in a paper discussing the challenges faced by systems engineers where the authors consider the roles of configuration manager and system designer (Sousa-Poza et al., 2014). In this example, the configuration manager is responsible for integrating the work of specialist engineers in a manner conducive to system realization. This role requires a macro view that is inherently unconcerned with specific system details. The system designer, in contrast, is responsible for details down to the component level. The authors list several examples of the challenges that arise from the ever-increasing complexities of modern systems to illuminate the necessity that SE satisfies a micro/macro dual functionality (Sousa-Poza et al., 2014). Author role mapping is illustrated in the following Table 2.6.

Table 2.6 Author-Role Mapping Table

	Systems Engineering Roles from Helix Report															
Paper	Requirements Owner	System Designer	System Analyst	Verification & Validation Engineer	Logistics/Operations Engineer	Glue Among Subsystems	Customer Interface	Technical Manager	Information Manager	Process Engineer	Coordinator	Systems Engineering Evangelist	Detailed Designer	Organizational/Functional Manager	Instructor Teacher	Program/Project Manager
1 Pyster 2014	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
2 Shenhar 1994	x	x	x		x	x	x	x	x					x		x
3 Roe 1995	x	x	x			x	x				x			x		x
4 Sheard 1996	x	x	x	x	x	x	x	x	x	x	x					
5 Frank 2000	x	x	x		x	x		x								x
6 Frank 2006	x	x	x	x		x		x	x		x					x
7 Frampton 2007	x	x	x		x	x	x	x	x	x	x	x	x			x
8 Jansma & Derro 2007	x	x	x	x			x	x	x	x	x		x		x	x
9 Kasser 2007	x	x		x	x			x	x	x	x			x		x
10 Lumpkin 2009													x		x	
11 Bay 2009	x	x	x	x		x		x		x			x		x	
12 Derro 2009	x	x	x	x		x	x	x	x	x	x	x	x		x	x
13 Souza 2009	x	x	x	x		x	x				x		x	x		x
14 Kasser 2010		x					x	x					x			
15 Sousa-Poza 2014		x				x					x		x			

Atlas: The Theory of Effective Systems Engineers (Pyster et al., 2014) was mentioned briefly at the beginning of this literature review. This report, being one of the most rigorous and comprehensive recent investigations into nature or SE and systems engineers, is used as the basis of comparison for the other works. In the Atlas report, a grounded theory-based approach is used to aggregate similar information in relevant data sources and produce 16 roles commonly performed by systems engineers (see Table 2.6).

2.3 Performance Measurement System Tools

Several studies (e.g., Chenhall, 2005; Kaplan and Norton, 1996; Epstein and Manzoni, 1998; Lynch and Cross, 1992) used comprehensive performance measurement systems to better understand all aspects of an organization's value chain and to connect these measures to the strategy to make the organization stronger. These studies used different performance measures tools, including the balanced scorecard, Tableau de bord, and performance hierarchies, to evaluate firms' performance. For example, the balanced scorecard is an accepted performance measurement system that uses various perspectives such as financial, customer, internal business, and innovation and learning perspectives to show a holistic view of an organization's performance (Kaplan & Norton, 2001; Kennerley & Neely, 2002). As Pun and White (2005) mentioned, a performance measurement system "must link to the achievement of strategy via (1) greater focus on creating stakeholder value; (2) the vogue for moving away from functional management and towards business process management; (3) delighting the stakeholder and motivating people; and (4) making improvements and innovations to services and products." (p.67). Additionally, Hall's (2008) study was one of the initial works that investigated the behavioral outcome of a comprehensive performance measurement system on managerial performance based on empirical studies. He concluded that a "comprehensive performance measurement system influences managers' cognition and motivation, which, in turn, influence managerial performance" (p. 141). Gregory (2007) highlighted the importance of a systemic approach to performance measurement systems, especially with respect to the performance of interaction of systems' components because the behavior of a system is a result of interaction between its components, not solely its components. In sum, all the aforementioned studies indicated that a holistic performance measurement system is needed to capture the actual behavior of a system and the role of individuals in complex systems within larger organizations. Although there is a wide gamut of theoretical and empirical studies focused on the analysis and characterization of performance measurement systems tools, there is scant research that has attempted to quantify the performance of individual systems engineers based on a unique set of determinants. To address this gap, this instrument assesses the skill of systems engineering based on the set of performance measurement indicators of fundamental SE attributes.

2.4 Defects of Systems Engineering

In systems engineering, it is critical to identify and eliminate defects from a system as soon as they are identified in order to reduce the cost of both acquiring and maintaining these systems. For systems engineering, there are eight clearly defined defects that can be infecting a system. These deadly defects are derived by Kasser (2007) and are discussed below:

The first is the selection of independent alternative solutions. Essentially this problem comes down to an assumption that one of the solutions that is presented is in fact, the optimal solution. In reality, this is not the case always, as design teams will consistently have varying strengths and weaknesses, so certain aspects of the system design will be stronger than others. So, if three choices are to be considered and one has the most efficient time out of the three, it is not the case that the most efficient of the three is the most efficient possible. This problem at its core is an example of the psychological factor of confirmation bias.

The second defect is the V-Model lacks a feed-forward or prevention component. The V-Model only takes in one view of systems engineering and so it can be quite limiting in its testing and evaluation in the several steps of the System Development Lifecycle. There is no section of the V-Model that incorporates the prevention of defects. In order to better use the V-Model, it needs to be changed in order to account for the explicit addition of preventing defects.

The third is the lack of a standard process for planning a project. Although systems engineering itself is typically described as a process, there is no standard way for conducting the planning phase of a task. To correct this, a standard flow must be established. For example, once the task is started, a single “architect” identifies the goals and resource limitations.

The fourth is the abandonment of the Waterfall model. Overall, it has been well established that the waterfall method is a failure due to the need for iterative development cycles. This could not be bad if the requirements remained static throughout the product development. However, due to the lengthy development time requirements often changed before development was completed. This left room for the spiral model to fill the new gap that had been created. The spiral model works similarly to the waterfall model except for the fact that it places emphasis on risk management. Unfortunately, the spiral does not delve deep enough and therefore is limited in its ability to enact quality change on the system.

The fifth is unanswered and unasked questions. The two major questions to consider are, what is the exact percentage of completion of the system currently, and what is the probability it will be completed on time and on budget. Due to the uncertain nature of these questions, they are impossible for the systems engineer to answer fully and accurately.

The sixth is a lack of measurements for the goodness of requirements. The issue of requirements is critical for a system to be able to get off the ground and be implemented. However, not all requirements are necessarily impactful for the quality of the system or for the system to reach its desired outcome. These requirements must be identified and removed in order for smoother creation and implementation of the system. Without a metric to directly measure these systems, it is a process that must be done carefully and thoroughly.

The seventh defect is a focus on technology solutions. Typically, systems engineers gravitate towards technology changes as a way to create solutions in problematic systems. This unfortunately, does not always prove to be an effective case. By not addressing the real problem, more optimal solutions are passed over as it is not considered a "modern" method for solving the problem.

The eighth and final defect is there is a strong need to focus on people as well as the process. When focusing on the creation of a system, what is often overlooked is the quality of the people who are both managing and creating the system. This leads to issues such as not placing people in the roles in which they would succeed, which can cause the system to suffer due to a lack of skills being properly utilized.

2.5 Limitations of Systems Engineering

Although systems engineering can be used in a multitude of situations, there are still three major shortcomings. These need to be identified in order to ensure that the systems engineer is not attempting a task that cannot be properly addressed through systems engineering.

The first limitation is the traditional tools that lay the foundation for systems engineering have not been optimized to solve complex systems problems at a high level when they come with a great deal of uncertainty (Keating & Katina, 2011). These traditional tools cannot adapt to dynamic requirements or problems that are inadequately structured. When looking to the future, this limitation becomes more of a problem as it would be foolish to think that problems and requirements of systems will not become more dynamic.

The second problem is that the context of problems solved with engineering are not put in the forefront of decision making and tend to be in the background when it comes to developing, analyzing, and implementing the systems. As systems have evolved and will continue to evolve, there has been a trend in the increasing amount in which the problem context has become integral in providing a quality solution to the given problem. This is due to the context of the problem creating further constraints that need to be fulfilled by the developed system in order to provide proper success (Keating & Katina, 2011).

The third and final problem is the increase in demand to deploy advanced systems that offer partial or incomplete solutions to certain problems. The need for these types of solutions has been due to limitations of resources (such as technology constraints) or constraints due to deadlines. Traditionally systems engineering has been able to consistently provide positive results when providing a complete solution after rigorous planning, developing, and implementing; however, this process cannot always be completed to the fullest (Keating & Katina, 2011).

Due to modern-day challenges, it has become imperative that systems be deployed at an incomplete state and then iterated upon after it has already been deployed. Moving in this direction is very different from the traditional linear approach to system design but could remove this limitation in the future.

Traditionally systems engineering has been structured around solving singular systems problems. The entire process from development to implementation is conducted to fit a specific need or problem. Through focusing more on creating a metasystem, a system of systems would allow for there to be more flexibility in solving problems that do not necessarily have a singular focus.

2.6 Systems Engineering Challenges

Through the writings of Cook and Ferris (2006), Koen (2003), and de Weck et al. (2011), One can understand that for systems engineering to be used in an effective way, there are four critical conditions that must be fulfilled (Souza-Poza et al., 2014). First, there is a specific system with clearly defined rules and boundaries that will fulfill a specific purpose. Next, the stakeholder's necessities for the way this system may function can be clearly outlined. After which, a critical technical component is planned to be used in the solution. Lastly, there is clearly an application of methods/processes that are engineering in nature created to address the problem illustrated by stakeholders. The four requirements are broadly applicable to most problems that are approached with an engineering 1st solution. Though there may be and almost loosening of the four critical conditions, due to their nature, the manner in which it can be done is incredibly limited (Souza-Poza et al., 2014). As an example, using spiral development approaches, it has been shown to create room to allow stakeholder expectations to be described throughout the design development cycle, rather than needing to be clearly outlined before the design process has begun. There is the clear limitation of these expectations to be relatively unchanging needs, as large changes that are done in an extreme manner cannot be accounted for (Souza-Poza et al., 2014).

It is crucial that for the future systems engineering becomes more aware of the various areas that its methods and principles are applied to. This is due to the fact that different areas may require different elements or approaches in order to be useful in those said areas. As systems Engineering is expanding to include many problems from all different aspects of society such as transportation networks, smart grids, or the Internet of things, it is crucial that systems engineering as a discipline takes one of two actions. Firstly, systems engineering could incept formal management governed approaches to deal with rapidly changing end highly reactive systems. This would act as a way to formalize these systems engineering `processes across many different discipline domains regardless of the specific task. Or systems engineering could research and identify the exact limitations of engineering govern solutions as well as the limits of systems engineering itself. These limits would give greater insights on how to integrate governance capabilities and external management in two systems engineering methods (Souza-Poza et al., 2014). The decision between these two options could possibly already have been overcome as numerous recent initiatives have begun to focus highly on management governed principles. There are many approaches that already follow management covered principles such as CSE, enterprise systems engineering, many systems of systems engineering efforts as well along with many others.

2.6.1 Integration of New Development

To better organize Systems engineering as a discipline, more nuance and detail is needed to distinguish minute differences between approaches, methods, tools, and other items that are invented and considered uses of systems engineering (Souza-Poza et al., 2014). The only constant throughout systems engineering is not its purpose; unlike other fields, systems engineering is not a single homogenous field. The ideas in this paper provide insight 2 examine many of the nuances between methods that have been created and are continuing to be developed as well as creating a way to organize the new methods and processes that will be developed in the future. This paper was not intended ;however, to identify methods of categorization for new systems engineering methods that are to be developed. It is the belief of this researcher that further investigations must be conducted in this area (Souza-Poza et al., 2014). Without further research in this area, systems engineering runs the risk of becoming Ineffective due to a lack of clearly defined methods.

2.6.2 Integrity of Design, Process, and Governance

It is conceivable to categorize new methods and procedures that are created as being both engineering-governed, and management governed, Currently there seems to be a concentrated focus on advances that are occurring more upon the management-oriented process side of engineering methods As well as approaches. However, there is a possibility of an exception to this notion, which may appear in the form of model-based systems engineering that has the potential to become more prevalent and powerful with its design capabilities. At first glance, there appears to be a missing link when considering how these concepts work in conjunction with each other. Currently, there is a lack of sharing information and ideas between researchers and professionals working within the balance of these concepts, as researchers from various organizations or institutions tend to focus on either or rather than a way to mesh the two concepts together. To be used effectively, it must be recognized that systems engineering has to incorporate both the design and process-based branches of engineering governed methods. Changes to one side of the balance can affect the other side, and without a concerted effort to incorporate both, the system cannot be designed or implemented to its full capabilities.

CHAPTER III

RESEARCH DESIGN AND METHODS

Research design is a paramount topic in numerous disciplines, including science, engineering, and social science, to name a few. A research design is a layout or blueprint for conducting the research study (De Vaus, 2011). The fundamental objective of the research design is to address the research problem rationally and as clearly as possible (Crewell & Creswell, 2017; Leedy & Jeanne; 2005). Luck and Rubin (1997) provided a broad definition of research design. According to Luck and Rubin (1997), "A research design is the determination and statement of the general research approach or strategy adopted for the particular project. It is the heart of planning. If the design adheres to the research objective, it will ensure that the client's needs will be served."

Aside from declaring the initial topic of interest for the research, developing the proper design and method for conducting that research is crucial to the overall project. There is a great deal of literature discussing a multitude of approaches to research design; however, this plethora of information can cause confusion for aspiring researchers and students. There is a lack of clarity and conciseness contained in the literature about research design, methodology, and methods within the systems engineering literature.

In this research, a mixed-method (quantitative and qualitative) research design developed by Earl R. Babbie is followed. This framework has consisted of *seven phases,* which are presented in detail in the following discussion. These seven phases of the research design were the blueprint that the researcher used to develop a new instrument to measure the performance of the system engineers. The objective of this chapter is to provide a clear understanding of Earl R. Babbie's approach to research design and how it helps to pursue and attain the objective of our research.

3.1 Babbie's Approach

Babbie's work provides a firm groundwork for research from all walks due to its comprehensive research design, theory, and statistics. In his work, Babbie considered the research design is a sort of plan that the researcher needs to fully flesh out. This includes the careful planning of what to observe, along with how the observations will be conducted and why these observations need to be conducted in order to aid the research. Though the scope and topic may vary from project to project, Babbie created two major goals for any research design. Goal one is to be absolutely specific about what exactly the researcher wishes to learn from the work. The second goal is to figure out the best method to gather said information. In Babbie's work, he stated that the clearer goal number one is, the easier it is to accomplish goal number two creating better results and more accurate conclusions. Babbie's recommendation in his findings is for the researchers to take great notice of three aspects "your interests, your abilities, and the available resources" (Babbie, 2020). This is in order to focus the researcher, as the process of topic selection can become a constant cycle of having the head turned in the directions of other ideas, thus preventing work from being started. Paramount to these three is the amount of resources at one's disposal. A great idea and plan are meaningless if the work can never come to fruition. Specifically, for developing a new instrument or theory, validating the research design can be a colossal task due to a shortage of open-source data available to the researcher. The work of Babbie has been boiled down into seven steps for designing a research project, as illustrated in Figure 3.1. These seven steps are to be dissected in the following sections of the chapter.

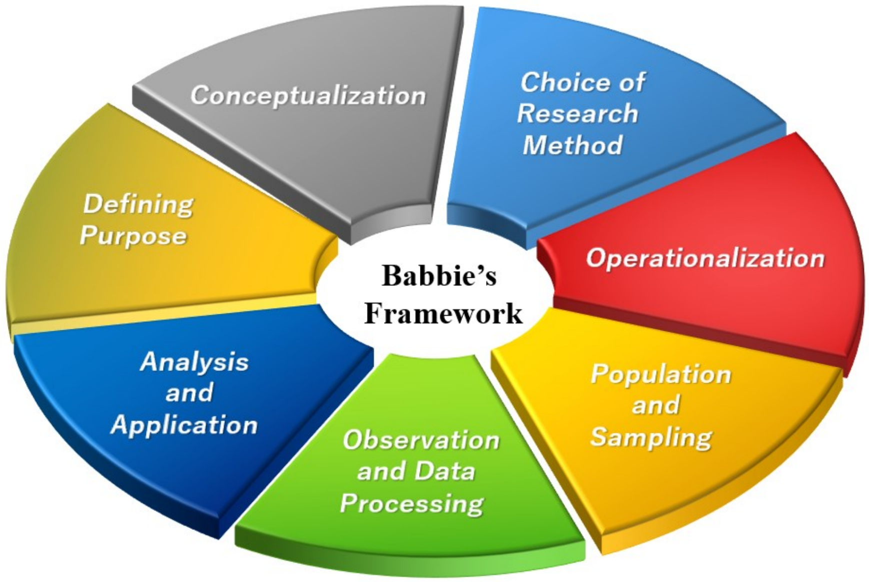


Figure 3.1 Babbie's 7-Stage Framework

3.2 Defining the Purpose of Research

This step is the beginning of the researcher investigating their topic of choice. The research may begin studying public literature on the said topic in order to familiarize themselves with it, as well as the work that has already been conducted in that area of interest. Once sufficient surface reading has been completed, the all-important step of defining both the purpose and focus of the project must come next. The purpose of the project will be the answer to the question of why the research is being conducted.

3.2.1 Developing Quantitative and Qualitative Research Questions

For example, bearing in mind the objective of the research, the following main questions were formulated. These important research questions are not well defined in the existing body of literature and needed to be addressed. The in-depth analysis and justified response to these questions will provide a set of systems engineering attributes and corresponding performance measures which can provide a strong ground to support the rationale of this instrument.

Question (1)*:* *What are the fundamental attributes of systems engineering that would impact the performance of individual system engineers?*

To answer this question, the researcher applied *Grounded Theory* analysis, which is a qualitative data analysis methodology with the help of Nvivo 12 (QSR International) software in organizing, analyzing, and synthesizing the qualitative data. This lead to derive the six fundamental attributes of systems engineering. Based on these six attributes, the performance of the systems engineers can be assessed.

Question (2)*:* *What are the leading indicators for appraising the performance of an individual systems engineer?*

To answer this question, we conducted an extensive review of the literature (qualitative approach) on systems engineering literature to identify the corresponding performance indicators for each fundamental attribute. To conduct this approach, the researcher studied, analyzed, and coded more than one hundred different resources, including peer-reviewed conference proceedings, peer-reviewed journal papers, technical papers, technical reports, and book chapters.

Question (3)*:* *How the performance of the systems engineers can be assessed based on the leading indicators of the systems engineering attributes?*

We hypothesize that there is a significant relationship between the proposed instrument and the state of performance for the individual systems engineer. To answer this last question, the researcher will use a quantitative approach to analyze and synthesize the hard dataset based on the participant response; and check the reliability and validity to demonstrate the effectiveness the new performance measure instrument.

The focus, in this case, requires an extensive and systemic review of existing systems engineering literature and if they impact the performance of the systems engineers. On top of this, what kind of study also needs to be decided. One option is an exploratory study, which delves into better understanding a problem rather than trying to discover a solution for said problem. The researcher may also consider a descriptive study in order to look into characteristics of a phenomenon or a population, allowing for a better definition of the 'what' of said phenomenon or population. Lastly, an explanatory study can be conducted in order to find the root cause or explanation of a phenomenon. Babbie states that "Usually, your purpose for undertaking research can be expressed as a report" (Babbie, 2020). What this means is that it is best to create a formal outline to dissect exactly what the purpose of the study is, as well as what type of study will be conducted. In this research, both exploratory and descriptive studies are conducted.

3.3 Conceptualization

After the purpose has been defined clearly, and the researcher has a great understanding of potential outcomes, the next step of the process can begin. This part, known as *conceptualization,* may seem benign to the researcher, but the step is very critical for carryout the research as well as generating consistent results. During this process, the specific terms and ideas need to be very carefully defined. For the example in the last section, one of the concepts that would have to be clearly defined would be, what a *are the attributes and corresponding performance indicators of systems engineering?* If the concept is not clearly defined, then inconsistencies can occur that would drastically throw off data. In Babbie's own words, "Conceptualization, then, produces a specific, agreed-on meaning for a concept for the purposes of research" (Babbie, 2020, p.169).

Through the process of conceptualizing, two sets of information are also defined: the indicators and the dimensions of the study. In terms of research, an indicator would be either a sign of presence or absence of the concept that is being studied. Using the example, this could be evidence of low well the past studies are correlated with the present study or no correlation as that would be a sign of absence. A dimension is a specifiable aspect of a concept. Dimensions allow the researchers to group entries that fit under the same general aspect of a concept, in our case the concept would be assessing the performance of the systems engineers (i.e., the skill levels of the systems engineers). The specific definitions, indicators, and dimensions allow for the smooth conduction of the research down the line, and as stated are paramount for quality research to be conducted by the researcher.

3.4 Choice of Research Method

This stage deals with the researcher evaluating and selecting exact methods of conducting the research. There are various observational techniques that Babbie outlines in his work, each coming with their own advantages and disadvantages it is up to the research to carefully way the following options in order to properly ascertain the information required in their study. The first method is one that has been historically used in the literature for centuries, and that is the act of surveying. This simply means to ask a population a series of questions in order to gain insight about the topic. Surveys can be used for all three types of research, making them a very dynamic option for the researcher. The survey technique tends to be used in studies where individual people are the units of analysis. Two major pitfalls of this method according to Babbie are open-ended questions, as well as internal bias in the question itself. Open-ended questions need to be categorized for the information to be of use, this can be difficult depending on question complexity and can breed inconsistency if not coded properly. Questions must be thoroughly constructed so that the diction does not lead the respondent to choose one answer over another. Another tool for the researcher to consider is the use of experiments. According to Babbie, "Experiments are especially well suited to research projects involving relatively limited and well-defined concepts and propositions" (Babbie 2013, p.271). This is due to experiments creating explanatory results. This fact; however, does limit the usage of this method to creating quantifiable results rather than more exploratory ones. The third option is the unobtrusive methods. What this means is using historical data and existing statistics to study the topic. For our example, this would be a great option due to the past playing a major role in the topic. This also allows the researcher to observe without interfering with social life. This option will not fit every topic, nor will there be the needed data for each topic; however, it is a powerful tool if available to the researcher. Next is qualitative field research. Qualitative field research is the act of observing social life in its natural habitat, simply put, going, and observing life. Babbie discusses how a major advantage to this type of research is how comprehensive it is. By going and directly observing the phenomenon, the researcher gains a very clear and exact understanding of what is going on, an advantage to studying topics that do not appear to be simply quantifiable. Also, this method lends itself to be great for studying social processes that develop over time, as they would be hard to recreate in a laboratory environment. The last method Babbie presents is evaluation research. As the name suggests, this is the evaluation of the impact or success of a phenomenon. Babbie's example of this is, "When the federal government abolished the selective service system (the draft), military researchers began paying special attention to the impact on enlistment. As individual states have liberalized their marijuana laws, researchers have sought to learn the consequences, both for marijuana use and for other forms of social behavior." (Babbie 2013, p.360) This type of research gives way to evaluate many different topics and is quite flexible in that sense. A problem with this method is the intervention that comes with it. The process is quite intrusive and can cause the subjects to act differently than if they were not being observed. This additional phenomenon must be considered and dealt with in order for proper conclusions to be met.

In this research, *Mixed method* has been adopted which discussed in detail in the following subsections.

3.4.1 Mixed-Method

Mixed methods (MM) research is a methodology for conducting research in which researchers integrate qualitative and quantitative research approaches (e.g., qualitative and quantitative standpoints, data collection, synthesize, analysis, interpretation techniques) to comprehend the overall goal of the research (Schoonenboom & Johnson, 2017).

The overarching purpose of mixed methods research is to combine qualitative and quantitative research approaches and justify the conclusion of the study. The mixed-method approach also answers the fundamental research questions and contribute to heighten the body of knowledge and validity of the research. In the following subsection, every step of the research design is discussed in detail.

3.4.1.1 Determine the Feasibility of the Mixed Method Approach

In order to determine the feasibility of the mixed-method approach, the feasibility of the combination of both quantitative and qualitative research is presented below:

Qualitative research relies on the use of participants' views, the behavior of the people, general questionaries', observations, video recording, case study, documents, and interviews to collect, extract, and analyze the data. The gathered data are subjective, lacking rigor, biased, but more exploratory in nature (Anderson, 2010). On the other hand, quantitative research is the structured way of collecting numeric data (hard data) from specific and narrow questions from the participant groups and analyze the gathered data through statistical and unbiased manner to pursue the interest of the research topic (Whittemore & Melkus, 2008; p.108). The underlying goal of quantitative research is to quantify the problem statement and interpret in objective manner.

In order to pursue the objective of the research, the researcher found the mixed approach would be the most suitable in terms of the design and context of the research. Mixed methods approach is also feasible because both quantitative as well as qualitative designs are required to address the research problem and answer the research questions.

3.4.1.2 Rationale of the Mixed methods

The rationale for the selection of the mixed method design is presented below:

- Subscribing the one type of research (qualitative or quantitative) is not sufficient to comprehend the research problem or answer the research questions. In addition, neither the qualitative or quantitative methods alone decide to accept or reject the research hypothesis (Greene et al., 1989; Jaradat et al., 2014).
- Combination of both approaches will aid in to transform and analyze the data robustly, examine from multiple levels, and finally provide a boarder understanding of research problem that one method is not capable of producing (Greene et al., 1989; Jaradat el al., 2014; Morse, 2016).
- The mixed-method is sequential (explanatory/ exploratory), concurrent (triangulation and nested), and transformative (sequentially and concurrent). Therefore, there is a flexibility of data analysis procedure, and research can be designed either way based on the objective of the study (Greene et al., 1989; Caracelli & Greene, 1997; Palinkas et al., 2011; Jaradat el al., 2014)

3.5 Operationalization

After the selection of the research, the method has concluded, the researcher must then begin operationalization. This is the development of specific procedures to measure and quantify observations that represent the concepts being studied. The variables in the study are in part defined by how they are exactly measured. This step is the crux of creating the experiment. An important factor is consistency, for example, if a survey is given, the question order, questions, and delivery method should all be the same in order to properly compare individual results. If this step is not conducted properly, the variable may have a different practical meaning than the one that was initially established inside the conceptualization stage. For example, *interdisciplinary* is a concept that if not carefully defined in the experiment, can take on a different meaning depending on the experiment. If this terminology is well defined, these differences in perspective could lead to a conflict in the definition of the variable that is being tested.

To conduct the operationalization and establish the initial theoretical concept, researchers employed qualitative method (grounded theory coding), later to check the reliability and validity of the instrument various quantitative approach such as exploratory factor analysis (EFA), confirmatory factor analysis (CFA), one-way analysis of variance (ANOVA), multiple group analysis, and factors analysis was conducted.

3.6 Population and Sampling

Population and sampling is a two-step process that narrows down the groups that the researcher is planning on investigating. Firstly, the population in question needs to be decided upon. The population is the large group (usually of people) that are involved within the topic and that the conclusions of the research are going to be based upon. This population can be large, small, and made up of any specific demographic that fits the topic at hand. If the population is too large to all be included, a sample is taken of the population at large. Selecting subjects for a sample is a critical and delicate step. If not done properly, there can be major biases in the data causing results to be skewed and the research meaningless. Babbie thoroughly discusses how to select a sample in his works and divides sampling into two methods: nonprobability sampling and probability sampling. The first, nonprobability sampling, is used in cases where the population does not have large scale social surveys to extrapolate results through probability. This could be for example homeless people, as there is not a national registry for homeless people, nor would it be possible to construct one. This method requires the researcher to know the population in question rather well, as they will have to judge whether an individual would be a typical case of the population and, therefore, a good respondent. In addition, the researcher may have to rely on respondents to discover more respondents in the case of hard-to-find populations. Probability sampling; however; selects samples in accordance with probability theory and typically involves some random-selection method. The key to this method is to ensure that the sample coincides with the probability technique that is selected in order to prevent a selection bias from occurring.

Sampling is the crux of creating a reliable and scalable study over a generalized population. What this means essentially is that since studying an entire population is infeasible, a researcher must select a smaller portion of that group, that acts as a representation. In order for this sample to provide accurate results; however, it must consist of the same makeup of the general population that is being studied. There are two main ways of generalizing a population according to Trochim (2000); these methods are proximal similarity and sampling model.

The proximal similarity is conducted by selecting different generalizable groups, then choose the group that best fits the study. In layman's terms, what this is stating, is that the process considers multiple different ways of organizing the population based off different traits, and from there the group that fits best with the intended goal of the research is chosen. By using this method, a systematic approach is given to selecting the group and allows for multiple options to be considered. Sampling is simply done by generalizing the population and then using that overall generalization to create trends and analyses over the entire population. It is key to select an even mix of representative demographics that could affect results, otherwise, the conclusions that are drawn may not be accurately scalable to the entire population. In the case of this study, a nonprobability sampling selection was conducted in order to remove the possibility of bias in the sample selection. This means that the sample selected was not intended to be used for a generalization over an entire population but as an individual slice to be observed within its own merit.

As previously noted, the systems engineering instrument is crafted to be usable in multiple disciplines due to the fact that systems skills are paramount in a field of study and therefore, the instrument has to be flexible. In this case, the population of study is individuals who consistently engage in systems engineering activities in large complex problems or at least has experience working in the systems engineering field in the past or students who has conducted a systems engineering project as a part of their coursework. The chosen sample for this particular study was heterogeneous in composition, in the fact that those included in it came from different educational levels, experience levels, as well as different fields.

The style of nonprobability sampling that was used for curating the sample is known as a convenience sample. Although this form of nonprobability sampling was chosen, the researcher feels this was out of feasibility rather than being able to use the best possible option. Due to the breadth of size in the population, it is impossible to survey everyone in the population (people in all fields who deal with complex problems), as well as the difficulty recruiting for the survey, and it is impossible to obtain an exact response rate. Therefore, the sample that was selected is a mostly homogenous one containing practitioners engineers, leaders from different government and federal agencies/industries such US Army, US Navy, Boeing, and NASA; and graduate and undergraduate students from specific universities. The exact demographics for the sample are outlined further in Chapter IV.

The rationale behind selecting such a homogenous sample falls into two main points. The first deals with the core concept of a systems engineering instrument. A system engineering instrument is designed in such a way that it is inherently specific to a systems engineering focused group. Lastly, the research conducted consisted of an inductive approach to data collection and analysis to determine the systems engineering performance of the individual being surveyed. Over one hundred respondents to part in the research phase of the project. An invitation was sent through e-mail to invite potential respondents from various areas to take part in an online survey tool-Qualtrics.

3.7 Observation and Data Processing

This is a twofold step that deals with the conducting and processing of collected experimental data. Observations are made during the experiment and are the foundation for establishing data. These can be individual survey results, events the researcher visited, or other various recorded results from experiments. It is expected the researcher will amass a large volume of observations in a form that is not immediately usable for interpretation. This is when the step of data processing occurs. Data typically fall into one of two categories: *qualitative or quantitative*. Qualitative data is nonnumerical information that is recorded and studies to understand underlying relationships. The processing of this data may lead to coding results and organizing observations depending on choices selected or actions that occur. According to Babbie, the coding of results is as much an art as science, and there are no cut and dry solutions to success, so it is important to proceed with caution. Quantitative data is converting observations into numerical information, such as statistics in order to gain insight. This is a more scientific approach, but in terms of the relationships and patterns of social science that can be observed, there are limitations to it.

In the mixed-method research design, two types of data collection strategy, namely: *sequential design* and *concurrently design,* are mainly applied. Sequential design can be further split into three types: sequential explanatory design, sequential exploratory design, and sequential transformative design, whereas concurrent design strategy has three forms: concurrent triangulation design, concurrent embedded design, and concurrent transformative design. Different Data Collection Strategy in mixed-method approach is illustrated in Figure 3.2 (Creswell and Creswell, 2017).

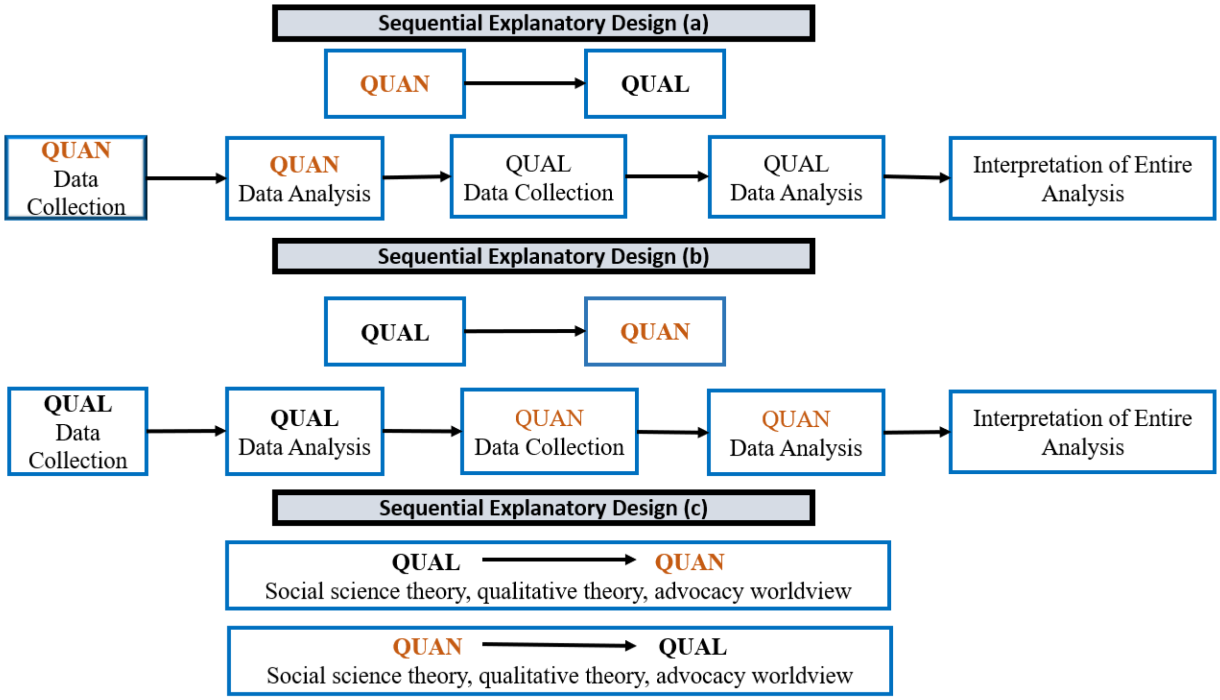


Figure 3.2 Different Data Collection Strategy in Mixed Method Approach (Creswell and Creswell, 2017)

In this research, the *sequential exploratory design(b)* research strategy has been applied. The sequential exploratory strategy is described by an initial phase of qualitative data collection and analysis, with the second phase of quantitative data collection and analysis to follow, which is conducted based on the findings of the first qualitative phase. This research design is very useful in exploring an emergent theory or developing a new instrument concept along with its quantitative findings. Morgan (1998) stated that "sequential exploratory design is appropriate to use when testing elements of an emergent theory resulting from the qualitative phase and that it can also be used to generalize qualitative findings to different samples."

3.8 Analysis and Application

In the final step, the researcher takes the data that has been processed and analyses it to draw conclusions. For the data analysis, different methods are going to be used depending on if the data is quantitative or qualitative. For quantitative data, Babbie lists numerous options such as univariate analysis, subgrouping analysis, and bivariate analysis. The univariate analysis involves describing a case with a single variable. The most basic form of this consists of distributions and basic statistics. Visualizations such as pie and bar charts are great for displaying this type of information. Subgrouping analysis is taking slices of the overall data in order to look at trends based off of a part of the sample. Lastly, bivariate analysis is used when there is a case of two variables. Some good options for the visualization of this data are scattered plots and tables as they allow for the easiest readability. For qualitative data, Babbie focuses on discovering patterns, grounded theory method, semiotics, and QDA programs. Discovering patterns entails looking at six major factors (frequency, magnitudes, structures, processes, causes, consequences) to see if there is a particular order they tend to follow. Grounded theory methods are theories that are created solely through the examination of the data. This means they are not put through any set method but simply the observations of the researcher. Semiotics is the breakdown of signs their meaning. This could be a group using the cross to symbolize suffering or a family using a bell to signify dinner time. Lastly, QDA programs are computer programs that will take in a spreadsheet of qualitative data and form results based upon those inputs. This is oftentimes more efficient than having the researcher study the data. Once an analysis has been completed and results are finally uncovered, the researcher must formalize their results, explain their methods, and present what has been discovered. This process can be done typically in the form of a presentation at a conference or the publishing of their own unique publication.

Since analysis occurred within both type of data: qualitative (text mining) and quantitative (descriptive and inferential numeric analysis), data analysis in mixed methods is somewhat different than the traditional research design approach. Some of the common mixed-method approaches, include, but not limited to data transformation, explore outliers, instrument development, examine multiple levels, develop a matrix, and test the reliability and validity of the instrument (Creswell and Creswell, 2017).

3.8.1 Qualitative Data

In this study, qualitative data gathering, analysis, and documented conducted by applying grounded theory coding.

3.8.1.1 Grounded Theory Coding

After an extensive review of the SE literature from 1925-2017, a set of SE attributes was derived based on grounded theory coding. Grounded theory, which is basically a text mining approach, was originally developed by sociologists Barney G.Glaser and Anslem L. Staruss's in 1967. In their book *"The Discovery of Grounded Theory,"* they described the strategies pertaining to grounded theory and demonstrated how meaningful hypotheses could be derived from the qualitative data analysis. Grounded theory coding is a qualitative coding technique to separate, classify, analyze, and synthesize the data. In coding, a label is assigned to identify or classify the segments of the data according to what each segment is about. The analysis starts with the generation of a series of codes that are directly related to the data and end with the production of theoretical ideas or meaningful emerging concepts from the synthesized data. Data does not necessarily have to be textual; it could be in the form of observations, experimentation, videotapes, interviews, documents or historical archives. Grounded theory is particularly beneficial when the existing theory about a phenomenon is either inadequate or non-existent (Cresswell, 2005). The strategies involved with grounded theory practices are outlined below (Corbin, Strauss, & Strauss, 2014), and a simple representation of the stages of the grounded theory technique is illustrated in Figure 3.3.

- Conduct data collection and synthesize simultaneously.
- Generate analytical codes from a corpus of data, not from preconceived inference, prejudices, or association of ideas.
- Group the similar codes in order to form the category.
- Derive inductive theory is based on the constant comparison and relationship among the different categories.

Figure 3.3 Stages of Grounded Theory Coding

In order to collect, gather, analyze, and document the data, we have studied, analyzed, and coded more than one hundred different resources including peer-reviewed conference proceedings, peer-reviewed journal papers, technical papers, and book chapters. We have applied Grounded Theory Coding (GTC) with the help of Nvivo 11 (QSR International) software that aided in collecting, analyzing, and synthesizing the qualitative data. Grounded theory coding is an established qualitative data analysis methodology that generates a theory directly from the large unstructured data set, including surveys, interviews, literature reviews, and others. Thus, it helps in building up a more general theoretical concept from the collected information from the available resources.

It is important to mention that the resources studied for this analysis are considered on the basis of three disparate standpoints: the perspective of the defense industry, the organizational perspective, and the space science perspective. We have selected the seminal works that discussed and synthesized the definitions of SE and contributed most to the related field as evidenced by the frequency of citation for the work.

The grounded theory approach was adopted in this research as it does not presuppose any particular theory/concept or offer any hypotheses at the beginning of the research. Grounded theory is a text mining approach that fundamentally ties to social sciences as a method to generate an emerging theory that is grounded in data that are systematically collected, organized, and synthesized during the different phases of coding (Goulding, 2002). This approach compensates for any bias that might be induced by the researchers, rather allowing the large unstructured data chunk from different resources through the research phase to derive a new emerging theory. Unlike the traditional research approach, where researchers initiate a theoretical framework and apply to the phenomenon/case study to be studied, this approach initiates with collecting qualitative data without having any particular hypothesis/concept in mind.

3.8.1.1.2 Coding

A primary task in most of the qualitative projects is to accumulate information by subject or coding. It gravitates towards to be a collective process rather than a single step process, while the connotation and structure of codes are varying with time. In other words, one of the methods for getting meaningful insights from data is coding- one can incorporate it alongside annotating, writing memos, linking, and generating maps. Considering the methodology and research design, one has to manage coding. The following ways describe how coding the content of files can subscribe to research:

- The method of coding is essential because it not only takes one closer to data but also concentrates on materials-question such as what is this about? is it just about one thing? how does it assist me to respond to my research question?- are asked.
- All the insights corresponding to a subject can be accumulated using coding (for instance, what did researchers contend about systems engineering attributes?). For this reason, it becomes easier to comprehend the patterns, conflicts, and to generate theories.
- By incorporating queries and visualization, coding helps to search for links between themes and to validate one's understanding. For instance, one might have a feeling that interdisciplinary skill might affect the performance of systems engineers - by utilizing coding query to collect materials coded as interdisciplinary skill adjacent to materials coded as performance and then discover the links. In later lessons, coding queries will be described.
- Not only to exhibit rigor in data analysis, retrieval, and reporting but also to notify audit trail a "codebook" is very convenient.

3.8.1.1.3 Inductive Vs. Deductive Reasoning

With reasoning, two primary types dictate the process in which humans draw conclusions. These processes are known as inductive and deductive reasoning. Learning these processes thoroughly can offer insight into a researcher's frame of mind and allow for said research to adjust their method of approaching a given research question.

Inductive reasoning can be likened to the traditional idea of pattern recognition due to its intrinsic method of problem-solving. This form of reasoning first begins by making a series of observations, such as measuring the heights of college students. From these observations, a broad conclusion is drawn, using patterns within the observations. This form of methodology is a bottom-up process.

Deductive reasoning is the opposite of inductive reasoning in that the conclusions that are drawn are very specific. The process is also reversed; it requires the researcher to start with broad premises and drill down into more specifics. This form of the methodology is a top-down process, as shown in Figure 3.4.

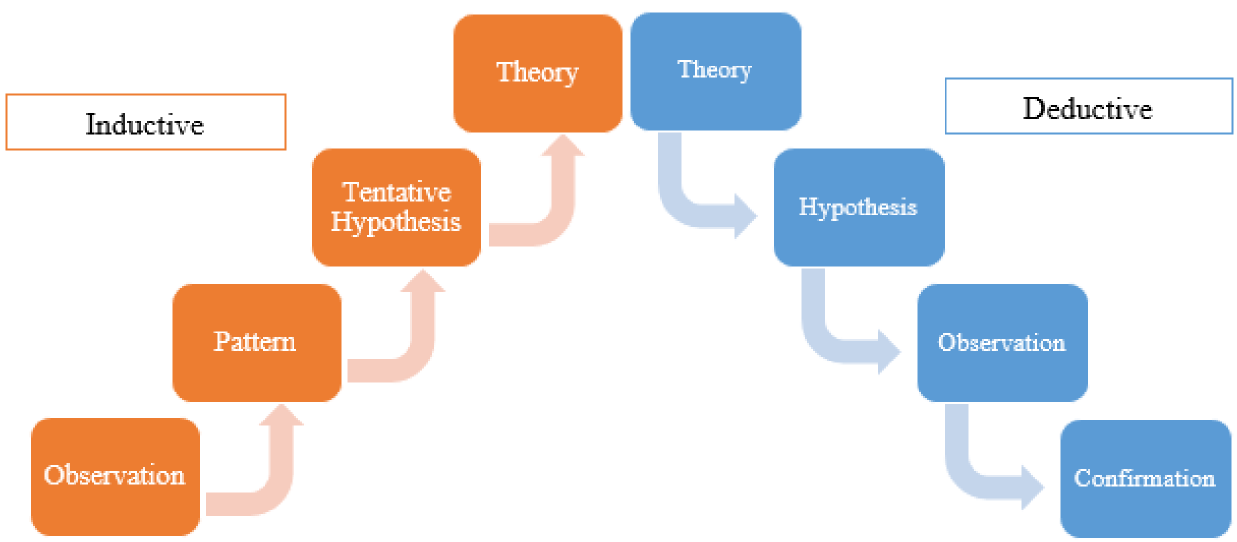


Figure 3.4 Inductive and Deductive Reasoning

In terms of research, an inductive approach is used to build a theory that is tested through deductive methods. This rationale of research design works in a cycle allowing the inductive and deductive sides to fuel each other until a proper conclusion is achieved. This cycle is illustrated in Figure 3.5 below.

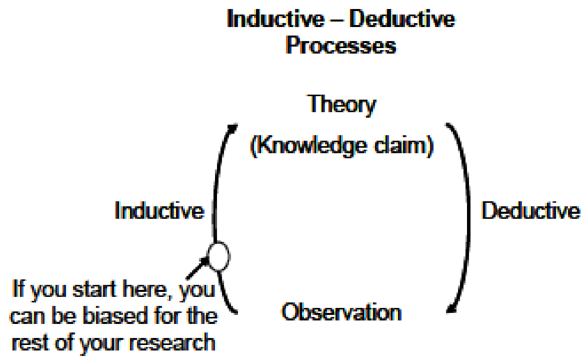


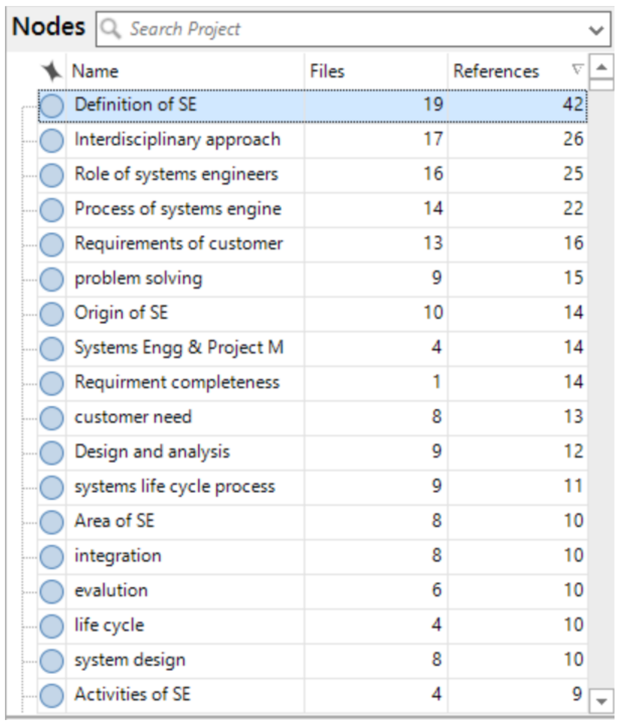
Figure 3.5 Cycle of Inductive and Deductive Reasoning (Jaradat et al., 2014)

Inductive reasoning according to Lee and Baskerville (2003, p.224), “Begins with statements of particulars and ends in a general statement.” Since the initial phase of research design was qualitative in nature, the researcher moved more towards the general theory that was being investigated diverging from the initial particulars that were being considered. Fiebelman recommended to begin with a more inductive approach as it lends itself to creating a more generalizable theory, which could then further aid in the development of more research. There were four major reasons that the researcher chose an inductive approach. The first of these reasons is due to the overall goal of the researcher. This goal it's the develop a general instrument that could be used in various areas of interest, such as military, industrial, and health care to just name a few. Next, the researcher did not have any specific premises about systems engineering characteristics. Due to this starting point, the process that needed to be undertaken lent itself to be more inductive in nature. Thirdly the researcher was aiming to sift through the data for patterns. If the researcher took a deductive approach, this would not be possible, yet this need fits perfectly within the inductive method. Thus, allowing for the researcher to decipher patterns that may have appeared from the 150+ different sources under study. Lastly the inductive approach, Became the clear appropriate choice for the nature of this study due to its core concept of building deliberate understanding from data.

After conducting a thorough literature review on systems engineering, a common concept among many studies was that they show and propose personal characteristics of a quality systems engineer. It is widely considered that personal characteristics can be grouped into two major categories. The first category being those that are *core competencies* of systems engineering, those are related to the fundamental characteristics of systems engineering such as systems design & integration, requirement engineering, and life cycle assessment. The other category is *management competencies,* which pertain to business and technical skills of the system engineers such as interdisciplinary, hierarchical view of a system, and management roles.

3.8.1.2 Phase 1: Open Coding

Glaser and Strauss (1967) referred to the procedure for developing initial categories as open coding. At this phase, we keep assigning the codes to distinct elements in order to label a phenomenon (see Figure 3.5). Initial coding is impermanent, fundamentally related to the text or data mining, and conducive to pointing out the gaps in the analytical process (Charmaz & Belgrave, 2007). Open coding is a procedure for generating categories of information, and it possesses direct ties to the data sources. Open coding could be word by word coding, line-by-line, paragraph by paragraph, or whole document coding. During the analysis, we attained theoretical sensitivity through deliberative involvement in the dataset using the sentence by sentence and line by line approaches along with the flip-flop technique, the red-flag technique, and saturation specified in Corbin & Strauss (1990). It is important that at the beginning of this procedure, the researcher has no preconceived ideas about what would emerge from the dataset. However, during the open coding, the researcher kept the following question in mind; *what are the patterns emerging from the data sources, through the open coding process, that support development of new theory?* A snapshot of open coding (line by line coding) of a document in the Nvivo interface is shown in Figure 3.6 and 3.7, respectively.

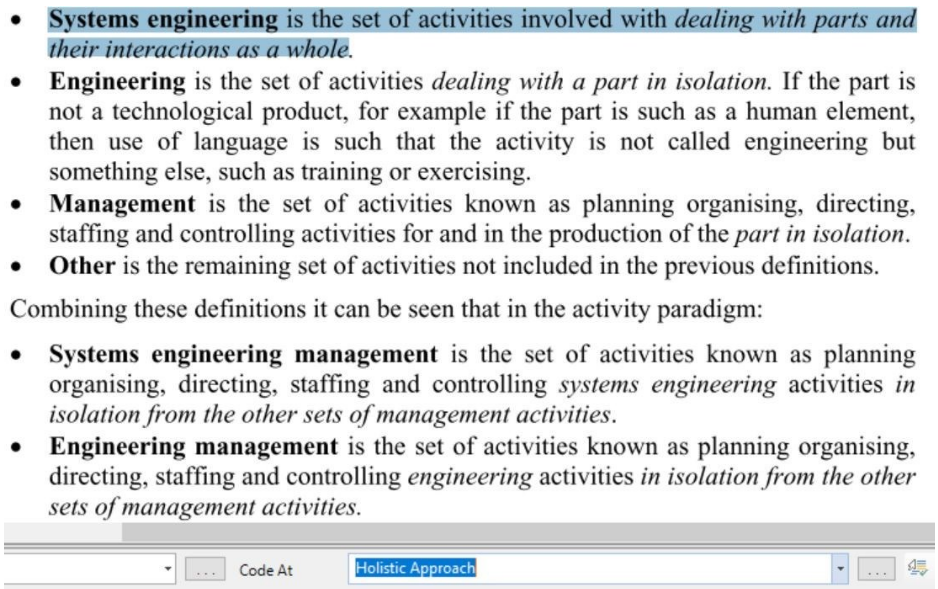


Nodes

Search Project

Name	Files	References
Definition of SE	19	42
Interdisciplinary approach	17	26
Role of systems engineers	16	25
Process of systems engine	14	22
Requirements of customer	13	16
problem solving	9	15
Origin of SE	10	14
Systems Engg & Project M	4	14
Requirment completeness	1	14
customer need	8	13
Design and analysis	9	12
systems life cycle process	9	11
Area of SE	8	10
integration	8	10
evalution	6	10
life cycle	4	10
system design	8	10
Activities of SE	4	9

Figure 3.6 Sample Nodes of Open Coding



- **Systems engineering** is the set of activities involved with *dealing with parts and their interactions as a whole*.
- **Engineering** is the set of activities *dealing with a part in isolation.* If the part is not a technological product, for example if the part is such as a human element, then use of language is such that the activity is not called engineering but something else, such as training or exercising.
- **Management** is the set of activities known as planning organising, directing, staffing and controlling activities for and in the production of the *part in isolation*.
- **Other** is the remaining set of activities not included in the previous definitions.

Combining these definitions it can be seen that in the activity paradigm:

- **Systems engineering management** is the set of activities known as planning organising, directing, staffing and controlling *systems engineering* activities *in isolation from the other sets of management activities.*
- **Engineering management** is the set of activities known as planning organising, directing, staffing and controlling *engineering* activities *in isolation from the other sets of management activities.*

Figure 3.7 Demonstration of Line by Line Coding

Different kinds of analyses were performed during the open coding, such as flip-flop, waving red-flag, and saturation techniques. These analyses helped to manage the bias. Flip-flop technique is a procedure that answers the questions related to the six W's; who, what, when, where, why, and how in the analyzing text. According to Corbin et al. (2014) "Flip-flopping consists of turning a concept 'inside out' or 'upside-down' to obtain a different perspective on a phrase or word." It also enables us to think analytically rather than descriptively". Flip-flop technique focuses on analytical thinking rather than descriptive by comparing the extremes of one-dimension Table 3.1 provides a sample demonstration of the flip-flop technique that we conducted in our research. The waving red-flag technique provides a reminder to the researcher not to assume too much. This approach encourages avoiding the use of sensitive phrases such as often, more, rarely, never, and always. Waving the red flag is sensitive to the phases like 'Never,' 'couldn't possibly be that way' and must know what might happen when things occur. This technique is advantageous at the initial stage or interview or puzzled. Saturation is the process that guided the researcher in making a decision regarding the right time to stop coding and move to the next procedure, axial coding. Saturation occurs when new coding doesn't provide further theoretical insights. A summary of open coding is illustrated in Table 3.2.

Table 3.1 A Sample Demonstration of Flip-flop Technique

Source: <Files\\18. Towards a Grand Unified Theory of SE> - § 1 reference coded [0.15% Coverage]
Text: the science of designing complex systems in their totality to ensure that the component subsystems making up the system are designed, fitted together, checked and operated in the most efficient way
Flip-flop technique: What are the stages of the system integration? Is there any overlapping among the stages?
Code at: Sub system design and integration

Table 3.2 Summary of Open Coding Procedure

Purpose	Development of a set of categories from the data chunk
Treatment of the dataset	Fragmentation of the raw data by assigning several codes
Approaches Used	Word by word coding, line-by-line, paragraph by paragraph
Techniques used	Flip-flop, Waving the red-flag, and Saturation
Output	2498 codes

During the first phase of coding, analysts have no bigotry objective with respect to the resultant dataset. The Summary of open coding:

- The data is divided, examined, compared, gestated, and categorized (Strauss and Corbin)
- The data is being questioned with a consistent or specific set
- The data is analyzed
- Theoretical notes are written by interrupting the coding often

Open coding can also be referred to as temporary, typically associated with data mining or text, and suitable for diagnosing the defect in the analytical process. It uses a Constant comparative approach to saturate the data and iterative process.

3.8.1.3 Phase 2: Axial Coding

Open coding is followed by the Axial Coding phase. Axial coding describes the studied experience by answering the questions such as 'When, where, how, who, and what consequences (Creswell, 2005). Axial coding is the second stage of the coding analysis technique that discovers the connections among the multiple codes. Strauss and Corbin have grouped the statements into components of schemes to answer the questions. One scheme includes Conditions, Actions/Interactions, and Consequences answering to:

- Conditions: Why, Where, How, and When questions
- Actions/Interactions: Whom and How questions
- Consequences: What happens because of questions.

Axial coding explores the interconnection among the categories and relates the categories to the subcategories. The object of axial coding is to sort, analyze, and organize a large amount of data and convert it into rational categories after open coding (Creswell, 2005). Axial coding consists of three main stages: explore the causal conditions, develop a central phenomenon, and delineate the consequence. In this research, axial coding was used to:

- Synthesize the fragmented data, 2498 codes to assign them to categories and subcategories.
- Connect and relate the categories to subcategories.
- Assemble the categories based on the underlying attributes of their interconnection.
- Generate a theory based on the relationship.

In this phase of coding, the researcher explored the interconnection among the 2498 codes (child nodes) and delineated them into 29 main categories (parent nodes). In order to develop the 29 main categories, the context and intervening conditions were explored, central phenomena were developed, and interconnection was created to visually display the link between categories and subcategories. The 2498 child nodes are linked to parent nodes in such a way that the parent node can comprehensively describe the aggregate meaning of the child nodes. Different kinds of analysis such as coding query analysis, project map analysis, and model coding analysis were performed during this phase to explore the causal relationship between subcategories and main categories.

In Figure 3.8, a snapshot of axial coding is illustrated.

Axial coding builds a ‘paradigm’ coding to

- Identify a central phenomenon,
- Analyze Casual conditions,
- Identify the context and intermediary conditions, and
- Depict the consequences.

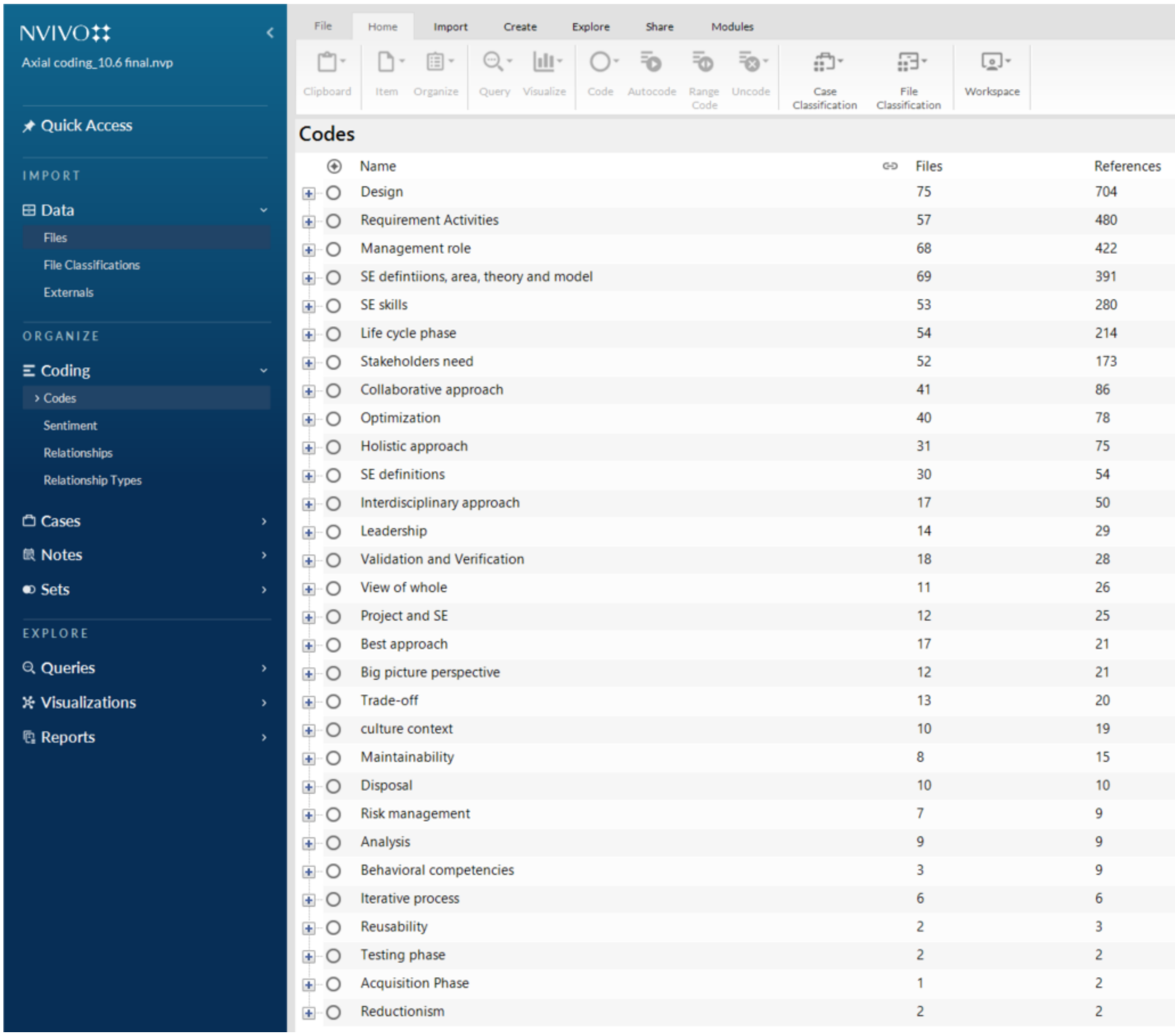


Figure 3.8 A Snapshot of Axial Coding

3.8.1.3.2 **Project Map Analysis**

Project maps are essentially a visual illustration of the various items in a project. The project map helps not only to explore but also to show the links in data.

In project maps, the various items in a project are depicted by different shapes. The connectors are used to demonstrate the relationship among items. That is why researchers need some data beforehand to formulate a project map. The first step for the project map is to determine what question to be asked regarding the project data. For instance, the questions can be the way these files are coded, the particular cases allotted to this classification, the definition of the attributes for this classification. After that, to draw a graphical illustration of the inquiry, project items that are essential to the query must be included in the canvas. In order to facilitate illustrating the answer, other related items must be included in the project map. Project maps are used for the following purpose:

- Exploring and organizing data,
- Developing ideas, building theory, and making decisions,
- Identifying emerging patterns, theories, and explanations,
- Visualizing the links between project items, and
- Providing a record of stages in a project.

After a project map is generated, it can be saved as an image in the project journal, and also observation and ideas must be noted. Figure 3.9 demonstrates the example of project map analysis where “management-oriented (management role)” is considered as the main category (parent node) and “organizing,” “lead,” “staffing,” “controlling,” and “directing” are some of the subcategories (child nodes).

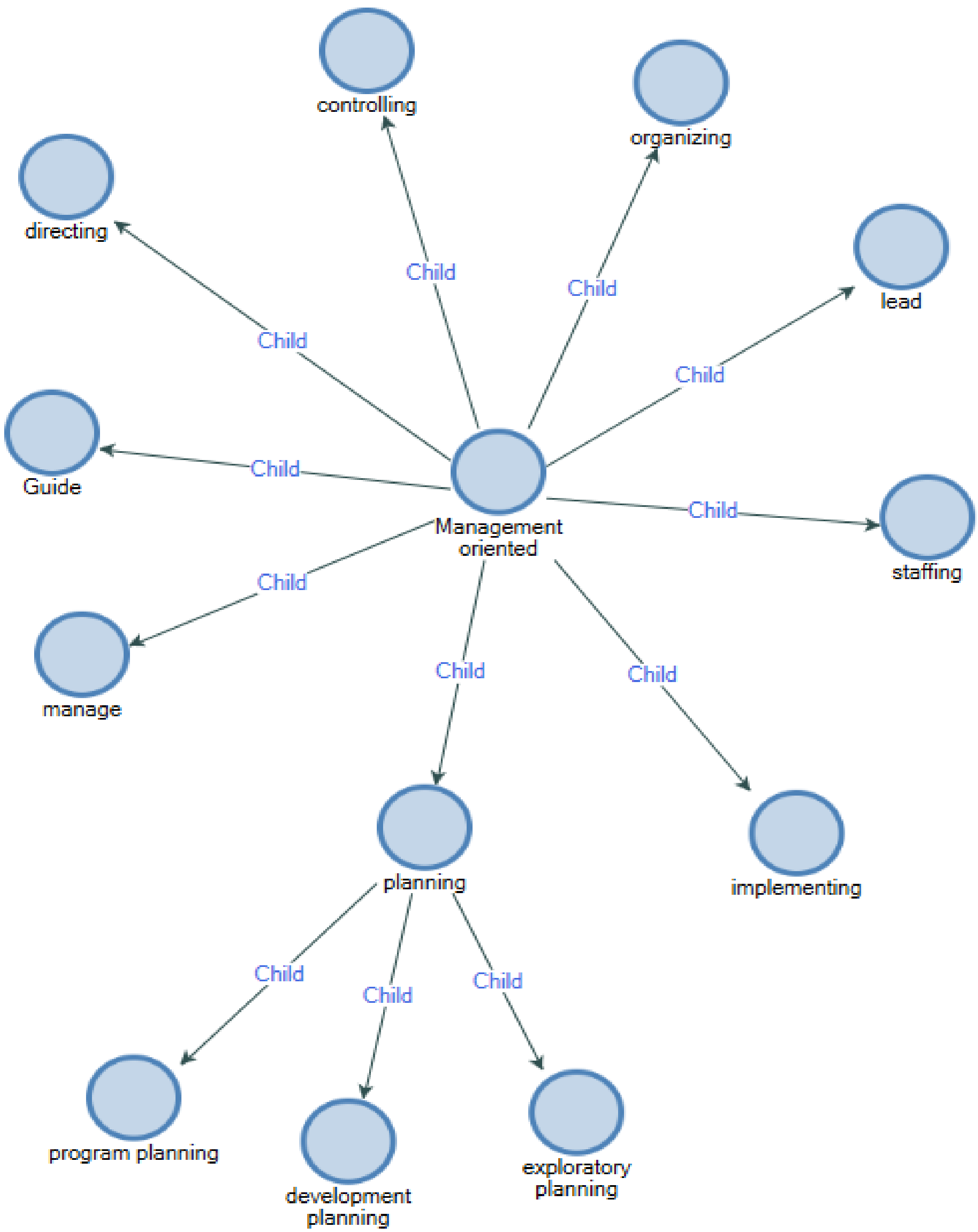


Figure 3.9 Project Map Analysis in Axial Coding (Management Oriented/Management Role)

In the same vein, the project map analysis of the "stakeholder need" node is graphically presented in the following Figure 3.10.

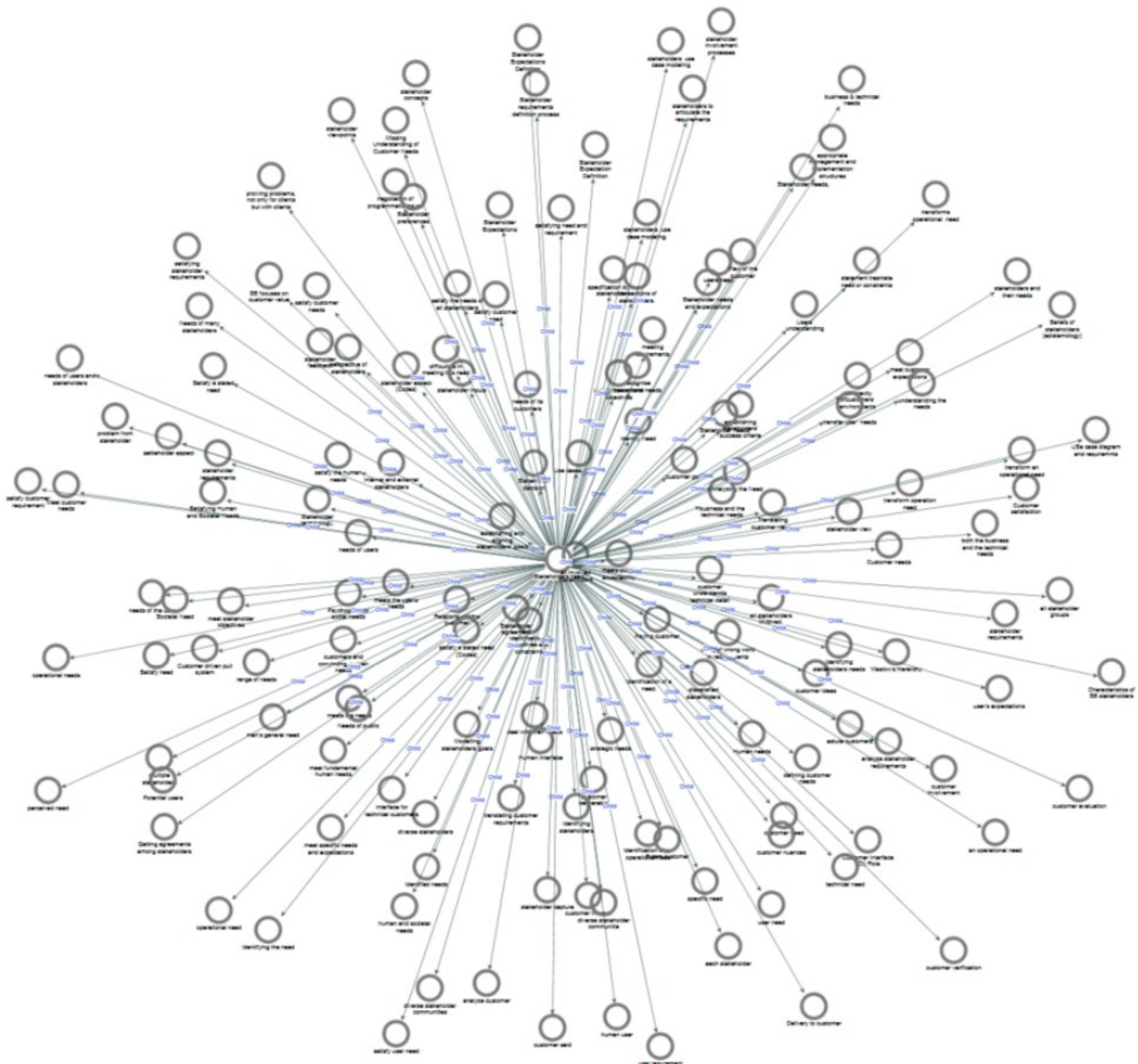


Figure 3.10   Project Map Analysis in Axial Coding (Stakeholder Need)

3.8.1.3.3 Word Clouds Analysis

A *word cloud* can be generated from a code or file in a detailed view. By running a word recurrence query on that item, NVivo generates a world cloud inside a file. Figure 3.11 and 3.12 demonstrates the word cloud analysis of “interdisciplinary knowledge/approach” and life cycle phase” theme.

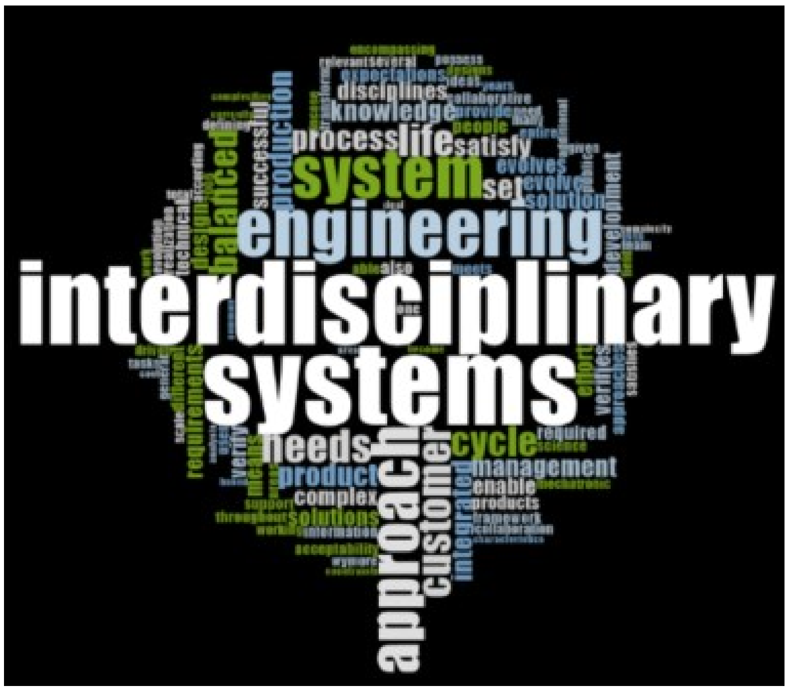


Figure 3.11 World cloud Analysis of “Interdisciplinary knowledge/approach” Theme

Figure 3.12 Word Cloud Analysis of “life cycle” Theme

3.8.1.3.4 Mind Map Analysis

A convenient outline of the variation among the different types of other visualizations accessible in NVivo is provided by the *map of visualizations*. One can incorporate these at every phase of their project, considering the type of thinking they want to do. Mind Maps in NVivo facilitate concentrating on the project, which is similar to other mind-mapping tools such as Mindjet, XMind, Cogglea and Freemind. In order to brainstorm a code hierarchy and to convert those insights into codes, Mind Maps are often used. The mind map analysis of the “interdisciplinary” theme generated in the Nvivo interface is graphically represented in Figure 3.13.

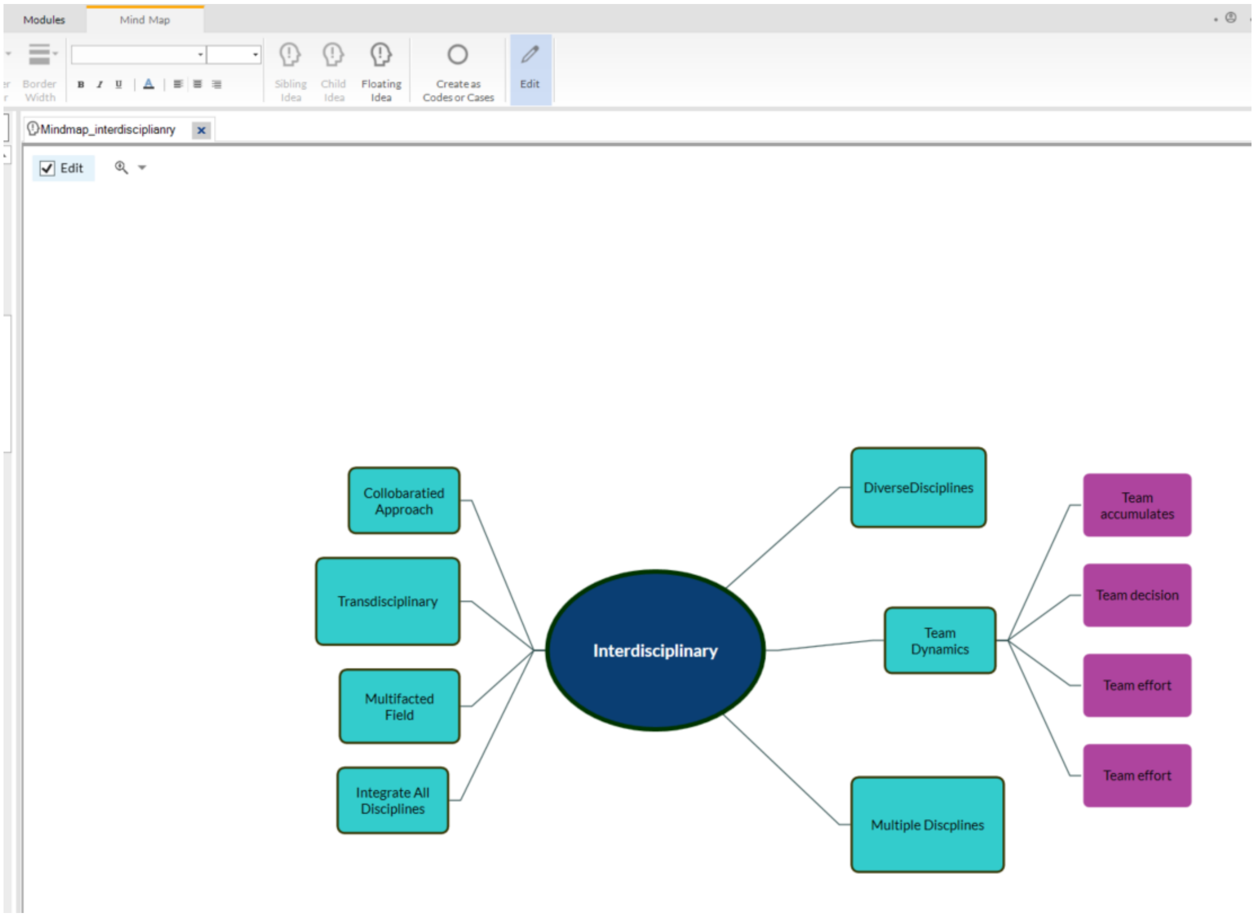


Figure 3.13 Mind Map Analysis of Interdisciplinary Theme

3.8.1.3.5 Hierarchy Chart of Codes/ Tree Map Analysis

Hierarchy charts/ Treemaps illustrate a hierarchy as it assists user to view or demonstrate patterns in coding. Using the hierarchy charts/ tree map analysis, researchers are able to evaluate—do any codes have much more coding references compared to others? Hierarchy charts facilitate not only to depict important themes in any project but also to isolate areas that require further investigation or research. The tree map analysis of "management role" and "stakeholder need" theme, generated in the Nvivo interface, is shown in Figure 3.14 and 3.15, respectively.

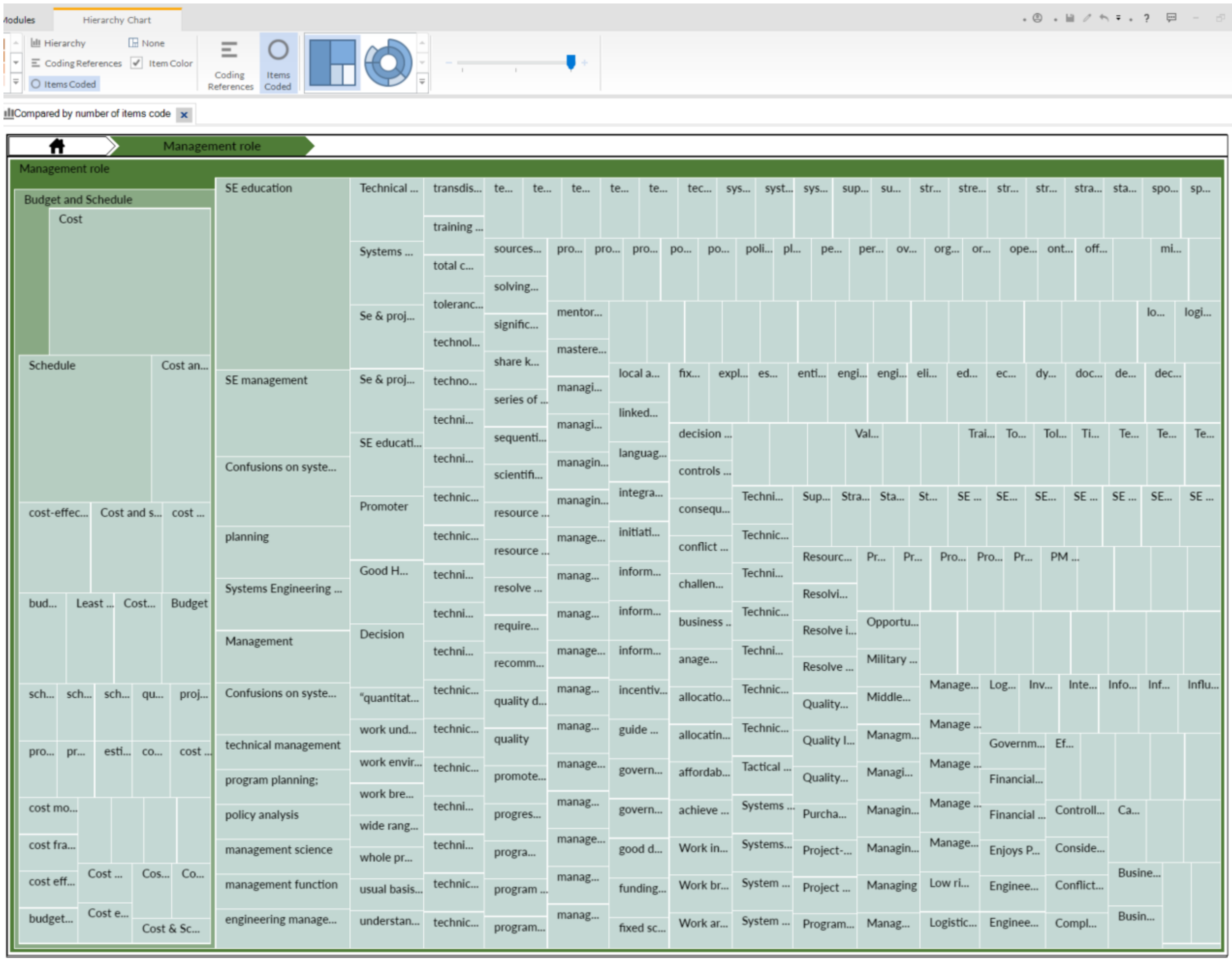


Figure 3.14 Tree Map Analysis of Management Role

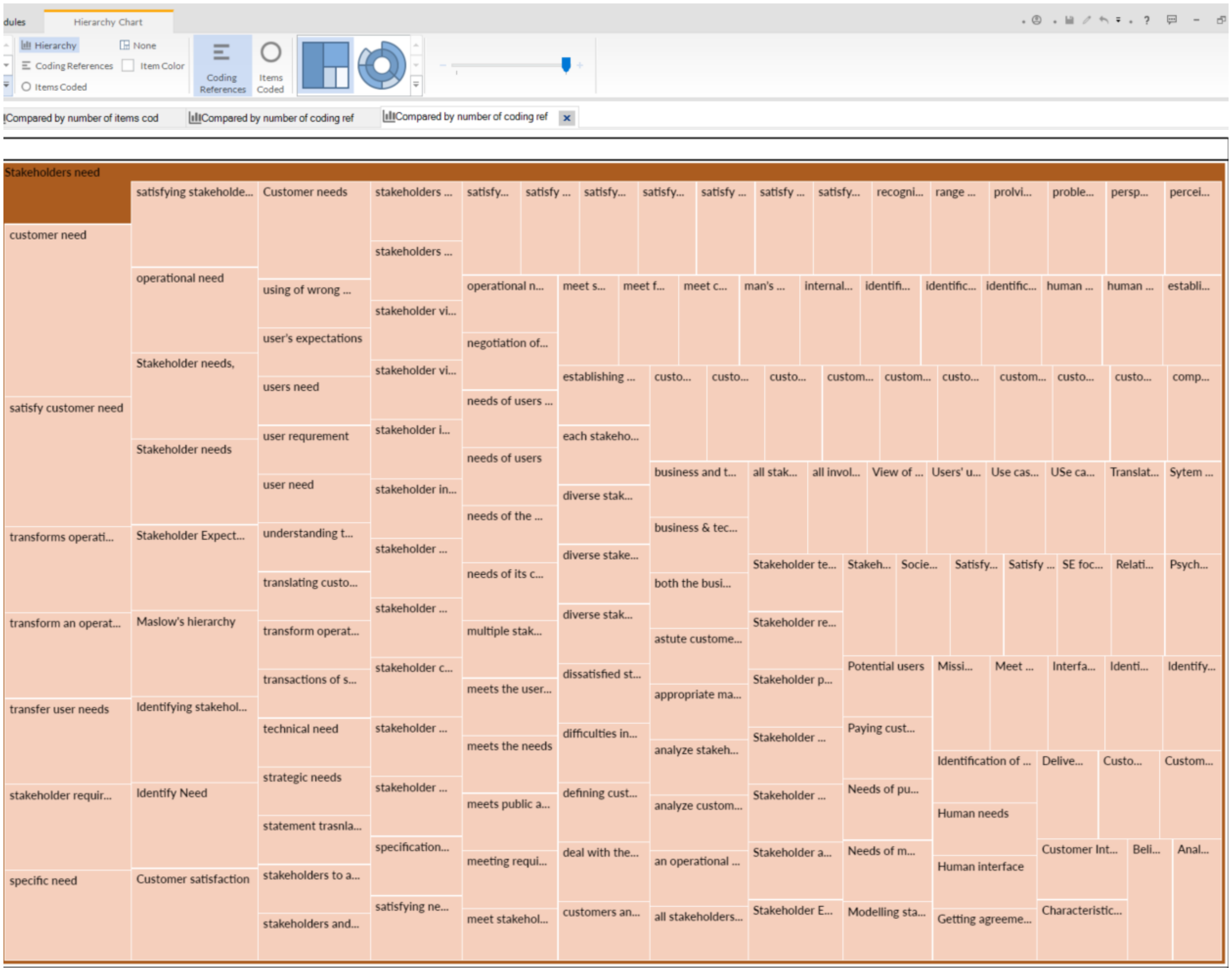


Figure 3.15 Tree Map Analysis of Stakeholder Need

3.8.1.3.6 Explore Diagram

Explore diagram let researchers step forward and back through project data while surveying the relationship between items, it is considered as a dynamic diagram. Starting with a chosen project item in the center of attention, all related items are presented around it. In other words, one can create a novel diagram presenting all its related items just by selecting any of the connected files, codes or cases, and realign the diagram on that project item, which shows the dynamic characteristic of this diagram. Figure 3.16 represents the explore diagram of "holistic approach" theme across different articles.

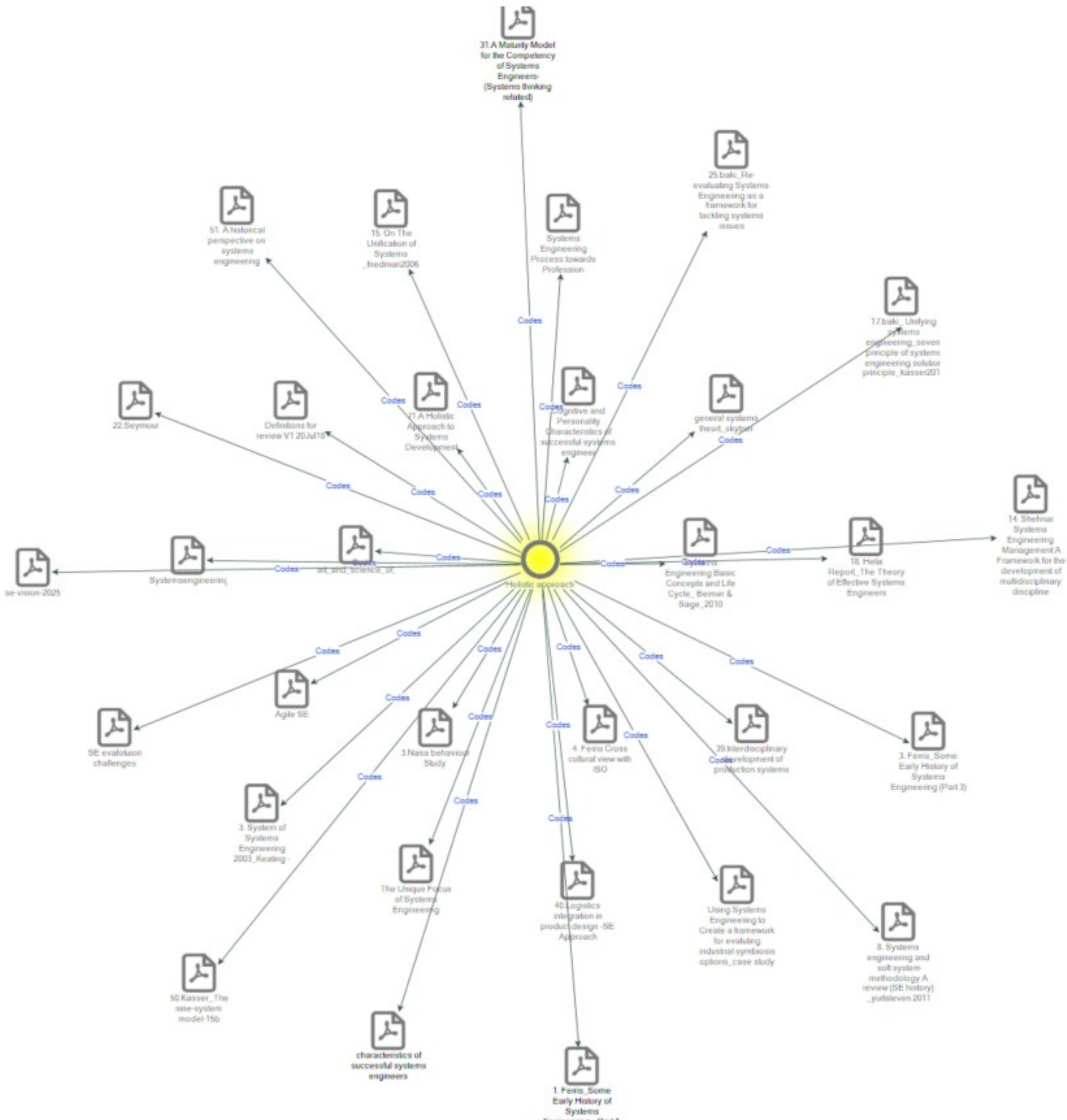


Figure 3.16 Explore Diagram of "Holistic Approach" Theme

Table 3.3 Summary of the Axial Coding Procedure

Purpose	Analyse the codes generated during the open coding and relate them to convert into rationale categories.
Treatment of the dataset	Compare the codes generated during the open coding
Approaches Used	Causal conditions => Central phenomenon => Consequences.
Techniques used	Project map analysis, Word cloud, Explore diagram, Mind map, Hierarchy Chart/ Tree Amp Analysis
Output	29 categories

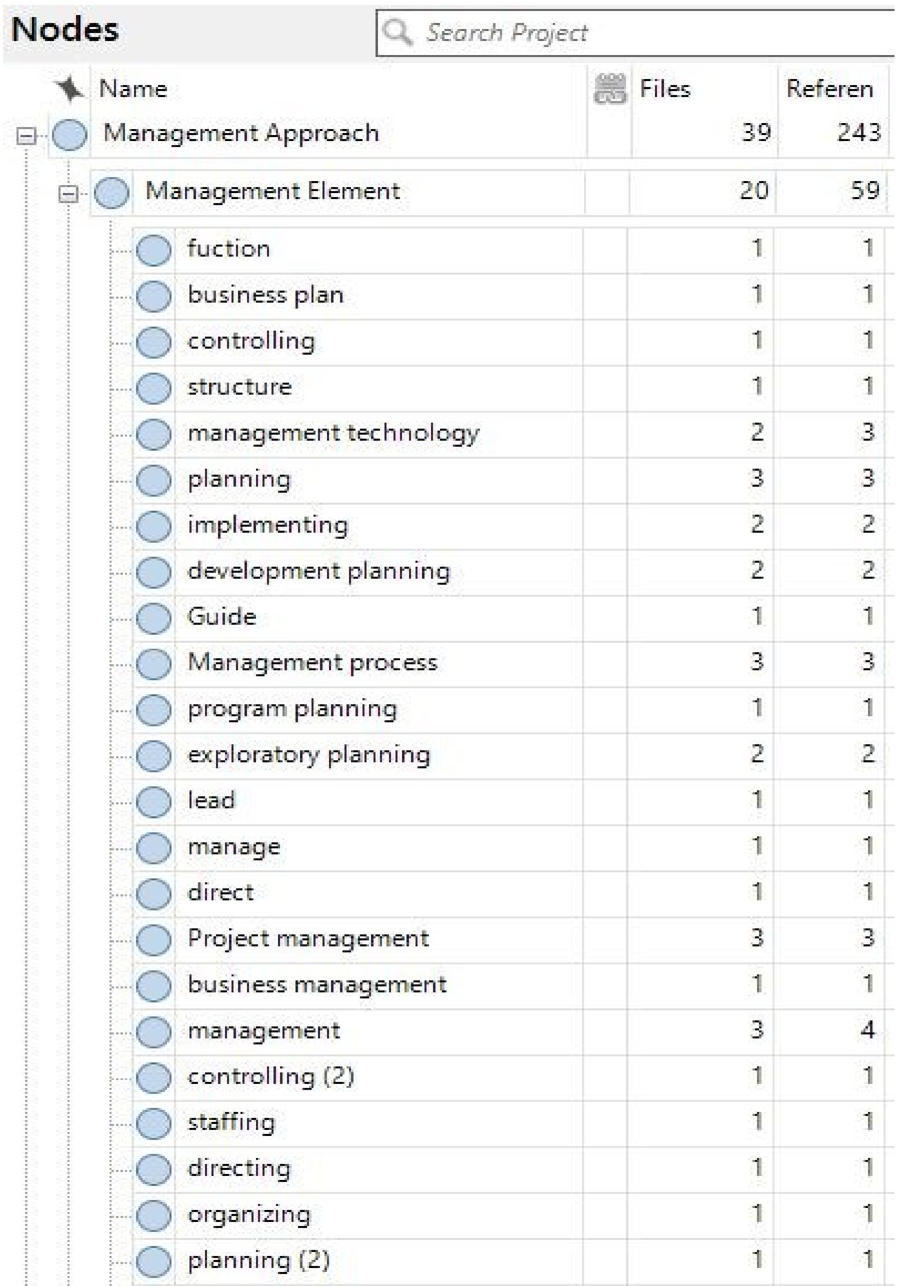
3.8.1.4 Phase 3: Selective Coding

Selective coding integrates all the categories developed during the axial coding phase and transforms them into core categories or main phenomena. The process of selective coding involves developing the central theme to generate a theory by summarizing all the categories and memos created during the previous coding phase. At this phase:

- The core category is selected,
- Other categories (including sub-categories) are connected systematically,
- Relationship between categories are validated, and
- Categories that require clarifications and development are loaded in selective coding.

The theoretical explanation of the data is grounded or confirmed by "Theoretical Sampling." The core category is selected based on frequent appearance, being a central phenomenon rather than the peripheral, logical, and comfortable fit of data, and with great explanatory power.

In Figure 3.17, if “management approach” is selected to be code number 1 and “management element” is labelled as code number 2, then the selective coding procedure would identify code number 1 to be the core category, and all other correlated codes (code 2) will be related to the core category.


Nodes

Search Project

Name	Files	Referen
Management Approach	39	243
Management Element	20	59
fuction	1	1
business plan	1	1
controlling	1	1
structure	1	1
management technology	2	3
planning	3	3
implementing	2	2
development planning	2	2
Guide	1	1
Management process	3	3
program planning	1	1
exploratory planning	2	2
lead	1	1
manage	1	1
direct	1	1
Project management	3	3
business management	1	1
management	3	4
controlling (2)	1	1
staffing	1	1
directing	1	1
organizing	1	1
planning (2)	1	1

Figure 3.17 Sample Nodes of Selective Coding

3.8.1.4.2 Cluster Analysis

For illustrating patterns in any project through clustering files or codes that contain the same keywords, alike attribute values, or are coded similarly by codes, cluster analysis is an exploratory technique can be incorporated. The graphical illustration of files or codes provided by the cluster analysis diagrams facilitates to discern the similarities and differences (see Figure 3.18).

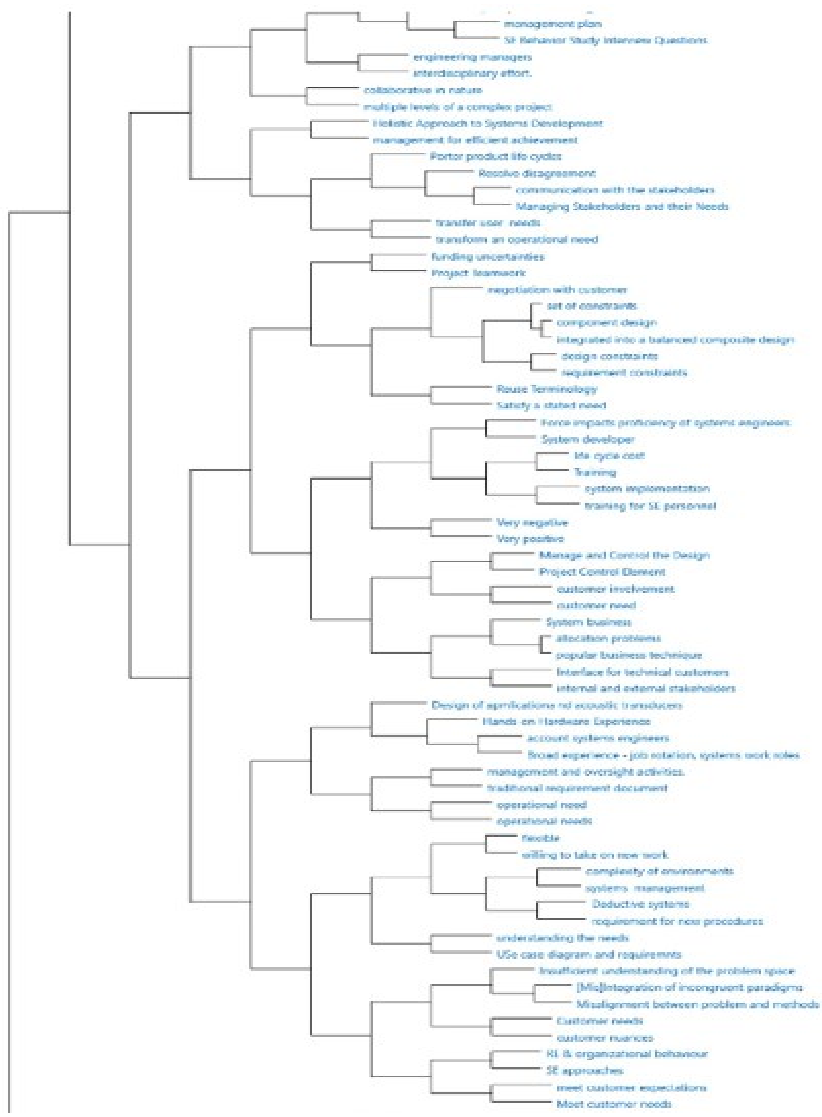


Figure 3.18 Demonstration of Cluster Analysis

Based on the coding procedure, a theoretical model was derived that describes the set of the systems engineering attributes (6 core-codes). These six codes include *Interdisciplinary, Holistic, Requirement Engineering, Design & Integration, Life-Cycle Focused & Management* (see Figure 3.19). Six fundamental systems engineering attributes were derived based on the highest frequency of coding from the literature during the GTC analysis (Figure 3.20 and Table 3.5). A summary of selective coding is presented in Table 3.4.

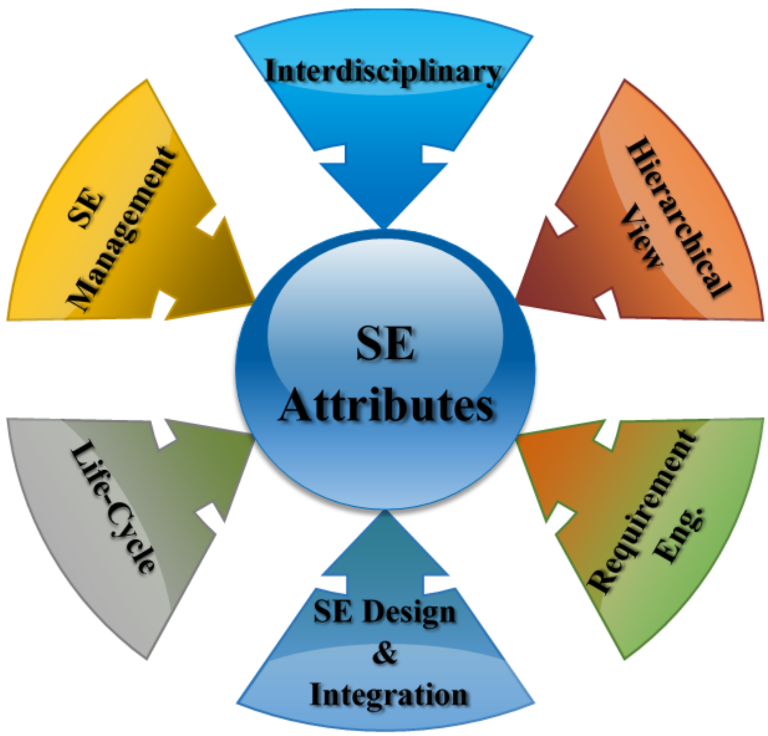


Figure 3.19 Fundamental Attributes of SE

Table 3.4 Summary of Selective Coding

Purpose	Derivation of the core categories
Approaches Used	Conceptualization of the entire analysis
Techniques Used	Cluster analysis, coding strip
Output	6 main systems engineering attributes

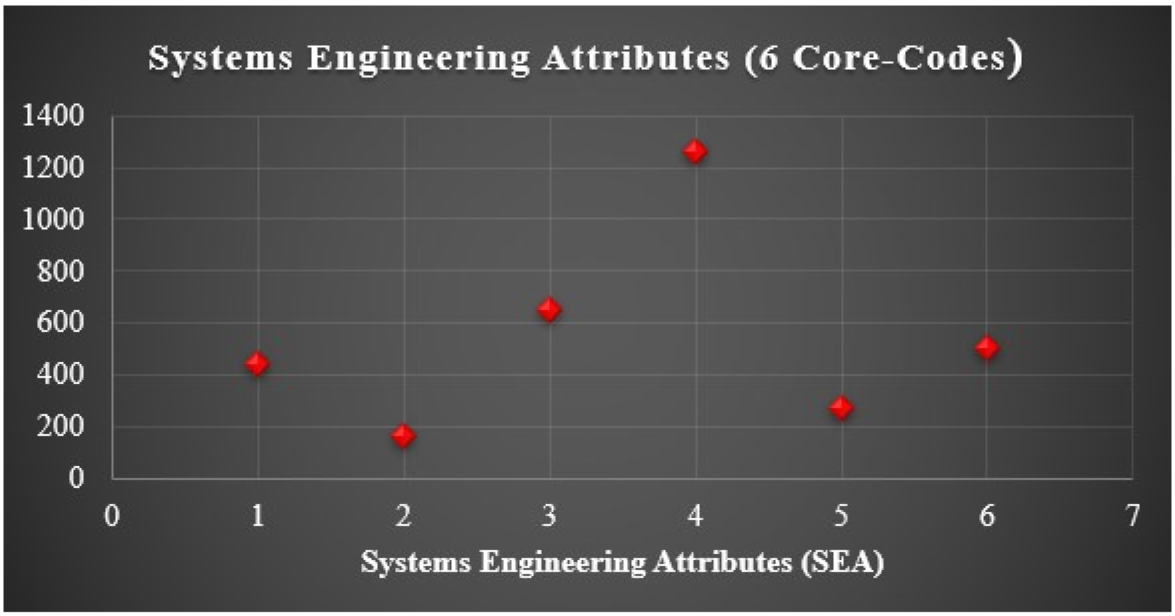


Figure 3.20 Total Number of Coding Reference of 6 Core Codes (attributes)

Table 3.5 Coding Frequency of Main 6 SE Characteristics

Systems Engineering Attributes (SEA) 6 Core-Codes	**Coding**	**Number**
Interdisciplinary	445	SEA1
Hierarchical View	166	SEA2
Requirement Eng.	653	SEA3
Design and Integration	1263	SEA4
Life-Cycle	272	SEA5
Management/ SE Mgt.	504	SEA6

Below is a comprehensive definition for each of the SE attributes based on the literature coding analysis.

3.9 Validation of the Instrument (Qualitative)

3.9.1 Synthesis of the Definitions of SE

Today, the term systems engineering encompasses many different meanings and interprets to mean different things to different practitioners. This lack of clarity has resulted from the SE literature, which is a fragmented compilation of the use of the term "systems engineering" by practitioners from different fields and domains who define the term from different perspectives based on the nature of their workplace (Kasser et al., 2009; Jaradat et al., 2014). Because of this lack of standardized usage of the term SE, a study of the semantics and terminology related to SE is needed (Jaradat et al., 2017). To meet this purpose, we review the existing definitions from different scholars to provide different perspectives with respect to SE and explore a set of terms that can advance the understanding of the SE domain.

There are many diverse definitions of SE in the current literature. All the definitions are difficult to incorporate here; however, we attempt to demonstrate a summary of SE definitions provided by different scholars that significantly contribute to understand different perspectives of SE. Table 3.6 provides an overview of the existing definitions and the current dialogue of SE.

Table 3.6 An Overview of the Existing Definitions and the Current Dialog of SE

Author(s)	**Holistic Approach**	**Interdisciplinary Approach**	**Requirement Driven**	**Integration & Design**	**Life-Cycle**	**Iterative Process**	**Management Oriented**
Engstrom (1957)		x					
Hall (1962)			x	x			
Jenkins (1969)	x			x			
Military Standard 499A (1974)			x	x		x	x
Wymore (1976)		x		x			
Blanchard & Fabrycky (1981)			x	x	x	x	
P.Mpherson (1986)			x	x			
Forsberg & Mooz (1992)				x	x		
Wymore, (1993)			x		x		
MIL-STD 499B (1993)		x	x	x	x		
INCOSE (1994)		x	x	x	x		
Shehnar (1994)			x	x			x
Shishko (1995)			x	x		x	
Sage (1995)			x	x	x		x
NASA S.Eng Handbook (1995)				x			
Skyttner (1996)				x			x
ECSS-E-10-01 (1996)			x	x	x	x	
Hazelrigg (1996)				x			
Jerome Lake (1997)		x	x				
Grady (2000)			x	x			
Rechtin and Maier (2000)	x	x		x			
Arnold, 2000.							
DoD System Mgt. (2001)		x	x	x	x		
CMMI (2001)		x	x		x		x
Ferris (2006)	x		x	x			x
Kossiakoff et al., (2011)	x			x			
Gräßler & Yang (2016)		x					x

This is further supported by the work of Buckle-Henning et al. (2012), where the authors describe systems thinking comprised of 5 major themes. The themes can be mapped to the 6 attributes of systems engineering in Exhibit 6. The themes described are: 1) use of tools, 2) use of cognitive competencies, 3) possession of worldview, 4) holding particular ethics, and 5) sense of belongingness (Buckle-Henning et al., 2012) with the mapping provided in Table 3.7.

Table 3.7 Attributes Mapped to Buckle-Henning et al. (2012) Themes

Attributes	***Use of Tools***	***Cognitive Competencies***	***Worldview***	***Ethics***	***Belongingness***
Interdisciplinary		•			•
Hierarchical View			•		
Requirements	•				
Design & Integration	•				
Life Cycle			•		
Management				•	•

In addition to the themes previously discussed, the INCOSE Systems Engineering Principles Action Team reviewed systems postulates, principles, and hypotheses identified in the literature, with a focus on the NASA Systems Engineering Research Consortium works. These 15 principles can be found in the work of Watson titled “Systems Engineering Principles and Hypotheses” (Watson, 2019). These principles are accepted truths that apply throughout the systems engineering discipline and guide the application of systems engineering practices. The six attributes put forth in Figure 3.19 can be mapped to the principles set forth by Watson. The mapping is shown in Table 3.8. While the principles identified are related to each attribute, the bolded principles map directly to the attributes as shown. For example, Principle 13 states “Systems engineering integrates engineering disciplines in an effective manner” (Watson, 2019), which is a direct mapping to the *interdisciplinary* attribute.

Table 3.8 Attributes Mapped to Watson (2019) Systems Engineering Principles

Attributes	*Systems Engineering Principles*
Interdisciplinary	5, 6, 9, 10, **13**
Hierarchical View	**2**, 6, 10, 15
Requirements	1, 2, 4, **6**, 7, 10
Design & Integration	1, 2, **5**, 6, 10
Life Cycle	1, 6, 7, 10, **11**
Management	3, 4, 6, 7, **8**, 9, 10, 12, 14, 15

**Digit represents the state number of the principles*

All the above discussions boiled down to the theme that *systems engineering* is inherently interdisciplinary in nature because it integrates several disciplines to create a new product or system to meet stakeholder needs. Taking a holistic perspective is fundamental to fully meeting customer requirements across the entire system life cycle. Requirement engineering is an essential aspect of the process of fulfilling customer demands from the identification of the need to final execution. Integration, design, and optimization refer to the iterative process of designing, evaluating, verifying, and refining a system to optimize its performance. A lifecycle view of a system considers the various sub-phases that fall into one of the two broad phases of acquisition and utilization. Along with technical skills, management acumen is critical to ensure the planning, development, and execution of an effective system. These core components form the basis of the definition of systems engineering as "a management-based holistic interdisciplinary approach that addresses the entire product life cycle, which involves designing and integrating the system elements in order to meet customer demand" (Hossain & Jaradat, 2018). *So, described succinctly, the synthesis of the SE attribute literature is consistent with our aforementioned six fundamental SE attributes that were derived from the grounded theory approach.*

There are few new disciplines such as systems of system (SoS), families of systems, model-based systems engineering concept, and cognitive psychology have been evolved over the years and converge with TSE. System of Systems (SoS), which is grounded in general systems theory, treats the problem domain problem from the holistic perspective and deploys the efforts by considering the common goal of the entire complex systems (Jaradat et al., 2017, Jaradat & Katina, 2011, Keating & Katina 2011, Katina et al., 2003). Groupings of SoS can be further characterized by the Federations of system (FoS)(Adcock, 2015). In the past decade, model-based systems engineering (MBSE) has appeared as a modern SE tool that covers all the SE approaches, including requirement analysis, architectural design, product development, verification and validations, and documentation and configuration management in order to make the job easy for the systems engineers (Elakramine, 2020; Kerr, 2020; Hallqvist, 2016).

3.9.2 The Development of Instrument (Summary)

As we discussed before, the instrument was developed using a mixed approach method by scrutinizing both qualitative and quantitative data for analysis. In order to pursue the objectives of the research, we have studied, analyzed, and coded more than three hundred different resources, including letters, conference proceedings, scholarly presentations, peer-reviewed journal papers, technical papers, and book chapters. The criterion that leads the selection of more than one hundred and fifty seminal works that contributed most to the domain of systems engineering as identified by the frequency of citation for the work. *The grounded theory* approach was applied with the help of Nvivo 12 (QSR International) software in organizing, analyzing, and synthesizing the qualitative data. Grounded theory coding is an established qualitative data analysis methodology that generates a theory or visual model by employing explicit coding and analytic procedures to organize a large unstructured data set including surveys, interviews, literature reviews, videos, and others into a coherent representation (Glaser & Strauss, 1967, p.103). Thus, this technique helps in developing a more general theoretical concept (or hypothesis) from the available resources.

After completion of the final stage of coding, a theoretical model has been developed, and a new theory is obtained. This theory represents the set of systems engineering attributes (6 core-codes) and the corresponding performance indicators for each attribute. The six core codes were derived after examining the patterns in the dataset using three main progressive stages of coding: open coding, axial coding, and selective coding. We further conducted an extensive review of the literature to derive the corresponding performance indicators for each attribute (please see the list of appropriate references on page 120). The description of the six attributes and the corresponding performance indicators for each attribute are presented in Table 3.9 and Figure 3.21, respectively.

Table 3.9 Definition of Six Main Attributes of Systems Engineering

Attributes	**Description**
Interdisciplinary	Integration of diversified disciplines in order to deal with complex system problems and to provide top-notch solutions during the design and development stages of a system.
Hierarchical View	Perception about a problem, its environment, and solution. The viewpoint of a systems engineers, whether he/she is considering the entire system as a whole or only focusing on a set of disconnected parts.
Requirement Engineering	Refers to a series of actions, including identification of stakeholder need, eliciting requirements, modeling and analyzing requirements, agreeing on requirements, and communicating the requirements in order to fulfill customer expectation.
System Design and Integration	Represents design, integration, verification of sub-elements/elements through a logical sequence to optimize the performance of the system.
System Life Cycle	Defines the stages involved in bringing a system from inception to phase out.
Management/Systems Engineering Management	Technical skill set in conjunction with a broad understanding of business principles to oversee the system processes in order to enhance system performance.

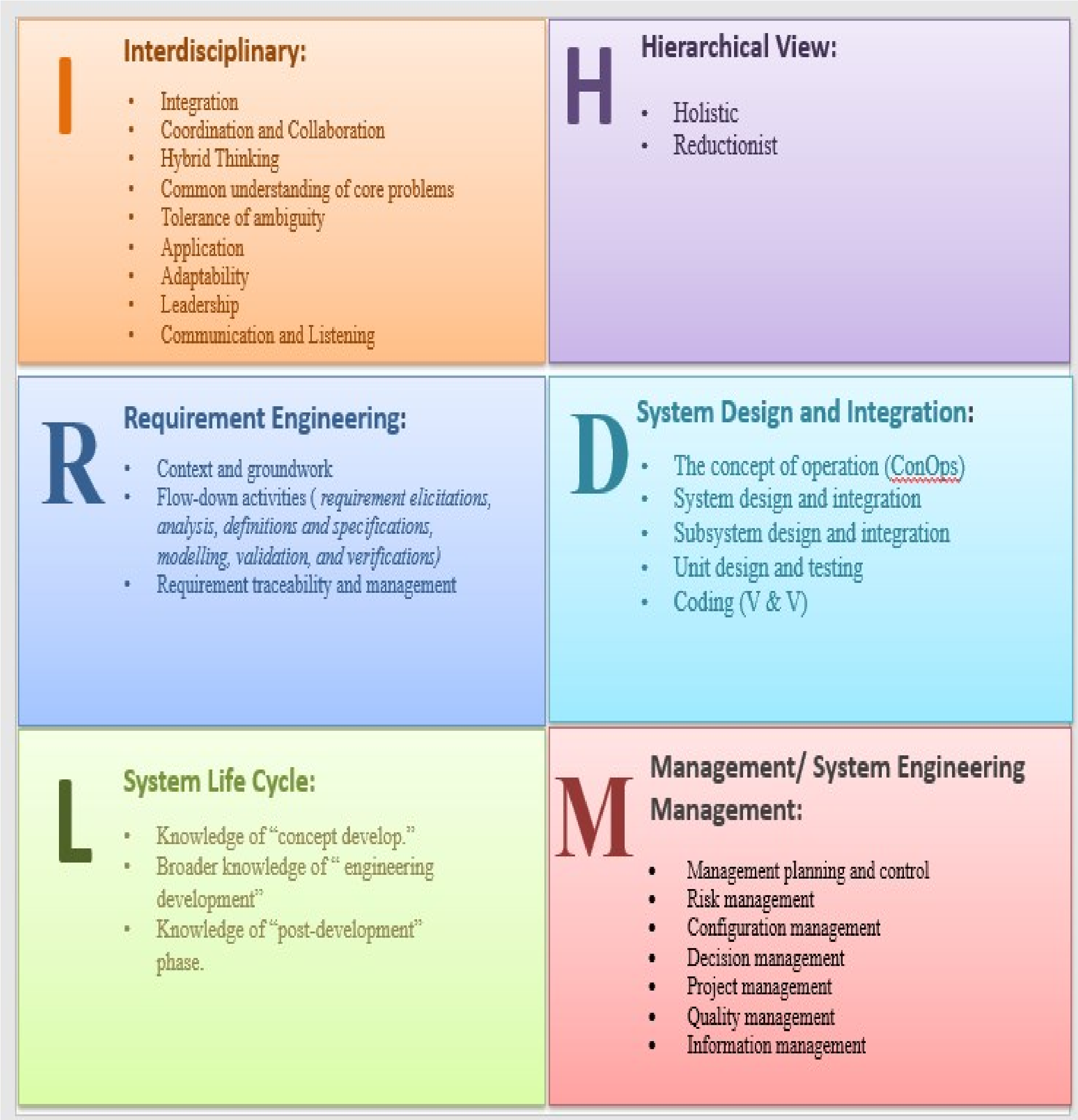


Figure 3.21 Performance Indicators of the Corresponding SE Attributes

The anatomy of the SE performance measurement instrument with its two extremes is illustrated in Table 3.10. To begin a detail foray into the performance indicators of SE attributes, readers are directed to study the works of the followings:

Interdisciplinary

- *Integration* (Gräßler & Yang, 2016; Green & Andersen, 2019; Topcu et al., 2020)
- *Coordination and Collaboration* (Silvia Mazzetto, 2018; SILVIA Mazzetto, 2017; Topcu et al., 2020)
- *Hybrid Thinking* (Guenther, 2012; Hopfe & McLeod, 2020; Hossain et al., 2020)
- *Common understanding of core problems* (Alpcan et al., 2017; Bielefeld et al., 2019; Naidoo, 2017)
- *Tolerance of ambiguity*(Khan, 2020; Shima et al., 2019; Tsirikas et al., 2012)
- *Application* (Eigner et al., 2012; Kernschmidt & Vogel-Heuser, 2013; Legner et al., 2017)
- *Adaptability* (Albers & Lohmeyer, 2012; Graessler et al., 2018; Sheard et al., 2015)
- *Leadership* (Legner et al., 2017; Niine & Koppel, 2015; Pineda et al., 2012)
  Communication and Listening (Costa et al., 2019; Gilbert et al., 2015; Silvia Mazzetto, 2018)

Hierarchical View

- *Holistic* (Königs et al., 2012; Locatelli et al., 2014; Madni & Sievers, 2018b)
  Reductionist (Bakshi, 2019; Jaradat, 2015; Rebovich Jr & White, 2016)

Requirement Engineering

- *Context and groundwork* (Dutta et al., 2013; Hossain et al., n.d.; Martins & Gorschek, 2016)
- *Flow-down activities*
  (requirement elicitation, analysis, definition (define constraint) and specifications, modeling, validation, and verification) (Salado & Nilchiani, 2017; Tabassam & Al-Qahtane, 2019; Yasseri, 2014)
- *Requirement traceability and management* (Osman, 2018; Shah & Patel, 2014; Shukla et al., 2012)
  (Change management, evolving requirement

System Design and Integration

- *ConOps (the concept of operation)* (Flores et al., 2012; Mindock et al., 2017; Watson et al., 2020)
- *System design and integration* (Retho et al., 2014; Seo & Park, 2018; Twomey, 2017)
- *Subsystem design and integration* (Madni & Sievers, 2018b; Reilly et al., 2017; Seo & Park, 2018)
- *Unit design and testing* (Alblawi et al., 2018; Flores et al., 2012; Rutishauser et al., 2019)
- *Coding (V&V)* (Akeel & Bell, 2013; Carrozza et al., 2018; Hossain & Jaradat, 2018)

System Life Cycle

- *Knowledge of "concept development"* (Fleming & Leveson, 2015; Haberfellner et al., 2019; London, 2012)
- *Broader knowledge of " engineering development"* (Buede & Miller, 2016; Frank, 2012; Schumacher et al., 2013)
  Knowledge of "post-development" phase (Bocciarelli et al., 2014; Hossain et al., 2020; Lester, 2018)

Management/Systems Engineering Management

- *Management planning and control* (De Graaf et al., 2017; Hirshorn et al., 2017; Wognum et al., 2019)
- *Risk management* (Fomin et al., 2017; Galli, 2020; Rebentisch & Prusak, 2017; Hossain et al., 2019e)
- *Configuration management* (Lopez et al., 2020; Madni & Sievers, 2018a; Xue et al., 2017)
- *Decision management* (Cilli & Parnell, 2016; Martin & Minnichelli, 2020; Schindel & Dove, 2016)
- *Project management* (Haberfellner et al., 2019; Hodges, 2018; Lachhab et al., 2017)
- *Quality management* (Brown et al., 2019; Carrozza et al., 2018; Hodges, 2018)
  Informantaion management (Chen & Jupp, 2019; Cui & Li, 2018; Legner et al., 2017)

Table 3.10 Summary of SE Performance Measurement Instrument

Low-level Competency	Attributes	High-level Competency	Performance Indicators
Autonomy (I-): Intended for or likely to work with a small number of people with a specialized domain of interest.	Interdisciplinary (I): Integration of diversified disciplines in order to deal with complex system problems and to provide top-notch solutions during the design and development stages of a system.	Collaborative (I+): Intended to cooperate with a different group of people from diversified disciplines.	*-Integration* *-Coordination and Collaboration* *-Hybrid Thinking* *-Common understanding of core problems* *-Tolerance of ambiguity* *-Application* *-Adaptability* *-Leadership* *-Communication and Listening*
Reductionism (H-): Focus more on a segmented view and prefer analyzing the individual elements for better performance.	Hierarchical View (H): Perception about a problem, its environment, and the solution. The viewpoint of a systems engineer whether he/she is considering the entire system life cycle as a whole or only focusing on a set of disconnected parts.	Holism (H+): Focus on the whole, interested more in the big picture, and interested in concepts and abstract meaning of ideas.	*-Holistic* *-Reductionist*
Underspecify Requirements (R-): Prefer taking few perspectives into consideration. Focuses more on the internal forces, like short-range plans tend to settle things.	Requirement Engineering (R): Refers to a series of actions including identification of stakeholder need, eliciting requirements, modeling and analyzing the requirement, agreeing on requirements, and communicating the requirements in order to fulfil customer expectation.	Embracement of Requirements (R+): Prefer taking multiple perspectives into consideration, over-specify requirements, focus more on the external forces, like long-range plans, keep options open, and work best in changing environment.	*-Context and groundwork* *-Flow-down activities (requirement elicitation, analysis, definition (define constraint) and specifications, modelling, validation and verification)* *-Requirement traceability and management (Change management, evolving requirement)*
Local Design and Integration and Optimization (D-): Focus on design, integration and optimization on the local subsystem.	System Design and Integration (D): Represents design, integration, and verification of sub-elements through a logical sequence to optimize the performance of the system.	Global Integration (D+): Focus on global integration, tend more toward dependent decisions and global performance of entire system elements.	*-ConOps (the concept of operation)* *-System design and integration* *-Subsystem design and integration* *-Unit design and testing Coding (V&V)*
Individual Phase (L-): Focused more on individual phases.	System Life Cycle (L): Defines the stages involved in bringing a system from inception to phase out.	Complete Life Cycle (L+): Traces a spectrum of iterative sequential methodologies from product inception to completion.	*-Knowledge of "concept development"* *-Knowledge of "engineering development"* *-Knowledge of "post-development" phase*
Low Managerial Skill (M-): Below par business, technical, and interpersonal skill.	Management/Systems Engineering Management (M): Technical skill-set in conjunction with a broad understanding of business principles to oversee the system processes in order to enhance system performance.	High Managerial Skill (M+): Strong business, technical and interpersonal skill.	*-Management planning and control* *-Risk management* *-Configuration management* *-Decision management* *-Project management* *-Quality management* *-Informantaion management*

3.9.3 Quantitative Data

Quantitative data collection, gathering, analyzing, and documenting consists of the following steps:

1. Survey design
2. Sample selection
3. Measure and procedure for data documenting
4. Interpretation of result
5. Data analysis

3.9.3.1 Survey Design

In this study, survey design will be considered as a primary research method. Survey Design provides a detailed description of developing surveys to fulfill the research goal. It allows an administrator(s) to run a survey(s) to a sample or the entire population of people to describe different demographics. The survey administrator will collect the quantitative data via an online survey tool or using ready-made questionnaires' or interviews.

In this study, a cross-section survey will be conducted via an online survey tool- Qualtrics. *The cross-sectional study* is also known as transverse study to analyze the data in order to measure a particular outcome from the study participants at one given point of time.

3.9.3.2 Sample Size and Data Collection

In this study, the performance measure survey instrument was used to collect data during the testing phase of the research. Primary data for the research was collected in two phases. During the first phase, data were collected from the participants who took part in the pilot test. The pilot test was deployed due to its ability to reduce the systematic and random errors in the instrument and to gather feedback and suggestions from experts in the field.

In the second phase, data was collected from the target group for this study that includes the systems engineers focused group. For data collection purposes, an invitation letter will be sent via e-mail to invite all participants who were working in systems engineering problem domains. Upon their written consent, a web-link with instructions and survey scenarios was sent via Qualtrics to the participants. The participant includes the practitioners from NASA, Boeing, US Army, US Navy; and undergrad and graduate students who have completed at least one SE project as part of their coursework. The participant will be asked to record the following demographics during the survey: age, gender, race, educational qualifications, employer type, job title, work experience, managerial experience, type of organization, and size of the organization.

3.9.3.3 Measures and Procedures for Data Documenting

The data reported here will be collected to assesses the skill of systems engineering based on the set of performance measurement indicators of six fundamental SE attributes. The proposed instrument consists of 29 scenarios with binary response question options. These scenarios were developed based on the extensive literature review pertaining to performance indicators for each SE attribute to assess the performance of an individual's systems engineering skills. As an example, the scenario for the *Requirement Engineering* dimension is presented below:

***Suppose you are a requirement engineer, working in an inflight entertainment (IFE) industry. Recently you have a meeting with XYZ airlines who are excited to launch their new aircraft Boeing 777 with most-updated, feature-rich, display system for customers to enjoy onboard.*

After successful conversation with the stakeholders, we assume that you have properly elicited the requirement for the inflight display features. Based on your requirement elicitation statement, design team will start designing the inflight monitor. As you are bridging the gap *between stakeholders (customers) and design team, so your elicitation performance matters, i.e, whether you have properly extracted or discovered the requirement information from the stakeholders (customer).*

1. *Based on the discussion with XYZ stakeholder, the requirement of the inflight passenger monitor could be elicited as:*

- *The inflight monitor display must be user friendly*
- *The inflight monitor display shall provide dual mode view, superior viewing angles, LED backlit LCD for the user*

2. Based on the scenario, proceeding requirement can be written elicited as follows:

1) For the setback monitor, temperature unit shall be displayed in U.S format and for central dropdown(overhead) monitor; temperature unit shall be displayed in European format.
2) The unit of the temperature shall be displayed based on the format of the destination country for both types of monitors.

2. *Based on the scenario (RQ#1), one of the features of the display system can be written as follows*

- *The seat back monitor display shall never be in sleep mode during the long-haul flight.*
- *The seat back monitor display shall be in sleep mode in every 10 minutes if its multimedia system is inactive during the long-haul flight.*

3. *Based on the scenario (RQ#1), one of the features of the display system can be written as follows*

- *All the monitors for the aircraft shall be configured with 4k resolution, 21:9 aspect ratio and 34-inch flat screen monitor.*
- *The central dropdown (overhead) monitors for the aircraft shall be configured with 4k resolution, 21:9 aspect ratio and 34-inch flat screen monitor.*

5. In order to make a concise requirement statement, requirement should be elicited as:

- *On the seatback screen, the user can only view one record*
- *Stored Flight screen, the system shall display only destination time zone*

6. *It won't happen often, but sometimes the display of the seatback monitor get frozen or appears with a black or blank screen. To provide the solution for this problem, you are developing user guide for the inflight seatback monitors. The instruction could be written as:*

- *If screen becomes frozen and unresponsive, press and hold the "Power" button for a short period.*

- *If screen becomes frozen and unresponsive, press and hold the "Power" button for 30 seconds.*

7. *The stakeholders provided multiple specifications for the user awareness such as during the high turbulence, warning light will flash out, and seatbelt sign will blink in the display. These elicited requirement should be easily traced through to the specification, design and testing phase. As a requirement engineer, which of the following statement is correct you think for better requirement traceability.*

- *High turbulence warning light shall flash out and seatbelt sign will blink in the display when the plane is travelling in turbulence zone*
- *The high turbulence warning light shall flash out in the display when the plane is travelling in turbulence zone.*

8. *Nowadays, the act of traveling is much more luxurious than it has ever been before. Therefore, XYZ airline like to upgrade the collection of inflight entertainment system by offering different films, musics, television programs, and games for different age group and tastes of people. To enhance collection of entertainment system, they are planning to store user information and browsing history while a user is watching and playing different things during the flight time. And they want to store this information in a text format.*

As a requirement engineer, you have elicited the above need from the XYZ airlines and passing this information to the design team. Your statement to the designing team shall be:

- *User information and their browsing history information shall be stored in a text file.*
- *User information and their browsing history information shall be stored in a text file by using Java script.*

**red text shows the correct systemic answer.*

Participants engage with each scenario in order to select the best options based on their systems engineering knowledge. For our scoring purpose, we have coded one point for a systemic response and zero points for each non-systemic response. Then, the sum of the individual response points is divided by the number of total questions for each attribute to obtain the cumulative score for the respective attribute. This score represents the weighted performance for an individual systems engineer's skill state for that corresponding attribute. Finally, the cumulative score will be converted into a percentage scale, which ranges from 0 to 100. The resulting score is then translated into a performance profile that contains six main letters. This translation is done based on the score obtained for the respective attribute. For instance, for the interdisciplinary attribute, if an individual scores more than 50, his/her letter tag is I^+ (I-plus), which represents that the individual possesses above-average interdisciplinary skill. On the other hand, if an individual score less than 50, his/her letter tag is I^-(I-minus). This means that the individual has below average skill on the interdisciplinary attribute. If an individual's score is equal to 50, he/she gets the letters I (I-plain), which entails that the participant has average knowledge on the interdisciplinary attribute. The performance profiles (6-letters) represent an individual performance in the domain of system engineering. The results of the instrument's application are instructive for systems engineers as well as the organization/teams to which they are assigned. For systems engineers, the results provide a professional development framework of areas that they may need to focus on to enhance their systems engineering skill sets. For organizations/teams, the results of the team members assigned to a particular effort can suggest the diversity of skills that exist on a team. This can be compared to the particular effort to identify potential skill set vulnerabilities that may need to be 'compensated' such that the effort will have a better chance for success. While the instrument results are not the 'definitive' guide to skills, they do provide a valuable indicator to suggest areas of deeper inquiry.

3.9.3.4 Result Interpretation/ Outcome of the Profile

The outcome of the proposed instrument will provide a profile that presents the systems engineering skill held by an individual. Each profile consists of six letters that entail the state of skill for each individual system engineer, and thus determine their level of performance to deal with problems emanating from complex systems domain. The systems engineering instrument will guide every individual to identify their strength and weakness on systems engineering knowledge and assess their potential capacity to successfully engage complex system problems. Additionally, while a systems engineer has a particular systems engineering profile, it should be noted that: (1) a profile can be modified through development activities such as training and (2) a particular profile can identify the degree of congruence between demands of a particular assignment and the degree to which an individual possesses skills demanded. An example of an individual systems engineer's profile is depicted in Figure 3.22, and the two extremes of each attribute are shown in Table 3.11.

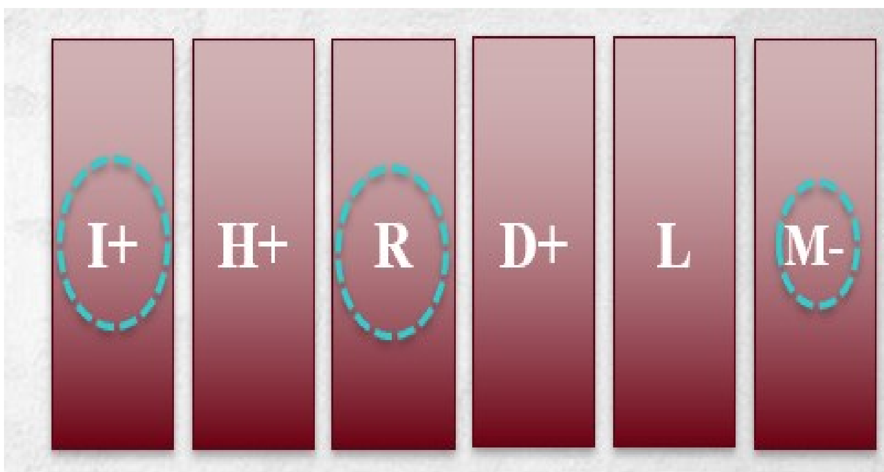


Figure 3.22 An Example of a Systems Engineer's Profile

Table 3.11 Two Extremes of Each SE Attribute

Low-Level Competency	Attributes	High-Level Competency
Autonomy (I^-): intended for or likely to work with a small number of people with a specialized domain of interest.	- Interdisciplinary Skill +	Collaborative (I^+): Intended to cooperate with a different group of people from diversified disciplines.
Reductionism (H^-): Focus more on a segmented view and prefer analyzing the individual elements for better performance.	- Skill on Hierarchical View +	Holism (H^+): Focus on the whole, interested more in the big picture, and interested in concepts and abstract meaning of ideas.
Underspecify Requirements (R^-): Prefer taking few perspectives into consideration. Focuses more on the internal forces, like short-range plans tend to settle things.	- Skill on Requirement Engineering +	Embracement of Requirements (R^+): Prefer taking multiple perspectives into consideration, over-specify requirements, focus more on the external forces, like long-range plans, keep options open, and work best in changing the environment.
Local design and integration and optimization (D^-): Focus on design, integration and optimization on the local subsystem.	- Systems Design and Integration Skill +	Global Integration (D^+): Focus on global integration, tend more toward dependent decisions and global performance of entire system elements.
Individual Phase (L^-): Focused more on individual phases.	- Skill on Systems Life Cycle +	Complete Life Cycle (L^+): Traces a spectrum of iterative sequential methodologies from product inception to completion.
Low Managerial Skill (M^-): Below par business, technical, and interpersonal skill.	- Skill on SE Management +	High Managerial Skill (M^+): Strong business, technical and interpersonal skill.

3.9.3.5 Interpretation of Profiles

The first attribute*, interdisciplinary skill (I),* describes whether an individual has the ability to work in a collaborative environment or not.? The second, *skill on the hierarchical view (H)*, indicates the way individual approaches solving system engineering problems. The third pair, *skill on requirement engineering (R)*, describes an individual's proficiency in the requirement engineering discipline. The fourth attribute, *systems design and integration skill,* indicate an individual's dexterity on understanding the fundamentals of systems design and integration. The fifth attribute, skill on *system lifecycle*, describes an individual's knowledge on systems life cycle management. The final attribute, *skill in SE management*, specifies the way an individual approaches managing systems engineering problems through their business, technical, and interpersonal skill. Based on the profile depicted in Figure 1, an individual has strong knowledge (more than average) on interdisciplinary, hierarchical view, and design and integration aptitude, whereas his/her proficiency level, is below par in management dimension. Additionally, there is a scope of improvement for the requirement engineering and life cycle attributes. The illustration of an example profile as depicted in Figure 3.22 is represented as a scale in the following Figure 3.23. The cross mark – "X" sign shows an individual's skill/performance on each attribute.

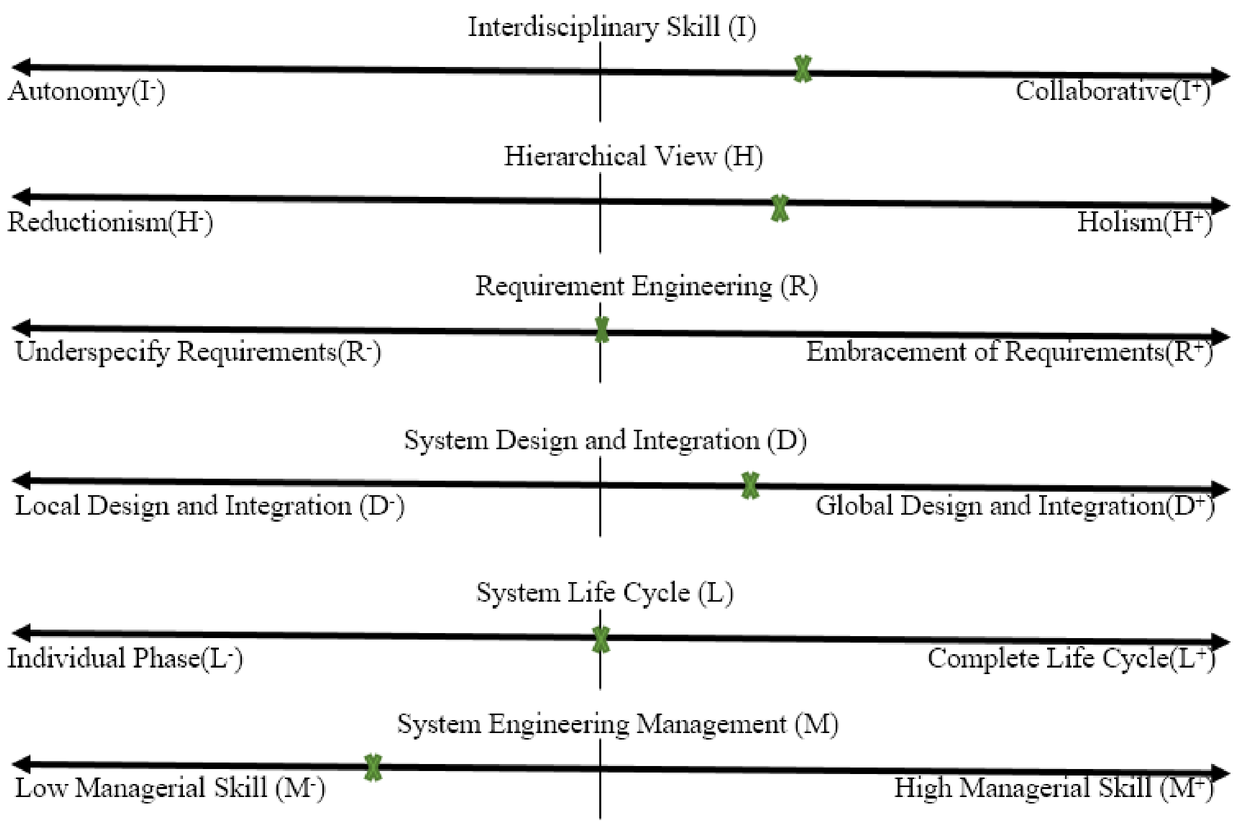


Figure 3.23 SE Performance Measurement Scale

A detailed description of each attribute along with their indicators, is presented below.

3.10 Interdisciplinary

Interdisciplinary is the integration of diversified disciplines in order to deal with complex system problems and to provide top-notch solutions during the design and development stages of a system. To effectively engage in complex systems problems in the systems engineering field, we need knowledge and expertise from disparate areas such as, technical, social, organizational, managerial, and administrative. (Gorod et al., 2008; Jaradat et al., 2018). Thus, measurement becomes an effective gateway to understand the particular capacity of an individual, and team, to engage the entire spectrum necessary to perform systems engineering. The mentioned interdisciplinary performance measurement approach should evaluate the capability of a systems engineer in diverse areas, including (1) integration, (2) coordination and collaboration, (3) hybrid thinking, (4) common understanding of core problems, (5) tolerance of ambiguity, (6) application, (7) adaptability, (8) leadership, and (9) communication and listening. This particular set provides a deep understanding of the capacity of an individual/team to address the holistic spectrum of dimensions essential to more holistically addressing complex systems.

The interdisciplinary characteristic is one that is defined by the engineer's ability to incorporate multiple engineering disciplines into their system, so that they can work in coordination with one another. This characteristic allows the engineer to create unique solutions to problems that may not have been clear to those without this characteristic, creating a valuable asset to any engineering team.

All characteristics have unique performance identifiers that present themselves in systems engineers. For the case of the interdisciplinary characteristic, there is a large amount of these performance identifiers. The first of the identifiers is *adaptability*, which is presented as the ability to change solutions and methods as the requirements for the system change. This relates to interdisciplinary as the systems engineer will be able to seamlessly integrate multiple disciplines in their improvised solution. In order to take charge and make use of all these domains, a strong competency in the indicator of *leadership* must be present. By having this trait, the systems engineer will be able to properly include the multitude of disciplines as well as coordinate their various feedback. One indicator that may not be as obvious is the *ability to tolerate ambiguity* in the system design process. With *coordinating* a multitude of engineering teams, there are going to be a large number of unknowns, it is important that the systems engineer is comfortable with this as their working environment. Being able to include multiple disciplines also within itself contains ambiguity as there is overlap between disciplines, allowing for different engineering disciplines to accomplish the same tasks within the system. Paramount to any systems engineer with the interdisciplinary category is the *ability to communicate and listen* effectively. Without this indicator, proper collaboration cannot be achieved, and more harm than good will be done to the system. Another indicator is that of hybrid thinking. *Hybrid thinking* is the ability to iteratively developing and implementing innovative systems through the use of human-centered experiences. Indicators that may not be a surprise, are integration as well as coordination and collaboration. With a characteristic that heavily involves multiple engineering domains and teams, the ability to organize those teams and integrate those domains,

The extreme of an engineer having a low-level competency in this attribute, would best be described as a sense of autonomy. What is meant by this is that the systems engineer would more than likely prefer to work alone or in a small group that has a specific focus on one aspect in particular about the system. On the opposite end, a system engineer with high competency would be described as collaborative. This engineer would look to involve many engineers from different aspects of engineering to cooperate with a diverse group.

3.11 Hierarchical View

The hierarchical view represents the perception about a problem, its environment, and the solution. More precisely, the viewpoint of a system engineer whether he/she is considering the entire system life cycle as a whole or only focusing on a set of disconnected parts. Jaradat (2015) defined the level of hierarchical view as a personal tendency to view complex problems from either a holistic or reductionist perspective. Keating et al. (2018) posited that “In addition to technical/technology aspects of a system, consideration for the entire influencing spectrum of human/social, organizational/managerial, policy, political, and information aspects central to a more complete (holistic) view of a system. Behavior and performance as a function of interactions in the system – not reducible or revealed by understanding individual constituents” (Keating et al., 2018). By the same token, Gasparatos et al. (2009) stated “our recent awareness of economies, societies, and ecosystems as complex adaptive systems that cannot be fully captured through a single perspective further adds to the argument. Failure to describe these systems holistically through the synthesis of their different non-reducible and perfectly legitimate perspectives amounts to reductionism. An implication of the above is the fact that not a single sustainability metric at the moment can claim to comprehensively assess sustainability” (p. 245).

The *holistic* characteristic can be described as looking at the system as more than just a series of elements, instead of looking at the themes that tie the overall system together. An engineer with this characteristic would focus on the coordination of the different elements and figuring out how they can support each other throughout the system process. This characteristic would be evident regardless of whether the systems engineer was in a position to make decisions regarding the entire system, a subsystem, or a singular element. Although depending on their level of control over design and implementation will impact their ability to utilize the holistic characteristic.

This characteristic has few but clearly defined performance indicators. This means an engineer's ability to think both the reduction and holistic mindsets. This is so that the engineer can view the system as a series of parts, as well as be able to focus on one of the parts in order to provide fixes to any problems that may arise. Having both sides at their disposal makes this engineer able to zoom in and out of the design process as needed, meaning that issues at a lower 'level' of the design should be identified for their impact on the entire system. Lastly, the systems engineer should have an overall sense of the hierarchal view of the project. With this performance indicator, the systems engineer will be able to note which parts of the proposed system is a larger combination of subsystems or a single element. Having this sense is crucial to identifying parts of a system to ensure the flow of the system is properly taken into account, allowing for the impact of the system to be as meaningful to the client as possible. A hierarchal view can also be conveyed to individual teams or engineers in order to ensure that everyone working on the system is aware of exactly how their work impacts the other teams on the project.

An engineer who is deficient in this area would be described as a *reductionist*. This systems engineer would focus on breaking down each element individually and analyze them as a singular unit. By having a narrow focus, the engineer would not look to see how their work affects other elements, but purely towards making their element function the best possible regardless of the impact to the overall system. A very competent engineer in this attribute would be unsurprisingly considered holistic. They would strongly focus on the interaction between the elements in the system and how they interact together as a cohesive unit.

3.12 Requirement Engineering

Requirements engineering (RE) is considered one of the mainstays of systems engineering. RE is concerned with series of activities pertaining to eliciting, analyzing, modeling, documenting, and maintaining stakeholder's requirements (Malviya, 2017; Nuseibeh & Easterbrook, 2000). Although a plethora of different tools, techniques, and methods exist, still developing system requirements in complex circumstances remains a difficult task. The successful accomplishment of this task heavily depends upon the performance of a requirement engineer or business analyst. More precisely, how the requirement engineer retrieves, collating, and combing information for diversified sources such as interview notes, scripts, observations, and business artifacts (Katina et al., 2014; Malviya, 2017).

The requirement engineering characteristic is defined by the ability for the systems engineer to focus directly on the needs of the client and ensure that those needs are met. This characteristic specializes in the ability to define and analyze the stakeholders needs and communicate those effectively to the various teams working on the project.

The performance indicators of this requirement engineering characteristic are very direct. The first is whether or not the systems engineer has the ability to discern the groundwork and context of the system from the given requirements. Ensure that the foundation of the system is solidly within the constraints right from the get-go is important to ensure as the system is built within the client's means. Another key indicator is the systems engineer's ability to *trace the requirements* throughout the system. To ensure the system meets the client's expectations, every element as well as a combination of elements, must fit within the requirements of the system. An engineer with a strong requirement engineering characteristic should be able to see that these requirements hold true under any conditions. Lastly, the performance indicator of *flow-down activities* must be considered. These activities are actions such as modeling, defining, and validating the requirements, be it with the various engineering teams or with the client themselves.

This ensures that all parties involved with the system have a clear and agreed-upon understanding of what the constraints of the system will be.

A system engineer who is not proficient in this area would be focused more on internal forces, such as short-range fixes and plans, and they tend to settle issues rather than taking on multiple perspectives. When an engineer has shown a high ability in this area, they tend to ensure they take in multiple perspectives as well as very specific requirements. Allowing for such openness creates a stronger sense of collaboration, keeping all interested parties invested within the overall outcome of the system. This engineer would also incorporate long term plans and keep their options open. This systems engineer would best showcase their abilities in a dynamic environment, with the opportunity to create order out of the chaos of constant change.

3.13 System Design and Integration

The fundamental purpose of SE is to integrate and design the sub-elements of the system to achieve optimal system performance. It assembles and synchronizes the possible technical inputs and checks the compatibilities among the different interfaces of the system to achieve maximum performance. System design from a systemic perspective emphasizes a holistic frame of reference. This frame must cross not only the technical aspects of design but also the organizational/managerial, policy/political, and human/social dimensions of a complex system. Additionally, integration is focused on making the system perform as a ‘unity’, not simply an aggregate of parts. Therefore, a more ‘systemic’ perspective of integration is focused on performance as unity across the entire perspective of the dimensions of a system.

When an engineer is considered to have the sub-element integration, design, and optimization trait, they possess the ability to discern the various elements of a system and incorporate them to have a strong sense of synergy. This allows for a strong and high-quality flow to the system allowing for the best results to occur.

With the sub-element integration, design, and optimization, there are performance indicators to see if the systems engineer in question has this specific trait. The first of these performance indicators is if the engineer shows strong system/subsystem design and integration abilities. This means the engineer has the ability to design elements that work in conjunction with each other to establish efficient systems or subsystems regardless of the scope or requirement of said systems. This performance indicator also is important in demonstrating the creative thinking of the engineer, as it allows for new and unique methods of combing subsystems and elements. In order to ensure this, another strong performance indicator is the ability to perform *unit testing*. This is to validate the elements and make sure that they function as intended, as well as provide the desired outcome. Checking the flow of the system as early as possible allows for adjustments to be made before time becomes a critical factor within the design or implementation phases. Next, there is the performance indicator of the *concept of operation*. This is the ability to view the system from the angle of someone who will be using the system, either the client or the client's employees. If the design is not viewed from this angle, it is possible that the system will not make sense to any of the operators and therefore be useless as a final product to the client. Lastly is the performance indicator of validation and verification. *Validation and verification* are conducted towards the end of the project and is done so in order to ensure the system design is feasible and running smoothly to the client's liking. This process is conducted through all layers of the hierarchy of the system as a method of checking every possible shortfall of the system before the client receives the final version of the system.

An engineer without competence in this area would focus on local design. This meaning they would focus on the integration and optimization of elements and subsystems at a local level. This can range from only viewing specific elements to individual subsystems with a 'tunnel vision' approach. A highly competent systems engineer would focus on the global outlook of the system. This would be the integration of multiple subsystems as well as considering the global outcome when making decisions to ensure harmony within the final system.

3.14 System Life Cycle

System engineering life cycle follows sequential activities that involve concept development through production and on to operation and ultimate disposal (Kossiakoff & Sweet, 2003; Hossain & Jaradat, 2018). Derivation and development of a life cycle model depends upon the experience and performance of a system engineer as iterative reviews and decisions are part and parcel of the system development life cycle (SLDC) process. To be a competent system engineer, an individual should have a comprehended grasp of knowledge on every phase of SDLC; however, knowledge on separate phase might also lead to be an effective systems engineer for that specific phase only.

A system engineer with the lifecycle characteristic is one who takes into account the broad lifecycle of the entire system. This includes the design phase all the way to phasing out the system, as well as the long-term impact the system will have.

As with the other characteristics, the lifecycle characteristic has its own unique performance indicators as well. The first of said performance indicators is the systems engineer must have an understanding of the post-development stage. This stage occurs once the system has been implemented and is being used by the client. It is very important to note as if the client receives a system with a poor post-development result, they will not receive the value intended from the system. The systems engineer must also show competency in the performance indicator of having knowledge of concept development. This is the development of the concepts that will dictate the creation and implementation of the system. Having new and unique concepts as well as using tried and true ones will result in a robust system that feels cohesive to the client. These concepts can be ones that range from individual element concepts or even span the entirety of the system, depending on the need of the client and system. Lastly, when evaluating a system engineer for the lifecycle characteristic, it is important to note their intuition for the performance indicator of broad knowledge over-engineering development. The performance indicator will manifest itself as the ability to understand a wide variety of development methods to ensure the best method for the system's goal is being used, rather than the first method the engineer can think of. Having more 'tools' in their 'toolbox' will benefit the client as well as the system as a whole.

One who is not well versed in this attribute would focus on the individual phases, and how exactly they are managed. On the opposite end of the spectrum, a highly skilled systems engineer in this attribute would focus on the complete life cycle. They would use iterative sequence methodologies staring with the creation of the product all the way to the completion of the lifecycle of the product.

3.15 Management/Systems Engineering Management

Management or systems engineering management is described as a technical skill-set in conjunction with a broad understanding of business principles to oversee the system processes in order to enhance system performance. From the management perspective, a systems engineer should develop and maintain excellent performance in diverse managerial facets such as (1) technical skill, (2) understanding of team dynamics and relationship management, (3) motivating people and develop others, (4) self-development, (5) communication, (6) guiding people and managing conflict, (7) problem-solving from a systems engineering perspective, (8) creative thinking, and (9) personal effectiveness. The aforementioned skills can be categorized into two sections- personal and team skillsets. The first category (personal skills) is relevant to the individual/personal capacities of a systems engineer and includes technical skills, self-development, problem-solving, creative thinking, and personal effectiveness. In addition to personal skills, a systems engineer should have team-skills inclusive of understanding of team dynamics and relationship management, motivating people and develop others, communication, and guiding people and managing conflict. The combination of personal and team-skills would complete the managerial skills of a systems engineer in dealing with complex systems. In other words, a systems engineer should have an appropriate level of personal and team skills to be able to manage complex systems problems.

The management characteristic is defined as having the technical and business skills to oversee a large system engineering effort. This characteristic focuses on the ability of a systems engineer to lead and organize the entire project through ensuring that both the goals and requirements are met in a timely manner. A system engineer with this characteristic is valuable at any level of the system design and implementation as effective leaders at all levels will make the process run efficiently.

Similar to the other characteristics, the management characteristic has its own performance indicators. When undertaking a project, a key indicator is *risk management*. It is very important to weigh the pros and cons of various elements and methods when creating a system, being able to manage these risks is an important aspect of the management characteristic (Hossain et al., 2016; Lawrence, 2020a; Hossain et al., 2019a,d; 2020b,d). Another key performance indicator is *information management*. The system works as a large combination of smaller more intricate elements. If the various elements and their engineers do not have proper information such as the deadline, goal, or even budget of the project, it will be impossible for the project to be able to be finished. Therefore, the direct and proper flow of information is key to a successful project. On top of that, the systems engineer must be proficient in *planning and controlling* the project. This has to do with laying out the order in which elements are to be completed, as well as ensuring the project sticks to that proposed schedule. Along these lines are also the indicators of *configuration and decision management*. Both of these indicators evaluate the planning process and have to do with ensuring that the proposed schedule fits all the various constraints that both the client and teams have developed. Lastly, the performance indicator of *quality engineering* must also be considered in the systems engineer. Quality engineering in this case is referring to the effectiveness of the various elements as well as the system as a whole. It falls to the responsibility of the manager to ensure the project is completed to the client's preferred precision level (Hossain et al., 2013; Hossain & Jaradat, 2018).

An engineer with low managerial skills could be described as having low interpersonal skills, which effects the ability to properly convey business and technical ideas. A system engineer with high managerial skills would use their exceptional interpersonal to easily convey business and technical ideas. Application of SE attributes are described in Table 3.12.

Table 3.12 Application of SE Attributes

Systems Engineering Attributes (6-SEA)	Application Process
Interdisciplinary	• Be knowledgeable about the abilities that different groups working on the system have. • Identify points in the system in which different engineering disciplines will need to be used together. • Utilize different disciplines to create an optimal system. • Meet with team members of different disciplines to ensure their discipline is being utilized to the fullest extent.
Holistic	• Identify the overall goal of the project. • Focus on the overall concepts that are dictating the creation of the system as a whole. • Utilize abstract concepts in order to enhance the overall productivity of the system. • Conceptualize the system during the design phase to allow for top-down tools to be implemented properly
Requirement Engineering	• Develop a concise list of what constraints are critical for the system to follow. • Itemize external forces that may affect the system once deployed. • Be reactive to changes that may occur and allow for room to make said changes to either the system or requirements. • Integrate multiple perspectives on solving the problem in order to ensure the best system is created.

Table 3.12 (continued) Application of SE Attributes

Systems Engineering Attributes (6-SEA)	**Application Process**
Sub-Element Integration and Design	• Focus on how individual parts of the system will work to improve each other. • Avoid focusing too much attention to a singular element within the system. • Base decision making to a global project scale. • Use verification tools to ensure the proper cohesion of the system.
Lifecycle	• Develop a clear understanding of how the system will evolve over time. • Focus on the long-term impact of the project. • Identify methods to allow for smooth transitioning between stages in the life cycle. • Be conscious of the current stage of the lifecycle and what the next stage is going to require in order to plan in advance.
Management	• Delegate tasks to each team member based upon their individual skills. • Develop and maintain a schedule to reach the appropriate deadline. • Keep track of costs in order to ensure the project is completed within the allotted budget. • Have the technical knowledge to help team members with problems that arise at any point in the life cycle of the system.

CHAPTER IV

DATA ANALYSIS, RESULTS, AND INTERPRETATION

4.1 Descriptive Statistics

In this section, patterns of the dataset are explored, which is the first step in analyzing a dataset (Field, 2013). The main theme of the descriptive statistics is to gather not only insights about the distribution of the sample but also garner ideas of various characteristics of the sample structure. There were 12 demographic questions designed in the survey instrument (see Table 4.1). The survey was carried out on a focus group in which participants were from academic/ research background including systems engineers/practitioners working in space and defense industries; and the students who have taken systems engineering courses as a part of their course project. A total of 102 respondents participated during the survey, while 69 complete responses were considered for further analysis. The formula for measuring central tendency: mean is shown below.

$$\bar{y} = \frac{\sum_{j=1}^{n} y_j}{n} \qquad (4.1)$$

where **n** = sample size

$\bar{\mathbf{y}}$ = Mean

y_j = value of each observation

The equation for measuring data variation: variance is also in equation 4.2:

$$d^2 = \frac{\sum_j^n (x_j - \bar{x})^2}{n-1} = \frac{\sum_j^n (x_j)^2 - \frac{(\sum_{j=1}^n x_j)^2}{n}}{n-1} = \frac{\sum_{j=1}^n (x_j)^2 - n(\bar{x})^2}{n-1} \tag{4.2}$$

In equation 4.2,

d^2 = variance

x_j = all the items in the sample

$\bar{x}$ = the mean

n = total number of samples

Table 4.1 Descriptive Statistics

Demographics	**N**
Gender	69
Highest Level of Qualification	69
Filed of Highest Degree	69
Current Employment Status	69
Course/Certificate Related to Systems Engineering and/or have an Institutional Degree on Systems Engineering	69
Type of Employer	69
Level of Decision-Making Authority	69
Work Environment	69
Years of Overall Work Experience	69
Years of Managerial Experience	69
Years Working in Current Organizations	69
Role as a Systems Engineer	69

Details of the Demographics

To graphically illustrate the patterns in the dataset and meaningful insights, graphs and figures are used. The bar graphs shown below depicts the distribution of the *gender* of the respondents. The vertical axis represents the number of respondents and on the horizontal axis, the type of gender is placed. From Figure 4.1 it is clear that the number of male respondents was 51 and female respondents were 17.

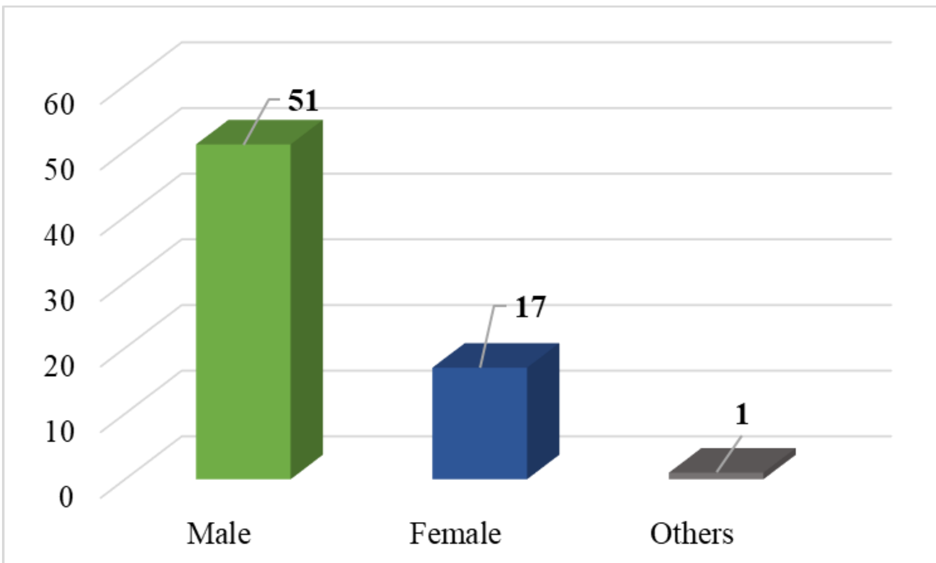


Figure 4.1 Demographic Details based on Gender

The pie chart shown in Figure 4.2 illustrates the proportion of respondents having a *different level of qualification*. From this diagram, it can be seen respondents having only a bachelor and masters degree adds up to more than half of the total respondents. Other groups constitute only 37% of the total participants.

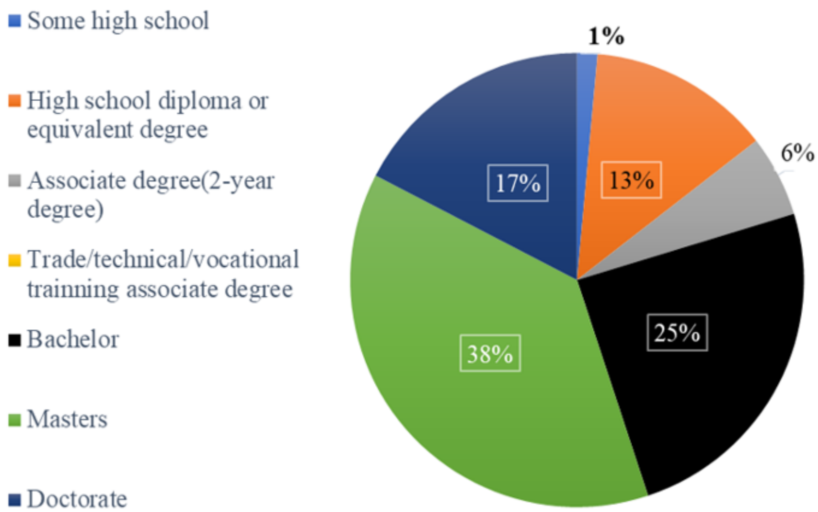


Figure 4.2 Highest Level of Qualification

In Figure 4.3, *the field of qualification* is presented graphically in a way to easily interpret the sample distribution. The highest number of respondents are from applied science background, and the business graduates come in the second position with nine respondents. Aside from these rest of the groups have the relatively same number of respondents; however, there are no respondents from the basic science group.

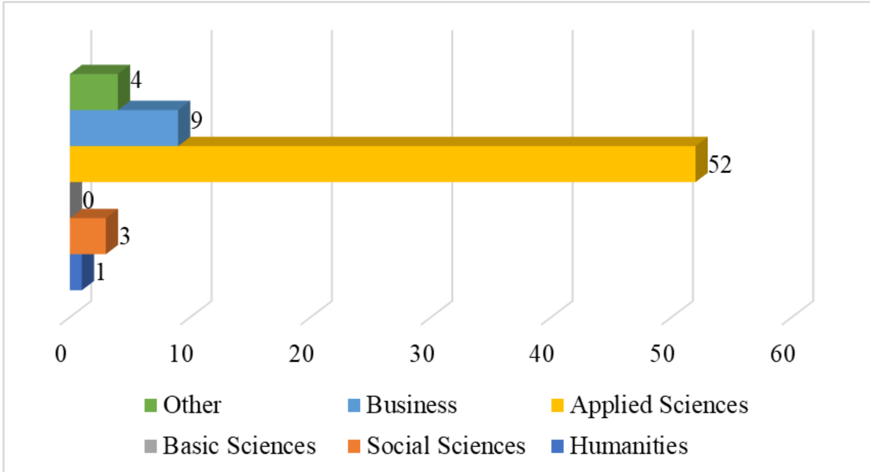


Figure 4.3 Field of Qualification

The bar chart in Figure 4.4 shows the *current employment status* of the respondents. From this diagram, we can see that the maximum number of respondents have a full-time job, which constitutes 30 respondents. Students come in second with 20 respondents. The rest of the groups have around 1 to 7 respondents.

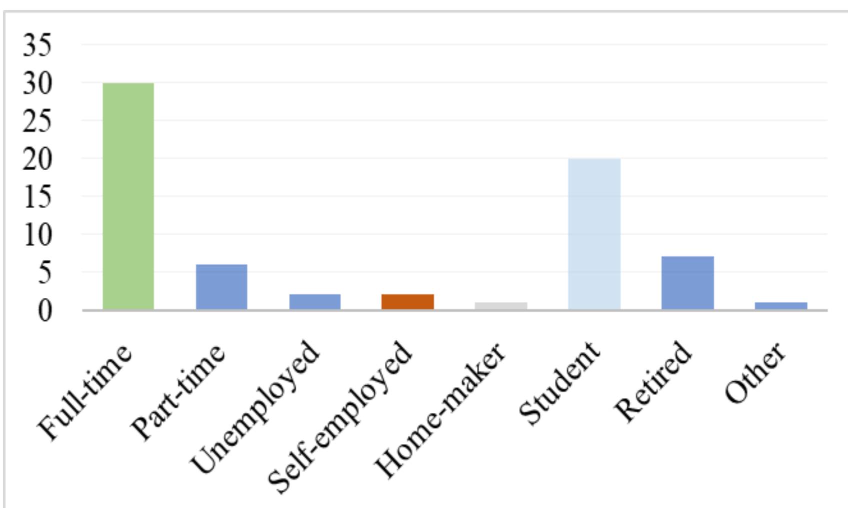


Figure 4.4 Current Employment Status

From Figure 4.5 it can be interpreted that more than twice the number of participants have either have a course/certificate related to systems engineering and/or have an institutional degree in systems engineering.

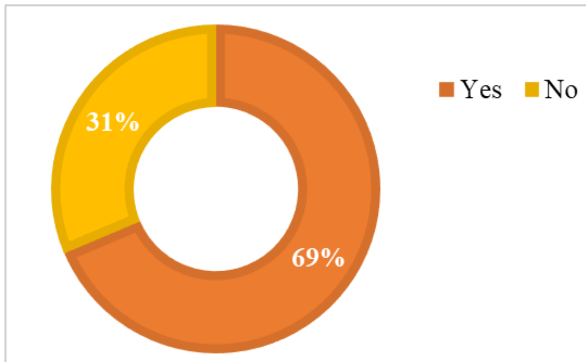


Figure 4.5 Course/Certificate Related to Systems Engineering and/or have an Institutional Degree in Systems Engineering

Figure 4.6 illustrates the *type of employer* of the respondents. It is evident from the bar chart that the highest number of employers are local, state, or government employers. The group of respondents that come in second are the private for-profit with 19 respondents.

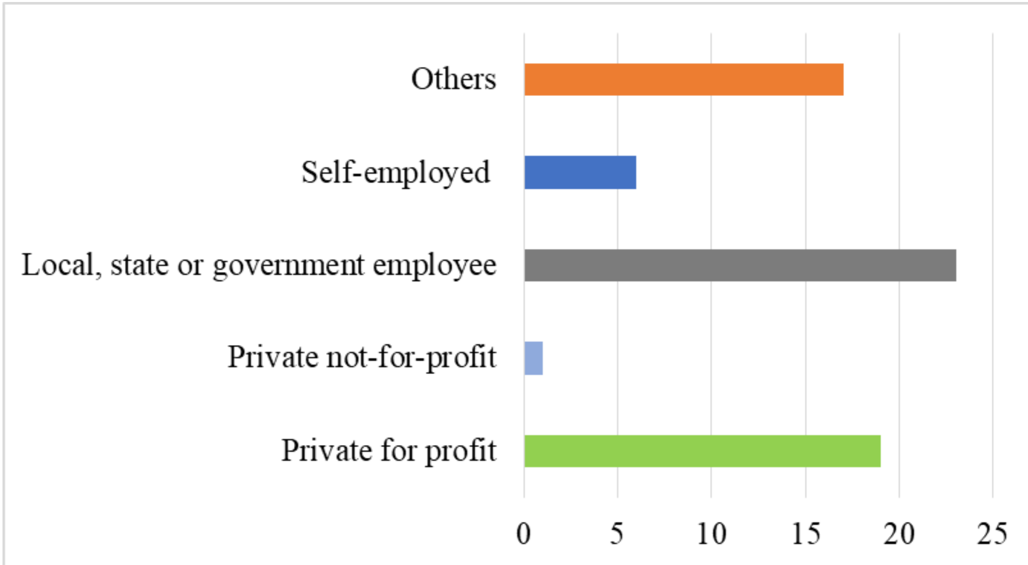


Figure 4.6 Types of Employer

The *level of decision-making authority* of participants is shown in Figure 4.7. The maximum number of respondents have significant decision-making authority. Among all the respondents, 18 have the final decision-making authority, and they come in the second position according to the number of participants.

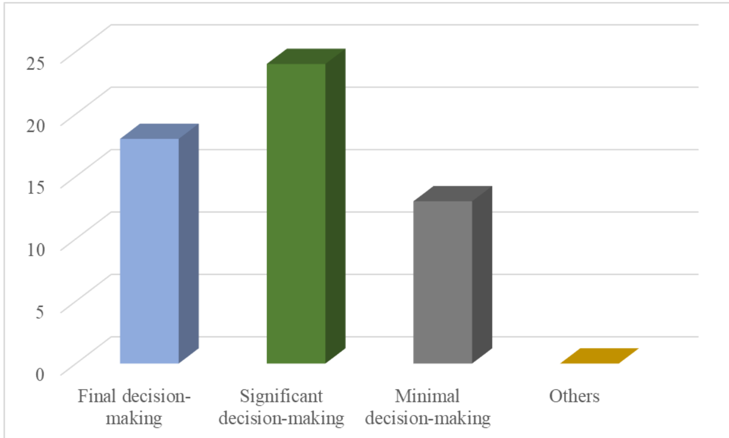


Figure 4.7 Level of decision-making Authority

The proportion of respondents according to the *type of work environment* is displayed in Figure 4.8. The highest percentage of respondents are from an academic/research environment, which accounts for 35%. More than half (68%) of the respondents are either from the academic/research or from the defense environment, which is clear from Figure 4.8. The lowest number of respondents are from the space industry, only 2%.

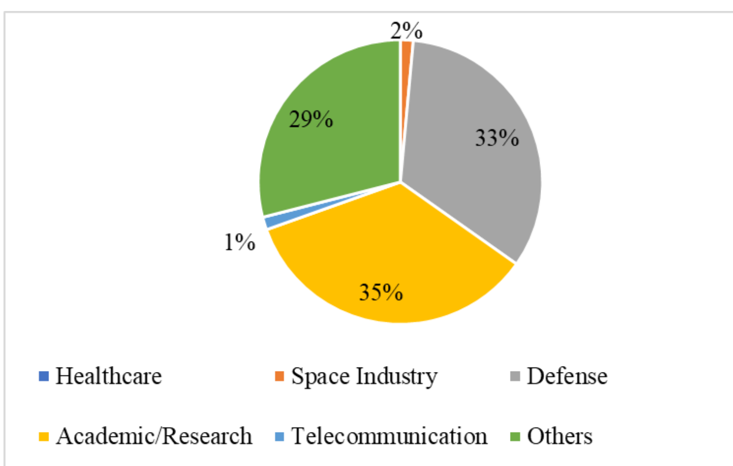


Figure 4.8 Work Environment

The *overall work experience* of the respondents is shown in Figure 4.9. It is evident from the diagram that the highest number of respondents have below 5 years of experience. The rest of the experience interval groups comprise of only 14 respondents.

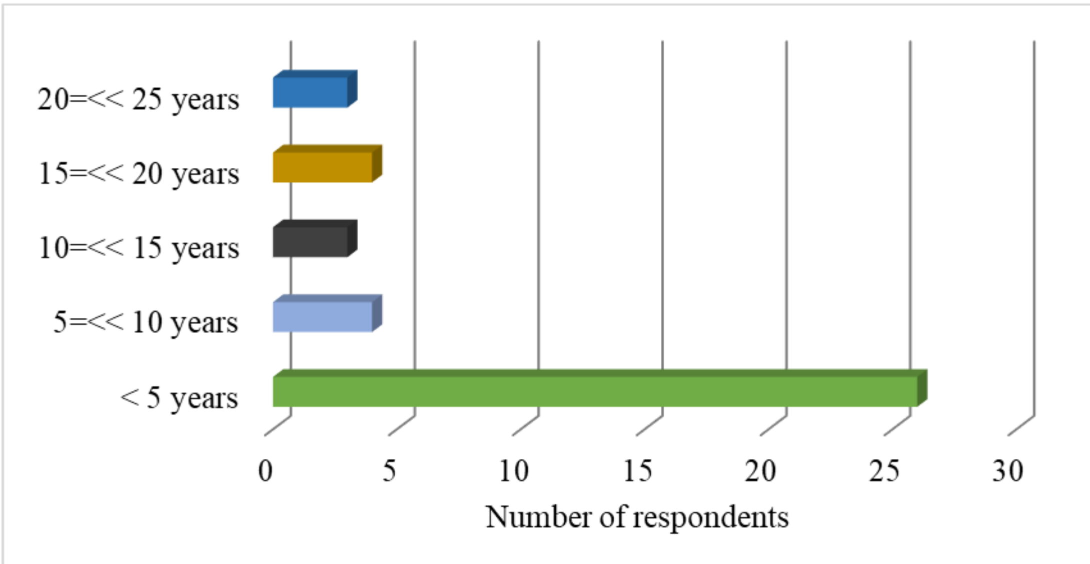


Figure 4.9 Years of Overall Work Experience

From Figure 4.10, we get an insight regarding the *years of managerial work experience* of the respondents. Same as the previous one, the maximum number of respondents have less than five years of experience. Employees having greater than 25 years of experience add up to 22 respondents who are in the second position.

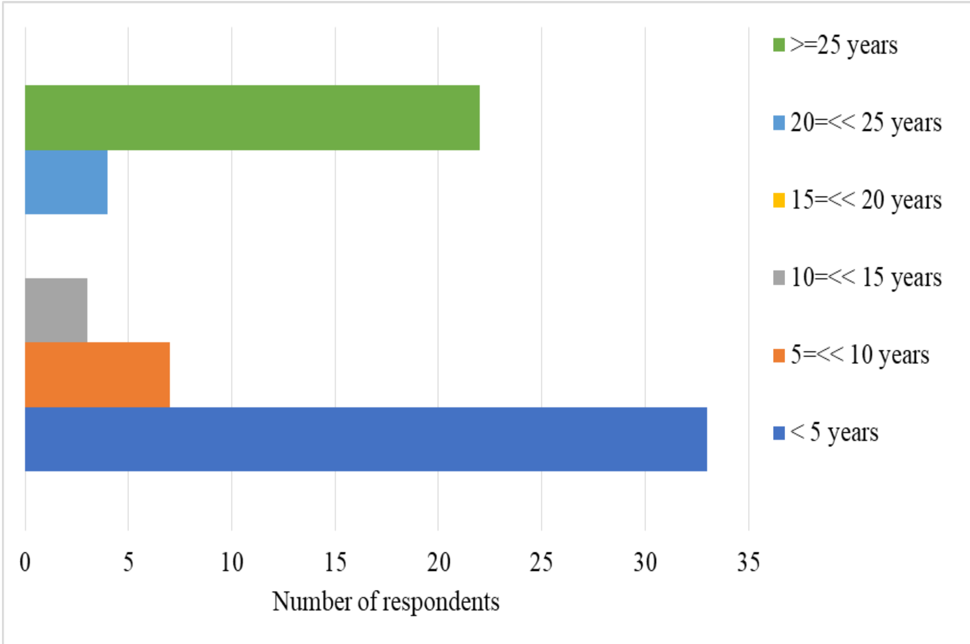


Figure 4.10 Years of Managerial Work Experience

Figure 4.11 illustrates the *years of employment* of the participants. As we can see most of the employees have less than 5 years of employment which comprises 38 respondents.

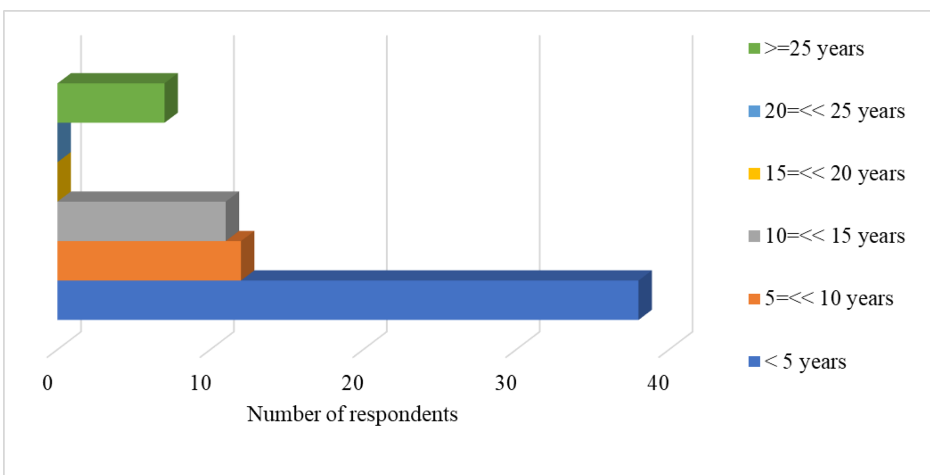


Figure 4.11 Years of Employment

The various *roles* that respondents play as a system engineer in an organization are summarized in Figure 4.12. Here we can see that systems engineers are mostly assigned as logistics/operations engineers and system analysts.

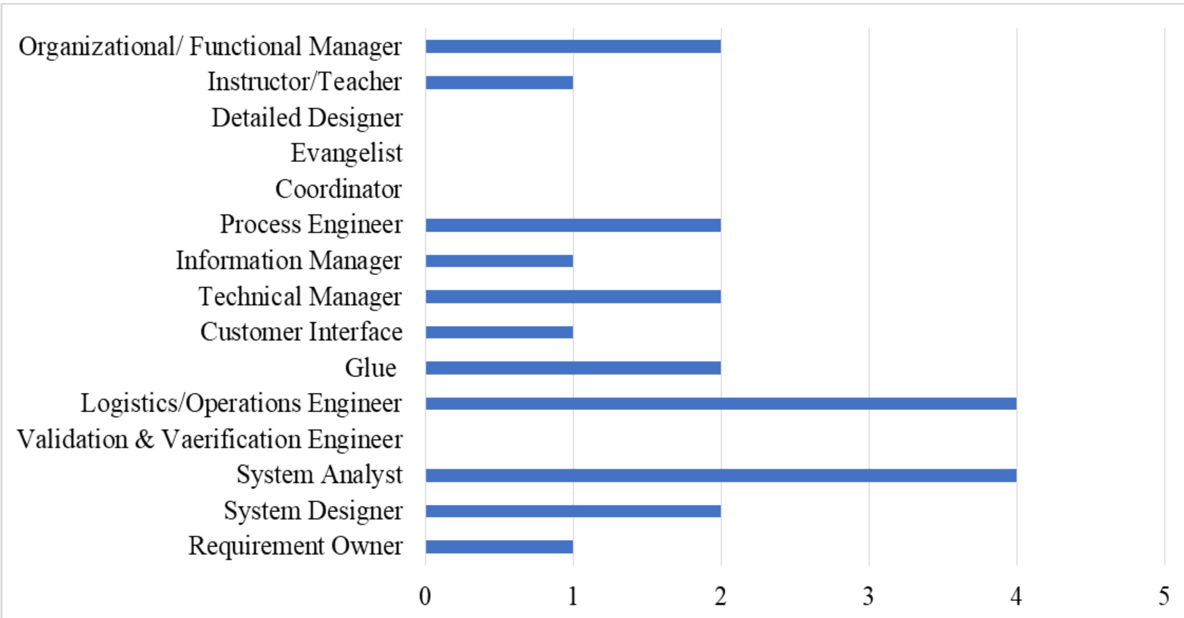


Figure 4.12 Role as a Systems Engineer

4.2 Validation of the Instrument

In any scientific experiment, measurement plays a predominant role, and for this reason, there is a widespread acknowledgment of the significance of 'good' measurement. Measurement is defined as " The assignment of a number to a characteristic of an object or event, which can be compared with other objects or events (Pedhazur & Schmelkin, 2013)". This definition makes it clear that measurement reflects the characteristics of the measured object or event. But how can researchers ascertain that measurements actually represent the measured characteristic, particularly when it is concerned with abstract concepts? In addition to that, it is also needed to quantify the degree to which a measured quantity in fact, represents the characteristics. Since researchers do not just necessarily assume that their measurements woks- they search for evidence in support, the evaluation of measurement is extremely significant. For this reason, two general dimensions are often considered while evaluating measurement methods: *reliability* and *validity*.

4.2.1 Reliability

Reliability of the data and results is one of the key requirements of any research project. It is defined as the extent to which a measurement of a phenomenon provides stable and consistent results (Carmines & Zeller, 2008). So, in essence, an experiment can only be attributed as reliable only when it can be utilized by a variety of researchers in controlled settings with a consistent result and the results don't differ. For instance, a weight scale can only be ascertained as reliable if, under similar conditions, it consistently gives the same results. Moreover, reliability is also concerned with repeatability. A reliable instrument must yield the same consistent result on repeated trials (Moser & Kalton, 1985).

Reliability is one of the fundamental concepts of research design that refers to the consistency of the measures. For any instrument to be reliable, the reading it produces must characterize some true state of the variable being measured. More precisely, the readings (score) generated by the instrument should remain the same unless there has been any genuine change in the variable that the instrument is intended to measure. Develis (2016) defined that "reliability can be measured as a ratio of the estimated true score to the observed score."

$$Realibility = \frac{True\ Score}{Observed\ Score} \tag{4.3}$$

Although the goal of every scientific experiment is to obtain error-free measurements, there is always a certain amount of chance error in the measurement. For example, in a school examination, if it is reliable, it is expected that a particular student who scored well for the first time would have the same score every time he takes the test. However, in reality, in repeated trials under the same condition, identical results are rarely observed in an experiment. There is always a certain amount of chance error in the measurements.

4.2.1.1 Inter Consistency Reliability

When researchers are more concerned with the question of internal consistency of the data rather than the stability across time, internal consistency reliability is assessed. In a reliable experiment, the results might not be identical, but they must be close to each other, or the values must ‘hang together’ (Huck et al.,1974). As a result, the data of the measurements which lie close to each other is attributed to having high internal consistency reliability. Among different methods of assessing the degree of internal consistency reliability, Cronbach's Alpha is most widely used (Streiner, 2003; Whitley & Kite, 2013). It is just a way of calculating the strength of the consistency of the data (Cronbach, 1951). The value of Cronbach’s Alpha is always a number between 0 and 1. Though there is no hard and fast rule regarding the Cronbach's Alpha value and the internal consistency, it is generally accepted that a value of 0.7 and above is considered a good reliability score (Whitley & Kite, 2013). So, if the data are correlated with each other, they have a higher Cronbach’s Alpha value. However, a high Cronbach’s Alpha value doesn't necessarily ensure high internal consistency reliability because the Alpha value is influenced by the length of the test (Streiner, 2003).

According to Nunnally and Benstein (1994), a minimum of 0.7 is acceptable at the exploratory stage, and 0.8 or higher is required at the later stage of the instrument development. The equation of Cronbach’s alpha (Cronbach,1951) can be streamlined as follows:

$$A = N/(N-1)\ \{1-\sum \Theta^2(Y_1)\ \Theta_x^2\} \quad (4.4)$$

Where N refers to the number of items, Θ_x^2 *variance of the total composite, and* $\Theta^2(Y_1)$ *refers to the sum of item variance.*

Table 4.2 Reliability Statistics of Alpha Cronbach

Reliability Statistics

Cronbach's Alpha	Cronbach's Alpha Based on Standardized Items	N of Items
0.668	.709	27

The alpha coefficient for the twenty-seven items is 0. 668, suggesting that the items have relatively shy of its threshold value of 0.70 (acceptable), which may be due to the low sample size.

4.2.1.1.2 Alpha if Item is Deleted

The equation of Cronbach's Alpha can also be written as follows (Kopalle & Lehmann, 1997).

$$\alpha = \frac{k\,\bar{r}}{1 + (k-1)\bar{r}} \quad (4.5)$$

Here, $\bar{r}$ represents the average inter-item correlation among k items while assuming the item variances are equal. So, Cronbach's Alpha becomes a function of both the average inter-item correlation and the number of items to calculate the inter-item correlation.

There is a considerable impact on the Cronbach's Alpha value if some items are eliminated from a set of items while keeping only those that correlate highly. The effect is even more substantial when the sample size is small (Kopalle & Lehmann, 1997). The results of the simulation of (Kopalle & Lehmann, 1997) corroborate the previously held analysis of (Churchill Jr. & Peter, 1984), which concluded that there is a negative relationship exist between the sample size and Cronbach's Alpha value. The reason behind this negative connection is that when the sample size expands the average of k largest items (From equation 4.4) total correlation, thus decreasing the mean inter-item correlation and ultimately lowering the Cronbach's Alpha value.

In addition, there is a positive relationship between the total number of items and the value of Cronbach's Alpha. It is because as the number of items increases, the $\bar{r}$ (average inter-item correlation) in equation (4.4) also increases, which in terms ameliorates the Cronbach's Alpha value (Kopalle & Lehmann, 1997). For instance, if we consider two identical distributions from which a set of 10 items and another set of 20 items will be drawn, the alpha value from the set of 10 items will be less than the alpha value calculated from the set of 20 items.

To sum up, the Cronbach's Alpha value can be inflated by both increasing the number of items and also by deleting items.

Table 4.3 Reliability Statistics of Alpha if item is deleted

Item-Total Statistics					
	Scale Mean if Item Deleted	Scale Variance if Item Deleted	Corrected Item-Total Correlation	Squared Multiple Correlation	Cronbach's Alpha if Item Deleted
Q1	279.6908	2246.268	0.086	0.508	0.608
Q2	279.8647	2239.085	0.23	0.506	0.666
Q3	279.5024	2248.436	0.054	0.508	0.508
Q4	279.5749	2246.806	0.087	0.508	0.608
Q5	279.7198	2248.135	0.043	0.508	0.608
Q6	279.4444	2247.184	0.123	0.508	0.608
Q7	279.7053	2244.959	0.114	0.508	0.537
Q8	279.7778	2249.233	0.018	0.509	0.599
Q9	279.6908	2248.141	0.044	0.508	0.598
Q10	279.5459	2240.493	0.267	0.506	0.566
Q11	279.7923	2234.787	0.325	0.505	0.535
Q12	279.7633	2228.088	0.473	0.504	0.504
Q13	279.8213	2237.766	0.259	0.506	0.524
Q14	279.7053	2234.086	0.356	0.505	0.505
Q15	280.0097	2234.842	0.333	0.505	0.51
Q16	279.4589	2245.699	0.168	0.508	0.608
Q17	280.1691	2244.407	0.149	0.507	0.507
Q18	279.5459	2234.77	0.426	0.505	0.505
Q19	279.5894	2227.614	0.574	0.503	0.503
Q20	279.401	2250.56	-0.018	0.509	0.509
Q21	280.1836	2238.831	0.304	0.506	0.506
Q22	279.4444	2241.658	0.347	0.507	0.607
Q23	279.4444	2241.916	0.336	0.507	0.507
Q24	206.4589	1508.176	0.419	0.412	0.612
Q25	212.256	1598.938	0.244	0.493	0.473
Q26	225.0097	1106.872	0.412	0.448	0.548
Q27	213.1014	1639.325	0.739	0.361	0.661

If “Cronbach alpha if item is deleted” for a component is higher than the overall reliability of the instrument, deleting that component from the instrument will increase the overall reliability of the instrument, which is favorable. On the other hand, if “Cronbach alpha if item is deleted” for all the components are less than the overall reliability, this is very desirable for the instrument, which shows all the components are contributing to the overall reliability and there is no need for removing any components from the instrument. The latter is the case in our instrument, which indicates there is no need for dropping any components of the instrument. “Cronbach alpha if item is deleted” immediately following discussion imply that reliability of each of the components is under original alpha Cronbach value of 0.668. It means all the components are adding to overall reliability of the instrument (that is, 0.668).

4.2.1.2 Composite Reliability (CR)

Just as Cronbach’s Alpha value, composite reliability is just another method of assessing internal consistency (Netemeyer, Bearden, & Sharma, 2003). It can be expressed as the total sum of true score variance in relation to the summation of the scale score variance. The equation to calculate the composite reliability is shown below here. The composite reliability ρ_y is of the p indicators Y_i of a scale score $Y= Y_1+Y_2+\dots\dots\dots+Y_p$ of the scale score (Brunner & SÜβ, 2005).

$$\rho_y = \frac{Var(\sum_{i=1}^{p}\sum_{j=1}^{k}\lambda_{ij}\eta_j)}{Var(\sum_{i=1}^{p}\sum_{j=1}^{k}\lambda_{ij}\eta_j \; + \; \sum_{i=1}^{p}E_i)} \qquad (4.6)$$

Where λ_{ij} represents the unstandardized pattern coefficient of indicator Y_i on factor η_j and the E_i term is the error indicator. The numerator in equation (4.5) stands for the summation of the true scale variance which is shown by the variances and covariances of the *k* common factors underlies the scale score Y, while the denominator denotes the scale score total variance. So the composite reliability is concerned with the assessment of the amount of variance recorded by the construct in the proportion of the amount of variance due to the error of measurement.

The composite reliability is different from the Cronbach's Alpha in the sense that it overcomes the limitation of Cronbach's Alpha measure. There is a certain restriction in Cronbach's Alpha value due to the assumption that items are equally related to the construct, therefore, interchangeable, and also its application with multidimensional measures is restricted (Brunner & SÜβ, 2005). Composite reliability measure overcomes those restrictions and thus different from Cronbach's Alpha.

The CR shows the reliability and internal consistency of a latent factor. A value of CR > 0.6 is required in order to achieve composite reliability for a construct (Field, 2018). The 6–factor model has achieved composite reliability because the CR value of the 6-factor model (that is, 0.868536) is much greater than range of 0.6 as reported in Table 4.4. Additionally, the average variance explained (AVE) of the model (that is, 0.584) is much greater than value of 0.5 which shows additional reliability of the instrument (see Table 4.4).

Table 4.4 Composite Reliability

AVE	0.584
CR	0.868536

In sum, after gaining good EFA results, composite reliability, and AVE, the instrument result will be valid, generalizable, and reliable.

4.2.2 Validity

Instrument validity is defined as the degree to which an instrument measures what it claims to measure (Kelley, 1927). So in a sense, validity describes how well the gathered data reveal the actual area of inquiry (Ghauri & Gronhaug, 2005). Validity in a scientific study is predominant as it helps to assess which type of test to conduct so that it truly measures what is intended to measure

(Popham, 2008). It is the method of collecting evidence to bolster the empirical basis for evaluating the scores as suggested by the test creator. Thus the concept of validity is closely associated with the word ‘accuracy’ (Huck et al., 1974). As there are many ways to evaluate the measurements to be accurate, there are various statistical techniques proposed by different researchers to determine validity. Among those methods most frequently used are content validity, construct validity and criterion-related validity (Huck et al., 1974). Figure 4.13 summarizes different kinds of validity tests.

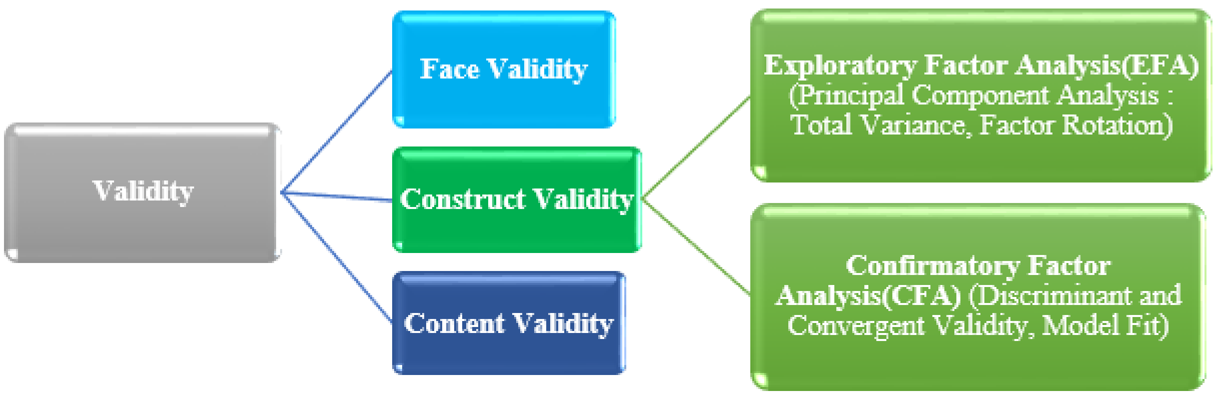


Figure 4.13 Types of Validity Test

4.2.2.2 Face Validity

Face validity is defined as “subjective assessments of the presentation and relevance of the measuring instrument as to whether the items in the instrument appear to be relevant, reasonable, unambiguous and clear”(Oluwatayo, 2012). Therefore, in a simple sense, it is the measure of the extent to which the contents of a test appear to be appropriate in the eye of the person taking the test. Thus, it is a judgment procedure of the non-experts who evaluate the test on the basis of viability, consistency of the format, clarity of the language being used and readability (Taherdoost, 2016). To measure the face validity, a categorical option of 'Yes' or 'No' is incorporated to distinguish the favorable and unfavorable sections, respectively. This collected data is further analyzed by Cohen's Kappa Index (CKI)(Gelfand et al., 1975). However, most of the researchers contend that Face validity is not really a measure of validity and should not be considered (Kaplan & Saccuzzo, 2017). In this research, face validity was conducted by a set of academic SE experts and experienced practitioners from reputed SE industries.

4.2.2.3 Pilot Testing (External Validity)

External validity refers to whether or not an observed correlation can be generalized across different measures, groups, persons, time, place, and settings. In other words, external validity answers the question regarding the applicability of the research in the real world. If the research can be used for other experiments and replicated in real-world problems, external validity is low. However, this is always not the case; therefore, external validity is often difficult type of validity to achieve. Another reason is that different hidden and confounding variables/factors might the impact the experiment outcome once this research is applied across different individuals, groups, places, time, and settings. A follow-up research will be conducted to examine the external validity of the proposed survey instrument with its applicability across different domains. Pilot testing is one kind of external validity.

It is defined as a 'small study to test research protocols, data collection instruments, sample recruitment strategies, and other research techniques in preparation for a larger study (Stewart, 2016). It is essential as it assists in pinpointing the flaws and the problems of the research instrument before implementing it in the full study. When there is a large pool of items, it is very beneficial to eliminate some items from the list to get that in a more manageable form even before estimating the reliability and validity of each item. Pilot testing is very helpful in this regard. It also often serves the purpose of a primary test for validity (Netemeyer et al., 2003). Four issues must be considered during pilot testing, which are:

1. The sample sizes
2. Composition of the sample
3. Primary reliability estimates,
4. The number and type of validity-related scales to include

Firstly, the sample size of the pool matters, as a pool with a small sample size indicates a narrowly defined construct. There is a debate among the researchers regarding the sample size; some contend that it should be in the range of 300 (DeVellis, 1991). Others posit that it should be between 100 to 200 (Clark & Watson, 2016).

Secondly, the issue of the composition of the sample. As the goal of pilot testing is to reduce the large pool to a more manageable form, it is always convenient to use samples from the appropriate population. Because a sample from a relevant population that also performs well will be more confidently assessed and have more chance to be included in the final list (Netemeyer et al., 2003). Thirdly, items might be assessed for internal consistency reliability before including them in the list. This is helpful as it allows us to analyze a large set of data. Finally, a primary evaluation of validity can be tested for the instrument to get an initial insight.

In this research, data and feedback were collected from 10 experts in the domain of Systems engineering through a pilot test to reduce the systematic and random error in the measurement. The researcher ran a pilot test on the instrument for two main purposes: (1) to reduce the random errors and systematic errors in the measurement and (2) to get feedback and suggestions.

4.2.2.4 Content Validity

Content validity is defined as the extent to which elements of a measurement instrument are germane to and representative of the targeted construct for a particular assessment purpose (Haynes et al., 1999). So content validity is concerned with answering the question: the degree to which the test incorporates elements from the desired content domain (Huck et al., 1974). This approach ensures that an instrument contains all the significant elements and get rid of all the undesirable elements. This is why during the development of a novel instrument, it is highly recommended to assess content validity (Taherdoost, 2016). In order to determine the content validity of an instrument recognized expert opinion to ascertain whether the test contains the defined contents and also a rigorous statistical test. This is where it differs from *face Validity* because it only takes opinion from non-expert to superficially assess if the test 'looks valid'.

After deriving the underlying systems engineering attributes and in-person interviews with academic experts were conducted who specialized in systems engineering domains in order to validate the SE attributes generated from qualitative analysis (grounded theory coding). Follow-up phone interviews were also conducted with different practitioners and industry experts in large organizations, including the U.S. Department of Defense, Boeing, and NASA. In addition, also after developing the scenarios and prior conducting the survey, same feedback procedures had been collected from the field specialists.

4.2.2.5 Construct validity

Construct validity is defined as the extent to which an instrument measures what it claims to measure (Cronbach & Meehl, 1955). Therefore, it is just a measure of how well measurements represent the theoretical constructs. For instance, one might try to assess whether an educational program enhances leadership qualities among students. In this case, construct validity can be used to assess if the research is actually measuring leadership qualities. Construct validity is predominant in psychological research area such as aptitude test (Cronbach & Meehl, 1955). Evaluation of the construct validity is a bit complex as one single assessment does not prove construct validity. It is a continuous process of evaluation, reevaluation, refinement, and development (Peter, 1981). One method of assessing construct validity is by examining the correlation among the measures that are already held as related to the construct. This is the same as the Multitrait-multimethod matrix proposed by (Campbell & Fiske, 1959) to assess the construct validity. There are other statistical methods to determine construct validity ; however, no approach has received widespread acceptance (Westen & Rosenthal, 2003). A method of quantifying construct validity using contrast analysis was proposed by (Westen & Rosenthal, 2003), which is beneficial in the sense that it provides a simple evaluation of validity and not being limited by the convoluted statistical processes.

4.2.2.5.1 Exploratory Factor Analysis

"Exploratory factor analysis is a data-driven approach, such that no specifications are made in regard to the number of factors or pattern of relationship between the common factors and dimensions the size and different magnitude of factor loading*"* (Develis,2016, p.11). During EFA, there is no prior restriction/observation are imposed on the type or pattern of relation between the observed variable and the latest variable. During EFA, factor loadings are presented as standardized estimates of regression slope in order to predict the indicators from the factors, thus, it can be used as tools for testing evidence of discriminant validity. If the cross-loading is higher than 0.4 and between loadings are less than 0.2, it violets the properties of discriminant validity, and on the other hand, if the factor loadings are higher than 0.7, then all the items successfully converge to the respective construct and meet the construct validity criteria. Along the same line, EFA can measure the evidence of uni-dimensionality. If all items design to assess the one construct have factors loading with the same construct and lower cross-loading with other constructs, every set of constructs are considered as unidimensional.

After conducting the EFA, the research will decide what kind of analytical approach should be conducted based on the designed scenario/ questions at hand, then research would finalize what indicators should be included in the analysis and determine the size of population for the survey. Principle component analysis is one of the well-accepted method to conduct the exploratory factor analysis.

4.2.2.5.2 Principal Component Analysis

One of the most popular methods of factor extraction among researchers is the principal component analysis (Westen & Rosenthal, 2003). This analysis not only assists in reducing the dimensionality of the dataset, thereby augmenting interpretability but also diminishes data loss. The main goal of this analysis is to reduce dimensionality while conserving as much statistical information as possible. So this is very beneficial while dealing with an enormous dataset for this reason, which is hard to comprehend (Jolliffe & Cadima, 2016). PCA starts with generating new uncorrelated variables, which are linear functions of the original dataset. These variables will in terms augment the variance of the dataset. So that it ends up an eigenvalue problem. The steps of PCA are described below (Jolliffe & Cadima, 2016).

Step 1: Standardization: In this step, basically, the original dataset is transformed into a comparable scale by standardizing the range of initial variables. The primary reason behind this step is to ensure each element contribute uniformly to the analysis. If standardization is not performed, then variables with a large variance will dominate over variables with a small range. The equation for step is

$$z = \frac{value - mean}{standard\ deviation}$$

Step 2: Covariance Matrix Calculation: The correlation matrix is incorporated in this step to indicate those variables that are highly correlated. It is performed because usually, those variables contain redundant values.

Step 3: Calculating the eigenvectors and eigenvalues of the covariance matrix to isolate the principal component: As the eigenvectors and eigenvalue pairs indicate the direction of axes where the most variance lies in and the quantity of the variance, respectively, it helps to isolate the principal components. By arranging the eigenvalues and eigenvectors in descending order, one can get principal components in the order of importance.

Step 4: Feature Vector: In this step, the decision to eliminate the values of less importance is made. The feature vector is the matrix that contains all the eigenvectors that are decided to be kept.

Step 5: Adjust the data along principal component axes**:** In this step, the feature vector is used to reorient the original dataset to ones represented by the principal components.

- *Factor Extraction:* Principal component analysis has been used as a factor extraction method for conducting EFA. It assesses the *factorability* of the instrument. In other words, it represents the derived attributes differentiae from each other and also have adequate expansibility power.
- *Total Variance Explained:* Six factors could explain 83.28 percent of the variability in the model, as shown in Table 4.5. All factor loadings were greater than 0.7, which show

very good model explain-ability and validity, as shown in Table 4.6. Six attributes were extracted as the final factor-item structure of the instrument.

Table 4.5 Total Variance Explained

Total Variance Explained

Component	Extraction Sums of Squared Loadings			Rotation Sums of Squared Loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	1.828	23.804	23.804	1	16.675	16.675
2	1.76	22.661	46.466	1	16.669	33.344
3	1.605	16.753	63.219	1	16.668	50.011
4	1.422	8.364	71.583	1	16.664	66.675
5	1.331	6.362	77.945	1	16.664	83.339
6	1.035	5.255	83.23	1	16.661	100

Extraction Method: Principle Component Analysis

Factor Rotation: Orthogonal (Varimax) was chosen as the factor rotation method. The Orthogonal rotation, in spite of non-orthogonal rotation methods, sperate the constructs/factors better from each other. This is very important for our instrument because each factor was designed to measure a different and separate dimension/aspect of a systems engineer's skill set. A rotated component matrix was obtained to further enhance the decision of the factor-item structure of the EFA model. The rotated component matrix indicates the final component-factor structure of the instrument, as shown in Table 4.6. The instrument shows very good component-factor structure without any cross-loading, which proves the orthogonal rotation was a good choice in conducting PCA.

4.2.2.6 Rotated Correlation Matrix

Correlation is defined as the statistical relationship between two random variables (Dowdy et al., 2011). It is significant because it shows a causal relationship among the variables. If two variables increase or decrease simultaneously, then it is indicated there is a positive relationship. On the other hand, if one variable increase as the other one decrease, there is a negative relationship. The correlation coefficient is a statistical measuring tool that indicates the extent to which changes to the value of one variable predict changes to the value of another (Dowdy et al., 2011). Among several correlation coefficients, the most widely used is the *Pearson correlation coefficient,* which assumes only a linear relationship among two variables (Croxton & Cowden, 1939). This assumption limits the use of the Pearson coefficient. A more robust form of coefficient Spearman correlation coefficient is developed, which is sensitive to non-linear relationships (Croxton & Cowden, 1939). The Spearman coefficient is denoted as *rs,* and the value ranges from –1 to +1. A positive Spearman coefficient value suggests a positive relationship, whereas a negative coefficient value designates a negative relationship. Also, a value of +1 demonstrates a perfect positive association, 0 implies no association and the value of -1 marks a perfect negative association. The equation to calculate the Spearman coefficient (rs) is shown below (Zar, 2005):

$$rs = 1 - \frac{6 \sum d_i^2}{n(n^2 - 1)} \tag{4.7}$$

where *n* denotes the number of observations and *d* is the difference between two ranks of each observation.

Researchers usually present their rs value within the text if they want to demonstrate the relationship between a small number of variables. However, when the bivariate association between many variables needed to be shown, it is expressed in a matrix format called correlation matrix (Huck et al., 1974). An example correlation matrix between 6 variables is shown from the study of Ellwood et al. (2009) in Table 4.6.

Table 4.6 Rotated Component Matrix

	Component					
	1	2	3	4	5	6
Req Eng.		0.699				
Hierrachical View	0.734					
Life Cycle			0.723			
SE Mgt				0.709		
Interdiscplinary						0.735
Systesm Design, Integration, & optimization					0.743	

It is apparent from the Table 4.6 that all the attributes have excellent factor loadings. In addition, there is no cross leading for each factor (attributes) are different from each other and explain only specific details. Base on the result of the rotated component matrix, each of the attributes can explain at least 50 percent (the least factor-loading in power of $2 = 0.699^2$) of that attribute within the instrument, which is desirable for a newly developed instrument. Table 4.6 indicates the final component-factor structure of the instrument, which shows very good component-attribute structure for the instrument.

4.2.2.6.2 KMO and Barlett Test:

To make sure that the sample size is adequate for factor analysis, the KaiserMeyer-Olkin measure of sampling adequacy (KMO-test) is conducted (Andale, 2017). In other words, KMO and Barlett test demonstrate the adequacy of the sampling, which is supposed to be >0.50 (see Table 4.7) , but for our case, it is 0.538 (reported in Table 4.8), which entails that we require more sample to be tested and this statement is valid since our sample size is comparatively small that only include the SE focused group.

Table 4.7 KMO test Values

KMO Test values	Remarks
<.5	Unaccpetable
0.6	Acceptable
>0.6	Adequate

Table 4.8 KMO and Barlett Test

KMO and Bartlett's Test

Kaiser-Meyer-Olkin Measure of Sampling Adequacy.		0.538
Bartlett's Test of Sphericity	Approx. Chi-Square	17.82
	df	15
	Sig.	.047

4.2.2.7 Model Fit

A mathematical model is the illustration of a system that is usually represented by an equation of any kind. Model fitting is performed on a model to predict the future estimates of the data. Therefore, it refers to the capability of the model to propagate data. There are different ways to model fitting such as regression, least squares, gradient descent, and others. Whatever method is applied, it is always necessary how well the model fits the data. Another way of saying it to measure the "goodness of fit" (Kline, 2015). There are several indices to ascertain how well the model fit ; however, there is a significant dispute among researchers concerning the question of which indices must be used to evaluate (Brown, 2015). It is because the fit indices are influenced by sample size, type of data, model complexity, and estimation method. This makes the whole process of determining the model fit a complex process.

Among the indices employed to determine the model fit, the majority of them compute the extent to which the covariance suggested by the data compared to the observed covariance of the data (Netemeyer et al., 2003). Chi-square test is the most widely used because it is shown through studies that it is statistically significant (Netemeyer et al., 2003). It is an adequate measure when the sample size is between 75 to 200, but it always becomes statistically significant when the sample size exceeds 400 (Sharpe, 2015).

There are 3 types of fit indices which are mentioned below (Netemeyer et al., 2003):

I. Absolute fit indices

II. Comparative fit indices

III. Parsimony-based fit indices

Without any adjustment for overfitting, the Absolute fit indices demonstrate the overall model fit. Adjusted goodness of fit and goodness of fit are two absolute fit indices whose value ranges from 0 to 1. Where values close to 1 indicate suggest a better fit compared to values close to 0. This should not be the only measure of fit because it is susceptible to sample size and model complexity (Hoyle, 1995).

Comparative fit indices compare the proposed model with respect to a baseline model. The baseline model has no relationship in the data means the covariance is taken as zero. Thus, these indices are only appropriate when comparing the two models.

With covariance structure analysis, parsimony-based indices determine the efficiency of the model. It is basically used to determine how the parsimonious model is. A parsimonious model is that which has just the right quantity of predictor to explain the model well. It can represent data with a minimum number of parameters. Models with low parsimony indices generally have a good fit compare to other models with high parsimony indices, so there exists a give-and-take between parsimony and goodness of fit (Williams & Holahan, 1994). The model fit indices of the instruments are presented in the following Table 4.9.

Table 4.9 Model-Fit

<3, good

CMIN

Model	NPAR	CMIN	DF	P	CMIN/DF
Default model	13.000	3.490	8.000	0.900	0.436
Saturated model	21.000	0.000	0.000		
Independence model	6.000	18.595	15.000	0.233	1.240

>.9, good

RMR, GFI

Model	RMR	GFI	AGFI	PGFI
Default model	25.810	0.983	0.956	0.375
Saturated model	0.000	1.000		
Independence model	44.564	0.917	0.833	0.655

>.9, good

Baseline Comparisons

Model	NFI Delta1	RFI rho1	IFI Delta 2	TLI rho2	CFI
Default model	0.812	0.648	1.426	3.352	1.000
Saturated model	1.000		1.000		1.000
Independence model	0.000	0.000	0.000	0.000	0.000

rsimony-Adjusted Measures

>.5, good

Model	PRATIO	PNFI	PCFI
Default model	0.533	0.433	0.533
Saturated model	0.000	0.000	0.000
Independence model	1.000	0.000	0.000

<.08, good

NCP

Model	NCP RMSEA	LO 90	HI 90	PCLOSE
Default model	0.060	0.000	0.061	0.937
Independence model	0.059	0.000	0.136	0.390

No threshold, but less is better

AIC

Model	AIC	BCC	BIC	CAIC
Default model	29.490	32.474	58.534	71.534
Saturated model	42.000	46.820	88.916	109.916
Independence model	30.595	31.972	43.999	49.999

All the model fit parameters illustrated in Table 4.7 meet the requirement/threshold. Moreover, Confirmatory Factor Analysis (CFA) concluded the instrument's proposed model fits well to the data (CFI = 1.0, RMSEA = 0.060, and Chi-square/DF = 0.436). The Overall Cronbach α (0.668) and the Composite Reliability (all greater than 0.7) presented the reliability of the proposed systems engineering instrument. Overall, the instrument achieved final validity and reliability in the CFA stage.

4.2.2.8 Criterion validity

Criterion validity is defined as the degree to which a measure is related to an outcome (Cohen et al.,1996). The goal of criterion validity is to express that real-life outcomes can be predicted through test scores. While determining criterion validity it is essential to assess measurements through statistical analysis with respect to either an independent criterion or a future standard (Bellamy, 2014).

There are two types of criterion validity, which are described below

Concurrent validity: It is the degree to which the result of a novel test comparable to an already accepted measurement of the same construct (Taherdoost, 2016). So essentially, it is a kind of evidence that is used to justify the use of the test to predict future events. For instance, in order to ascertain the concurrent validity of a novel survey method, the researchers should conduct the novel survey and an established survey on the same group of respondents simultaneously. Now by comparing both of the responses, concurrent validity can be measured, which is done for this instrument.

Predictive validity: A measurement is predictively valid if the measurement accurately forecasts what it is supposed to forecast (Taherdoost, 2016). So, in essence, it is a tool that expresses the ability of a measurement to predict future performances. For example, to assess the predictive validity of an employability test, it must be conducted among the job applicants. After that, the measured test scores are evaluated whether they correlate with the future performance of hired employees or not. For this reason, it takes a substantial amount of time as well as a large sample size to conduct predictive validity studies. For this instrument, in order to check the predictive validity of the instrument, multiple group analysis, and other relevant analyses were conducted to predict/assess the performance of the systems engineers.

4.2.2.9 Discriminant Validity

It is a type of construct validity which tests if measurements that are not intended to be related are actually unrelated (Campbell & Fiske, 1959). So it just a way of determining that a measure does not correlate highly with measures from which it is supposed to differ (Churchill & Iacobucci, 2006). Discriminant validity aims to discriminate between measures of disparate construct. Due to the nature of the discriminant validity test, it is of utmost significance while assessing novel test methods.

The discriminant validity can be calculated through the average variance extracted (Fornell & Larcker, 1981). It is a measure of the level of variance extracted by the construct compared to the level because of measurement error. The average variance extracted (AVE) is expressed as

$$AVE\xi_j = \frac{\sum_{k=1}^{k_j} \lambda_{jk}^2}{\sum_{k=1}^{k_j} \lambda_{jk}^2 + \theta_{jk}} \quad (4.7)$$

Here, k_j denotes the number of indicators of the construct ξ_j , λ_{jk} are factor loadings and $\theta_{jk}$is the error variance of each indicator of the construct.

The discriminant validity can be determined by comparing the AVE and the covariance with other constructs according to the Fornell-Larcker testing system (Fornell & Larcker, 1981).

$$\sqrt{AVE\xi_j} \geq \phi_j$$

Here, ϕ_j represents the shared variance.

So, the square root of AVE must be greater than or equal to the covariance involved in the construct when doing a CFA. If your factors do not demonstrate adequate validity and reliability, moving on to test a causal model will be useless - garbage in, garbage out! There are a few measures that are useful for establishing validity and reliability: Composite Reliability (CR), Average Variance Extracted (AVE), Maximum Shared Variance (MSV), and Average Shared Variance (ASV). The thresholds for these values are as follows:

Reliability (we already succeed in this)

CR > 0.7

Convergent Validity (we already succeed in this)

AVE > 0.5

Discriminant Validity

MSV < AVE

ASV < AVE

If you have convergent validity issues, then your variables do not correlate well with each other within their parent factor; i.e., the latent factor is not well explained by its observed variables. If you have discriminant validity issues, then your variables correlate more highly with variables outside their parent factor than with the variables within their parent factor; i.e., the latent factor is better explained by some other variables (from a different factor) than by its own observed variables.

AVE = 0.584 (previously calculated)

MSV is the square of the highest correlation coefficient between latent constructs.

MSV = 0.552 (0.734^2)

MSV < AVE confirmed [I]

ASV is the mean of the squared correlation coefficients between latent constructs.

ASV = $(0.699^2 + 0.734^2 + 0.723^2 + 0.709^2 + 0.743^2 + 0.735^2)/6 = 0.432$ < AVE confirmed [II]

[I] and [II] →Discriminant validity achieved.

4.3 Multiple Group Analysis

4.3.1 Based on Gender

Table 4.10 entails that gender doesn't impact to an extensive extent in terms of performance of the systems engineers accept the lifecycle dimensions.

Table 4.10 Gender Group Statistics

Group Statistics					
	1. What is your gender?	N	Mean	Std. Deviation	Std. Error Mean
requirmenteng1dmsn	Male	51	69.0196	22.02316	3.08386
	Female	17	68.2353	20.07339	4.86851
HieviewQ1113	Male	51	78.4314	27.34433	3.82897
	Female	17	82.3529	23.91434	5.80008
lifecycleQ1520	Male	51	61.7647	20.89501	2.92589
	Female	17	45.0980	17.44506	4.23105
SEMgtQ3943	Male	51	74.9020	15.92138	2.22944
	Female	17	70.5882	14.34860	3.48005
IndsQ4447	Male	51	67.3203	16.98391	2.37822
	Female	17	70.5882	20.00817	4.85269
SD2226	Male	51	54.5098	25.00510	3.50141
	Female	17	57.6471	15.62426	3.78944
Overall	Male	51	67.6580	9.17210	1.28435
	Female	17	65.7516	8.22602	1.99510

Table 4.11 Gender Group Independent Sample Test

Independent Samples Test

Binary option- independents ample T-test : .004<.005 t 2.959>2

T shows difference between male and female.

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
requirmentengldmsn	Eq. var. assumed	1.197	.278	.130	66	.897	.78431	6.03988	-11.27469	12.84332
	Eq. var. not assumed			.136	29.876	.893	.78431	5.76304	-10.98743	12.55605
HieviewQ1113	Eq. var. assumed	.288	.594	-.527	66	.600	-3.92157	7.43648	-18.76897	10.92584
	Eq. var. not assumed			-.564	31.095	.577	-3.92157	6.94996	-18.09435	10.25121
lifecycleQ1520	Eq. var. assumed	1.023	.316	2.959	66	.004	16.66667	5.63279	5.42045	27.91289
	Eq. var. not assumed			3.240	32.578	.003	16.66667	5.14418	6.19560	27.13773
SEMgtQ3943	Eq. var. assumed	.014	.905	.990	66	.326	4.31373	4.35619	-4.38369	13.01114
	Eq. var. not assumed			1.044	30.200	.305	4.31373	4.13293	-4.12450	12.75195
IndsQ4447	Eq. var. assumed	2.188	.144	-.657	66	.514	-3.26797	4.97503	-13.20094	6.66499
	Eq. var. not assumed			-.605	24.163	.551	-3.26797	5.40413	-14.41757	7.88162
SD2226	Eq. var. assumed	3.960	.051	-.485	66	.629	-3.13725	6.46473	-16.04451	9.77000
	Eq. var. not assumed			-.608	44.584	.546	-3.13725	5.15943	-13.53157	7.25706
Overall	Eq. var. assumed	.004	.952	.760	66	.450	1.90632	2.50704	-3.09915	6.91179
	Eq. var. not assumed			.803	30.342	.428	1.90632	2.37276	-2.93722	6.74986

4.3.2 Based on Current Organization

It is apparent from Table 4.13 that practitioners with greater employment experience with their current organization have significantly *higher requirement engineering, life cycle, SE management, and interdisciplinary* scores than practitioners with less employment experience with their current organization (*p-value* is considering against 90% confidence interval).

Table 4.12 Multiple Group Analysis based on Current Organization Experience

Attributes	Significance
Req Eng.	.056
Hierarchical View	.156
Life Cycle Mgt.	.012
SE Mgt	.049
Interdisciplinary	.063
Systems Design	.720

4.3.3 Based on Managerial Experience

Practitioners with higher managerial experience have *significantly higher requirement engineering and life cycle management* score than others who have comparative less managerial experience (*p-value* is considering against 90% confidence interval). Results are reported in Table 4.13.

Table 4.13 Based on Managerial Experience

Attributes	Significance
Req Eng.	.086
Hierarchical View	.754
Life Cycle Mgt.	.001
SE Mgt	.078
Interdisciplinary	.287
Systems Design	.495

CHAPTER V

CONCLUSION

This chapter discusses a summary of this research, illustrates the practical implications of the research from different standpoints, presents the shortcoming of the study, and offers recommendations for future research avenues based on the results of the study.

Chapter I highlighted the purpose of the study against the backdrop of the research questions and hypothesis. The framework was demonstrated by the structure of the research inquiry. This chapter also presented the contribution of the research from theoretical, methodological, and practical perspectives; and anchored the research as a genuine contribution to the systems engineering domain.

Chapter II structured the boundary of the literature and reviewed the literature of the systems engineering domain. Particularly, this chapter traced the historical development of SE from 1926-2017 and presented a histogram analysis, citation analysis, and data cluster analyses to better illustrate the development of SE literature. This would provide a comprehensive overview of the SE domain. Besides this, to lessen the confusion pertaining to SE and its derivative terms, this chapter attempted to derive common themes of the SE literature. This would allow the practitioners to understand the applicability of SE terminology and how these nomenclatures are embedded in SE definition. Finally, to shed light on the disagreement on the role of systems engineers, this chapter presented a broader discussion on the activities of systems engineers to unify the various roles of the systems engineers.

Chapter III presented rigorous research design and the method by adopting Earl Babbie's framework, which includes phases of *defining the purpose of research, conceptualization, choice of the research framework, operationalization, population and sampling, observation and data processing, and analysis and application*. *Defining the purpose* of research talked about the objective of the study which was "development of an instrument to assess the performance of the systems engineers". *Conceptualization* provided broader understanding of potential outcomes of the study against the backdrop of the research questions and hypothesis. Thus, this phase included developing quantitative and qualitative research questions. *Choice of research framework* discussed about the Mixed method approach that we have adopted for our study. This phase talked over feasibility of the Mixed method approach, followed by the rationale of the aforementioned approach. *Operanatization* phase described the observations that represent the concepts being studied. *Population and sampling* is a two-step process that narrows down the groups that the researcher considered to investigate, which was limited to systems engineering students and professionals for this research case. *Observation and Data* processing steps included different kinds of data collection strategies for the mixed-method approach. Finally, the *analysis and application* phase exhibited qualitative and quantitative approaches followed by validation and reliability assessment of the proposed new instrument.

Chapter IV discussed the results of the study. The organization of this chapter was three-fold. First, the descriptive statistics were demonstrated for different demographics of the study, followed by the different statistical analyses pertaining to reliability and validity of the study, including confirmatory and exploratory factor analysis. Finally, this chapter wrapped up by demonstrating the multiple group analysis to investigate the influences of different demographics on the performance of the systems engineering activities through the application of the proposed instrument.

The summary of the research is presented in Figure 5.1 below:

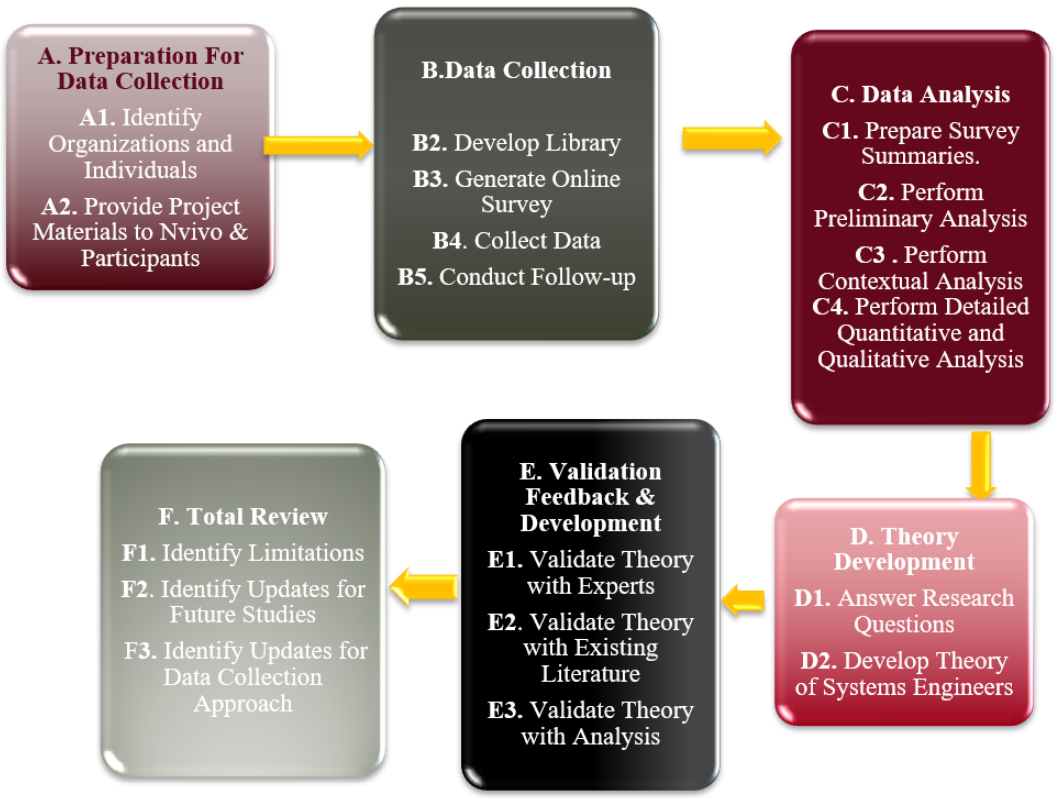


Figure 5.1 Research Summary

5.1 Implications of the Study

In this research, we have provided a histogram analysis and corresponding synthesis of major themes, both historical and present, that demark the still very young SE discipline. We recognize the inherent limitations of organizing such an expanse of literature for an emerging discipline. However, this research is offered as 'an' organization as opposed to 'the' definitive organization of the SE discipline. As such, the research is provided to encourage: 1) a deeper dialog for the SE discipline, 2) focus the substantive debate on the foundations, nature, and directions for the SE discipline, and 3) provide an invitation for a deeper examination and dialog concerning the implications for the future trajectory of the SE discipline.

In conclusion, for this effort, we suggest two primary contributions. First, we provide a brief summary of major threads of continuity that stand out in the histogram analysis across the three time intervals in SE discipline development: Introductory, Exploratory, and Revolution. The significance of these themes concerning the current state of the SE discipline as a function of the historical development is examined. Second, we suggest the SE discipline implications for the six primary themes developed from the Grounded Theory data reduction. Implications are suggested for what is potentially 'missing' with respect to further development of the SE discipline in relationship to complexities of current and future systems.

The examination of the three time intervals for SE discipline development is provided in the following summary points. Although these points are not suggested to be the definitive or absolute final set, they offer a range of perspectives for the historically based response to the question: How did the SE discipline get here?:

- *Introductory Time Interval for SE Discipline Development* – This period was marked by the inception of SE. There were several important aspects from this beginning. First, the history of SE during this period has shown the originating emphasis on addressing difficulties in dealing with increasingly interconnected elements forming systems. The World War II impacts of trying to coordinate the confluence of men, material, and equipment to effectively engage hostile forces emphasized such underlying paradigms as 'optimization', 'technology emphasis,' and 'process emphasis' experienced through such developments as standardized approaches to SE following the wartime posture. Second, the post World War II developments in SE maintained the heavy technology emphasis as well as seeing the beginnings of search for universal understanding and explanation for system behaviors (e.g. General Systems Theory). Third, the forward movement of SE was heavily influenced by this early beginning, including the continuing emphasis of military/industrial applications and a strong process orientation.

- *Exploration Time Interval for of SE Discipline Development* – This period of SE discipline development was marked by an explosive expansion of practice-based applications. In this sense, SE began to 'come of age' from the initial grounding influences found in the inception of the discipline. This further development of SE included several important points of departure from the previous introductory development stage. First, there was still a desire for pursuit of an 'optimization' based paradigm for development of systems. However, there was also a recognition that, while this pursuit might be appropriate for well understood/bounded science-based problems, this paradigm was beginning to be called into question for increasingly complex systems that exhibited emergent behavior. Second, the heavy military and technology emphasis continued, although some fragmentation in different underlying paradigms for SE were beginning to emerge. The fragmentation in SE discipline development might have been inevitable. Especially since the underlying incompatibilities of the divergent paradigms (positivist/antipositivist, reductionism/holism) were quite pronounced. Nevertheless, development continued. Third, the domains and problem types for which SE was seen as potentially appropriate began to expand during this period. Along with this expansion were the different approaches, methods, and supporting tools to assist in providing improved SE capabilities. Unfortunately, the lack of development emphasis for the conceptual/theoretical foundations in the SE discipline were becoming pronounced during this period, as the practice orientation was dominant.

- *Revolution Time Interval for of SE Discipline Development* – This period of SE discipline leads us to the current state. During the revolutionary development period, there were several significant movements. These movements were both grounded in the rich history of SE, but also appreciative of the increasing difficulty related to application of the discipline. A notable influence was the increasing emphasis on the managerial aspects of SE, including casting SE as a 'management technology.' This shift began to usher in a different trajectory for SE development. Some of the historical trends in moving beyond the more tightly bound technology-centric applications of SE continued to evolve. This evolution set the stage for the inclusion of a wider range of perspectives in grappling with increasingly complex, ambiguous, and contextually dominated systems. In addition, the strong military technology influence continued with the emphasis on 'requirements' as a central concern for SE. Finally, there was a noticeable emphasis on four focal aspects that would project the SE discipline into the future, including (1) recognition of the need for SE to be interdisciplinary, including multiple and diverse perspectives, (2) complex problem focus across a more holistic spectrum, beyond more narrow bounding in technology-centric problem formulations, (3) increased formalization of the SE discipline by the development of more standardized processes, methodologies, tools, and professional bodies (e.g. International Council on Systems Engineering), coupled with increasing literature generated in the discipline, as well as more formal codification of the body of knowledge defining the discipline, and (4) extension into different variants, related but showing some distinction from the traditional SE discipline (e.g., System of Systems Engineering).

The Grounded Theory coding effort identified several important themes that delineate the current state of the SE discipline. These themes and their significance included:

1. *The interdisciplinary nature of the SE discipline.* Suggesting that the breadth of SE is not bound as an independent discipline that exist as mutually exclusive of other disciplines. Instead, SE is truly a diverse discipline that can be inclusive of perspectives from multiple disciplines/fields. Consistent with the tenets of General Systems Theory, SE does provide for wide ranging inclusion of associated disciplines/fields and projection to a variety of interdisciplinary problem domains.

2. *The holistic nature of the SE discipline.* As SE evolved over time, so too did the types of problems consider. SE has evolved to also include consideration for not only the technical/technology aspects of complex problems, but also the organizational, managerial, human, social, policy, and political dimensions. In this sense, SE is truly evolving to be a holistic approach to addressing societies most vexing problems and needs. This also engenders a necessity to more rigorously ground the SE discipline in a more 'theoretical' basis found in the underlying tenets of Systems Science.

3. *Sub elements integration, design, and optimization.* The drive to develop the best (optimal) solution of a systems based problem has been a historically built mainstay for the SE discipline. Inherent in this perspective is the notion that optimal solutions can be designed, and systems can be integrated such that optimal performance can be established.

4. *Life-cycle is a dominant perspective for the SE discipline.* The consideration of system from inception through disposal has been, and continues to be, a hallmark of the SE discipline. Considerations across this 'life-cycle' dominate the processes, standards, and underlying paradigm that drives the SE discipline.

5. *Management is a central role in the SE discipline deployment.* There is an important role to be played by the managerial nature of the design, execution, and development of complex system

solutions. Introduction of the management based paradigm in relation to SE invokes a different level of thinking and execution. This different level includes consideration for the planning, organization, coordination, controlling, and direction functions traditionally associated with management. This amplifies the evolving interdisciplinary nature of SE and the need for holistic approaches that move beyond technology-centric formulations of SE.

In closing, based on this analysis, three perspectives concerning the challenges for future development of the SE discipline are offered. First, there is a need to more firmly ground and develop the underlying theoretical/conceptual underpinnings for the SE discipline. Although, there has been work done with respect to the systems nature of SE (e.g. General Systems Theory), this has not effectively permeated the SE discipline. On the contrary, there has been an over indulgence of SE on the application (tools, technique, methods, models) side of the development equation to the detriment of the conceptual (theoretical, philosophical, methodological) developmental emphasis. Sustainability of a discipline is held first at the base knowledge that is consistent, stable, and provides continuity. The opportunity for SE discipline development is to more rigorously anchor development in the underlying conceptual/theoretical foundations that have been to this point noticeably minimal in development. Second, continuation of the interdisciplinary inclusion of a wide breadth and depth of associated disciplines/fields for both development as well as application presents a significant opportunity for SE discipline evolution. These extensions can offer both body of knowledge expansion as well as increasing application opportunities to propagate the discipline to disparate domains. In this sense, SE has the opportunity to not only be interdisciplinary by inclusion of other fields/disciplines, but also interdisciplinary in application to other domains. This is the essence of the interdisciplinary nature of the SE discipline and represents a significant future developmental opportunity. Third, a continuation and extended emphasis on the ability of the SE discipline to address an emerging class of complex systems and their problems. As society continues to experience increasingly complex, ambiguous, holistic, and contextually bound systems and problems, the SE discipline has a substantial opportunity for future impact. With increased emphasis on development and demonstration of SE capabilities (theory, methods, practice) to address societies most vexing problems and needs, the SE discipline can offer a substantial contribution for future societal prospects.

The scope and application of SE continues to expand. New SE methodologies, perspectives and applied fields are emerging to substantial reductions in budgets and schedules in everyday operation. From the literature, it is clear there are numerous perspectives, definitions exist around SE. To lessen the confusion, we synthesized the definitions provided by scholars and institutions and derived terminologies (a set of attributes) based on grounded theory data reduction. We emphasize that these terms should be incorporated into the definition of SE. These terminologies along with the other terms would help in defining the body of knowledge of SE and providing a better understanding of SE discourse

While there is a list of works that were specific to the characteristics of individual systems engineers, this study discusses the need for and presents an instrument to quantitatively measure the performance of systems engineers in the workforce. As shown by several studies the need for training and development of these systems engineers is paramount to the successful execution of projects. Additionally, as systems and technologies increase in complexity, the need to rapidly assess and assign task among the workforce will be more important than ever. Given an instrument to accurately capture the performance of a systems engineer, organizational decisions will be supported by quantitative data. The implications of the research across theoretical, methodological, and practical dimensions are summarized as follows:

- This research fills the gaps in the literature and the need for an instrument to evaluate the systems engineering abilities for individual engineers.
- The instrument provides a quantitative assessment of the performance of a system engineer based on identified characteristics of a successful systems engineer in the literature.
- Further, this instrument could serve as a tool for engineering managers to support selection, training, evaluation, or hiring of personnel for complex systems engineering tasks.

This instrument offers organizations several advantages by supporting organizational decision making on multiple levels. First, at the organizational level the instrument can provide assessment of systems engineering training or the need for additional training. Given the aggregate scores of the systems engineering staff, the organization can allocate resources efficiently to provide training targeted at the deficient attributes within the workforce. Additionally, as training is administered the instrument can provide rapid feedback on the effectiveness of the training. Secondly, given the performance assessed by the instrument, candidates can be classified based on their strengths and assigned to tasks that require specific attributes. If a systems engineer is strong in Requirement Engineering, this engineer could support the requirements analysis and definition phase of multiple projects providing their strengths across a broad portfolio of programs. Lastly, candidates can be screened and hiring decisions can be based on the candidate's performance profile. Hiring and termination take a significant amount of resources to manage, therefore more confidence in the selection of a candidate for hire would help alleviate this unnecessary expense. The use of an effective performance assessment instrument can provide organizations yet another important tool for improving their operational efficiency.

5.2 Application of the Proposed Instrument in the Defense Industry

A base center with a radar, data receiver, and transmitter with the secured link of satellite connection is being considered to see the application of SE in the defense industry. To ensure the seamless operation of base center, there is a need to develop an efficient group of systems engineers who can solve complex problems in a timely manner. The base center using radar monitors the sea to avoid unofficial entry of any kind of transport, they have a fleet with communication systems to alert the base of any suspicious entry into the national boundaries. As the ship from the fleet identifies any suspicious entry, it sends a signal to the base center via a secure link about the scenario and receives commands from the base center. The base center provides commands to the fleet with direction to act as a group or an individual depending on the level of severity to attack or scope. Like many scenarios in the defense industry, this system is complex. The system includes large ships, electronic communication equipment, radars, and command and control. Given the level of complexity and system-of-systems nature, system engineering plays a key role in the defense industry.

The complex landscape of systems can be understood in three ways by the engineering managers and the developed tool is capable of assisting practitioners within defense industry. The three ways are: i) improvement of decision making which will lead to assigning appropriate work according to the capacity of the individuals for complex systems tasks. Although a higher score does not necessarily mean one individual is superior to another, it provides insight into the performance of the individual with respect to the systems engineering characteristics. Within the defense industry, many tasks involve very complex scenarios with many components that are all working together toward a common goal. This is the definition of a system, therefore systems engineering performance indicators could extend to this domain. ii) The scores expedite the team building which introduces complementary perspectives in a quantifiable manner. Diversification of a group during the establishment of teams for projects and missions can be done by using knowledge of a variety of systemic perspectives possessed by individuals. iii) For determination if the capacity for system thinking is sufficient for engaging required activities for a unit in consideration, assessment is required. The system and its requirements are better understood by stakeholders on the basis of system thinking capacity.

For engineering managers, the primary drivers for decisions revolve around schedule, cost, and performance. In utilizing this tool, the engineering managers can assess the personnel for their individual systems engineering profile. This will inform decisions related to training required, roles for the engineers within the project, and staffing needs of the team. Given a set of profiles within the team, the engineering manager can identify gaps in skills that need to be filled. The tool can be utilized to screen candidates joining the team to ensure the right engineer for the job is attained. The data generated from assessing the team and the actions taken to fill the gaps in systems engineering skills will improve all three drivers. Ensuring the team is balanced and includes a diverse group of engineers to perform the complex system design will lead to improvements in schedule, cost, and performance.

5.3 Application of the Instrument in Managing Technical People in Different Industry

Today's technological environment is far from tranquil. The proliferation of disruptive technologies in science, engineering, and information technology and the speed of adoption of newly commercialized technologies by the public are increasing at an exponential rate. Discussions on artificial intelligence, robotics, the Internet of Things (IoT), data analytics, machine learning, renewable energy, lighter-weight composites, biodegradable materials, and innovative therapeutic compounds abound at the highest levels, as organizations seek to remain abreast of dynamic developments in fields that have the potential to impact performance of their operations and better satisfy their customers.

This revolution is placing an enormous amount of pressure on organizations to develop and continually adapt their technology strategies to meet the ever-changing needs of stakeholders. To remain competitive, organizations must be creative, agile, and effective in using new technologies to design and manage technological systems that deliver the right value, amidst trends of increasingly shorter product lifecycles. This is by no means a simple challenge as it requires organizations to have a well-developed cadre of individuals with the range of skills that are necessary to lead the development, implementation, operation, and management of technological systems that are becoming more and more complex. Since individuals oriented toward technical careers often find it easier to hone the requisite set of hard skills, it is incumbent upon the organization to determine the appropriate balance of both soft and hard skills needed to execute changes that serve the contextual needs of all stakeholders.

Even highly skilled individuals can fail to achieve an organization's desired technological objectives due to an incomplete skill set that lacks critical competencies required for innovation, collaboration, interpersonal communication, problem-solving, and decision-making in a rapidly changing environment. The role of technology managers is broad, encompassing a wide range of responsibilities that range from providing technical support to interacting with customers and other stakeholders. Thus, a fundamental approach to technology management should begin by asking and answering the following question: "*What skills should an organization acquire to support the development and management of complex technological systems operating within an uncertain environment*?" This is not an easy question to answer as consideration must be given to the manner in which soft skills will need to complement technical skills to effectively design, develop, and support technology applications in different industries. In this regard, insights can be drawn from the work of some researchers in the fields of systems engineering and systems thinking.

Systems engineering is a useful field for eliciting insights into the skills required of technology managers because it applies a structured approach to the design, management, and optimization of a system's performance (Hossain et al., 2019c; 2020c,h). To achieve this goal, a systems-thinking approach, which takes an interdisciplinary perspective, is applied to evaluate a system's performance characteristics over the life cycle of the system – that is, from conception, through utilization, and final disposition (Nagahi et al., 2019b, 2020b,d; Jaradat et al., 2019, 2020; Dayarathna, 2020). The overall goal of systems engineering is to design and optimize a system to meet the needs of stakeholders. Systems thinking provides the skillset to analyze and evaluate the design and operation of a system from different perspectives and to make predictions about its ability to perform in a manner that achieves a desired purpose (Karam et al., 2020; Lawrence et al., 2019,2020; Nagahi et al., 2019a,c; 2020b,d; Hossain et al., 2020e,g; Jaradat et al., 2015, 2017a).

Six (6) critical attributes required of technology managers to successfully navigate and operate in today's technological climate to meet organizational goals are discussed below. These are (i) interdisciplinary knowledge, (ii) holistic thinking, (iii) proficiency in requirements engineering, (iv) sub-element integration, design, and optimization capabilities, (v) system lifecycle assessment, and (vi) leadership and management acumen. These attributes are applicable to a range of systems and sectors. A detailed discussion of each follows.

5.3.1 Interdisciplinary Knowledge

Technical personnel cannot afford to be limited to a specific domain of knowledge, with only deep expertise in a single area. Technical individuals must be lifelong learners who actively seek out learning opportunities to master the dialogue and application opportunities relating to emerging technologies, while simultaneously gaining a general background in other disciplinary areas. The sheer number of interconnections and interactions that exist between parts of a system, sub-systems, and the system and its external environment require that individuals be conversant and comfortable in discussing a wide range of technological issues and implications. This learning approach is essential to be competent and versatile in the technological arena. The ability to integrate ideas from various disciplines, critically evaluate different perspectives, and synthesize new knowledge into novel applications for the organization's competitive advantage are necessary skills for today's technology manager. A technical individual who possesses cross-disciplinary knowledge and experience will be able to assess the value of new ideas more readily, think more innovatively, and be better at predicting systemic interactions and outcomes over time.

There are several examples of situations in which the knowledge of technical individuals needs to be complemented by knowledge from other fields to support optimal decision-making. One example is in the area of aviation technology innovation, which has historically been driven by three factors[1]: (i) rising oil prices, (ii) increasing societal environmental awareness, and (iii) demand for convenient air travel options. Focusing on only one of these areas is likely to result in sub-optimization of stakeholder needs. Growth in one area is also likely to impact another, with potential implications. For example, as demand for air travel increases, the environmental impact of emissions will correspondingly increase (Lee & Mo, 2011). Furthermore, because innovation in the aviation sector, such as the development of new fuels, requires large outlays of capital and long development timelines, technology managers must have the vision and analytical skills to consider alternative scenarios and the agility to adapt appropriately to potential future changes from strategic plans. To widen the scope of this vision, technology managers must seek to continually develop knowledge in new, relevant areas.

5.3.2 Holistic Thinking

One of the most essential skills required of individuals responsible for complex technology-based systems is holistic thinking. In the past, many technical fields sought to solve a problem by breaking down the system into its constituent parts and "trouble-shooting" to devise a solution. The problem with decomposing a system into its parts, also known as reductionism, is that the focus is on developing a part of the system without considering its integration into the system and the role of the sub-part in overall system performance. This happens because the dynamic relationships between parts of the system are excluded when reductionist thinking is applied. Technology managers need to understand recurring patterns of interactions within complex systems and the resulting consequences on system performance. This does not imply that a technical individual should not be knowledgeable of the functioning of the individual parts of a system, but rather, holistic thinking will ensure that the focus is placed on the ultimate output of the system as a whole.

Technology managers must also be prepared to address the issue of emergence as a function of holism. Emergent properties or unexpected behaviors that result from interactions between the system's constituent parts and the environment, and which produce outcomes beyond the collective capabilities of the individual parts, are risks encountered in complex technological systems. Emergence can be beneficial or adverse. In situations in which emergence results in beneficial outcomes, technology managers must be creative and versatile in adapting the system to capitalize on the benefits. Technology managers must also have a plan for mitigating negative outcomes associated with emergence – for example, the unanticipated competition for resources between different sub-parts of the system (Zeigler, 2016).

Modern day supply chain management is based on the idea of holism, where the constituent elements (such as suppliers, manufacturers, distributors, retailers, and transportation suppliers) are collectively considered to be a single enterprise (Aghalari et al., 2020a,b; Nur et al., 2020a,b). The logic behind moving from a focus of individual entity performance to one that examines the final deliverables to the customer is based on the premise that performance of the whole is greater than the sum of performance of the parts. This approach has led many companies to spearhead collaborative solutions with partners upstream and downstream in the supply chain to minimize total cost, minimize risk exposure, and maximize profits for all partners in the supply chain (Hossain et al., 2020a). A simple example is the decision to offshore a production operation versus producing the product locally. A reductionist approach might look solely at the decreased cost of production in countries where low labor rates and taxes apply. A holistic approach, on the other hand, would consider the overall impact on supply chain performance in terms of cost and customer satisfaction by making appropriate trade-offs between the cost of production and the costs of quality, transportation, inventory, and sustainability (Quddus et al., 2016). The impact of new technological solutions, such as robotic process automation, might also be considered in the quest to obtain the best overall performance of the supply chain.

The COVID-19 pandemic has drawn into sharp focus the need for a holistic view of the supply chain in advancing technological solutions to solve complex global problems that have been previously ignored or subjected to myopic examination. With Industry 4.0 driving the next supply chain revolution, the integration of new technologies, such as advanced robotics, the Internet of Things (IoT), additive manufacturing, cloud computing, and Big Data Analytics, will require a firm understanding of how these technologies facilitate or impede the interactions between supply chain entities and the resulting overall performance of the supply chain. A technology manager who can view both the "forest" and the "trees" will be an asset in leading such endeavors in organizations.

5.3.3 Proficiency in Requirements Engineering

Requirements engineering is an elaborate process that precedes the development of a technical product or complex technical system. It involves several sequential activities to ensure that the product created and delivered to the customer meets expectations. Technology managers are an integral part of this process, which involves several steps. These include (i) identifying stakeholder needs, (ii) extracting requirements that may not be easily determined without the input of the customer and other stakeholders, (iii) modeling and analyzing requirements, (iv) reaching consensus on requirements, (v) and disseminating requirements information to all relevant personnel to facilitate the design and deployment of the technical product or system. The ultimate goal is to capitalize on new technologies to develop a system that meets the needs of all stakeholders while making appropriate tradeoffs between risk, cost, and desired features and attributes.

The need for capable technical individuals to manage the requirements engineering process exists in all aspects of society (Hossain et al., 2017). One example that is receiving increasing attention is the digitization of healthcare information systems to better facilitate robust, real time communication between practitioners, between practitioners and healthcare support personnel, and between healthcare personnel and patients. The benefits of digitizing healthcare processes are many and include reduction in medical errors; enhanced communication between patients, patients' families, and healthcare providers; greater convenience for patients and their families; and decreased healthcare costs.

Hospitals that are advanced in technology utilization have already implemented automatic identification and data capture (AIDC) technologies, such as radio-frequency identification (RFID), for tracking and tracing[3]. RFID is a wireless technology that is used to capture and disseminate information on a person or a thing. For example, RFID can be used to track the routing and progress of a patient through critical healthcare processes such as day surgeries. Using RFID tags, information on a patient undergoing surgery can be transmitted in real time or near real time and made available to healthcare support personnel to provide updates to patient families in waiting rooms. RFID tags are also used to ensure patient safety. One example is in tracking surgical instruments to ensure that all pieces are accounted for at the end of a surgical operation.

There are many other areas in which emerging technologies, from machine learning to data analytics, are finding valuable applications in healthcare systems. The key to developing these advanced systems, however, is to thoroughly understand all stakeholder needs so that the system is developed with the customer requirements in mind. The need for individuals, who are not only conversant in the technical aspects of the job, but also effective in leading the process, is increasing exponentially as emerging technologies displace legacy systems. Failure to consider all stakeholder requirements prior to developing a complex technological system will not only result in a waste of financial resources but also tremendous disappointment and trust in the system. For example, a telehealth system that is designed to accommodate the delivery of healthcare solutions by a provider but does not appropriately accommodate patient needs by factoring in appropriate socioeconomic and demographical data will not provide the intended benefits to patients. While the system may work for the provider, users might find it difficult to navigate, frustrating to use, or even obstructive in achieving the desired purpose. In the worst case, patients may feel more at ease in circumventing the system if only partial requirements are met.

Effective technology managers must be capable of assessing customers' needs and translating these needs into technology requirements in a manner that aligns with an organization's strategic plan, while retaining sufficient flexibility to adapt to a constantly changing external environment.

5.3.4 Sub-elements Integration, Design, and Optimization Capabilities

Technological systems consist of many sub-parts and layers and are characterized by dynamic interactions between them and between users and the technology. The integration of all of these components must be performed in such a way as to deliver the greatest capability of the system. The technology manager must recognize these interactions and be knowledgeable about methods to optimize the interactions to achieve the maximum benefit possible. As socio-technology systems, integration and optimization must address both the human and technical dimensions of the interactions. The ultimate goal is to develop technological solutions that meet stakeholder requirements through effective and efficient application of technology within the imposed constraints.

Technology managers must also be knowledgeable of best practices and how to apply the protocols, through repeated iterations, to optimize system performance. Optimization techniques can be applied to several aspects of a technological system to optimize factors such as usability, serviceability, maintainability, sustainability, resiliency, safety, traceability, quality, and productivity. Optimization requires the weak links in a system to be identified and strengthened to the extent that they are balanced with other elements of the system to improve system performance (Duan et al, 2020; Nur et al., 2020a).

Different technological strategies and methodologies can be applied to optimize a system. For example, a warehouse operation could be redesigned as a “smart warehouse” in which technologies such as mobile devices, automatic guided vehicles (AGVs), automated picking tools, smart glasses, and collaborative robots are integrated into the system to optimize productivity, reduce total cost, and improve service. Technology managers must be knowledgeable of issues such as work design, ergonomics, and cognitive capabilities of users to make the right adjustments to optimize interactions between users and the technology and to advocate for changes to achieve the same.

Another example is the increasing use of blockchain technology to integrate supply chain entities and optimize the flow of information to enhance performance in areas such as traceability, safety, security, and ethical practices. Blockchain has found significant application in the pharmaceutical supply chain to mitigate counterfeit risks and in the food supply chain to ensure product safety and sustainability of natural resources.

A technology manager with a sharp skillset that combines state-of-the art technologies with integration and optimization principles can have an immeasurable impact on the competitiveness of an organization. Technological systems can be optimized through repeated improvements during the development stage or through routine evaluation during the utilization phase. In the latter case, technology managers need to be on the lookout for new technologies that can help the organization achieve quantum leaps in performance.

5.3.5 System Lifecycle Assessment

The development and operation of technology-based systems require full consideration of the entire life cycle of the system from inception of idea to phase out and retirement. During the development stage, due consideration must be given to issues such as usability, scalability, cybersecurity, reliability, serviceability, maintainability, interoperability, network topology, cost, sustainability, toxicology, legality, and other factors that are relevant to technology-based systems. After the system has been developed and prior to utilization, the system must be installed, configured, and rigorously tested to validate performance against stakeholder specifications. In many situations, it may also be necessary to operate outgoing and new systems concurrently to prevent disruptions in operations and to validate performance of the new system against the legacy system. During customer use, it will be imperative to manage the system's operation and maintenance, and to perform regular technological updates to maximize performance. In the final stage of retirement, careful thought must be given to dismantling and disposing of the system to minimize adverse consequences to all stakeholders.

When the useful life of a technological product or system is over, either due to wear and tear or obsolescence, the system must be retired and disposed of in a manner that is consistent with industry, state, federal, or country regulations. In recent years, the proper disposal of technology products, particularly electronic devices, has become a growing controversial issue as sustainability demands from a variety of stakeholders increase. Failure to take a full lifecycle approach to assess the potential ramifications of the technology during use and upon disposal can result in challenging, and even disastrous, situations for the organization. Technology managers need to anticipate potential problems ahead of time and plan for pain points that may arise during the lifecycle of systems, particularly those that employ new technologies.

The fifth-generation wireless network technology, 5G, is poised to radically change telecommunications by offering faster data transmission speeds, lower latencies, increased network capacity, seamless connectivity, greater consistency, and overall higher service quality at lower cost. In late 2018, telecommunications companies around the world began the process of commercializing and rolling out 5G phones. The general prediction is that within the next decade or two, significant worldwide adoption of the technology will occur across a variety of mobile devices and industries ranging from agriculture to defense. The Internet of Things and augmented reality are two applications that are expected to drive the use of this technology. With increasing adoption of 5G devices, lifecycle implications associated with the technology will also become increasingly evident. Technology managers will be required to take a central role in leading the technical issues of design and testing of network infrastructure, as well as less traditional activities associated with sustainability issues. For example, technology managers will have to contend with the upsurge in electronic waste that will result due to the vast numbers of 3G and 4G phones that will become obsolete, while simultaneously devising solutions to cope with increasingly stringent regulations on the disposal of toxic electronic devices in landfills. To address these challenges, technology managers will need to possess strong interpersonal and negotiation skills to motivate and influence the development of more efficient approaches for recycling of parts and harvesting of rare minerals from discarded devices.

5.3.6 Leadership and Management Acumen

Technology management involves the planning, organizing, coordinating, documenting, and controlling of tasks related to the development and operation of technological products and systems to meet an organization's strategic goals. To be a successful technology manager in today's rapidly changing technological climate, a powerful technical skillset, complemented by broad knowledge of business fundamentals, and adroitness in managing interpersonal interactions and behaviors, is required. As a technical person moves up the organizational ladder and assumes greater responsibility for the leadership of technical support personnel, both soft and hard skills become essential for success. Exceptional interpersonal skills and a strong ethical compass have been identified among the most critical skills for technology managers.

Planning for technology management is the initial and most critical step as it involves both strategic and operational decisions. The strategic planning process precedes tactical and operational planning. Its main purpose is to establish the organization's priorities and set goals, determine the allocation of resources, and define important performance targets. The planning stage is characterized by intense interaction with key stakeholders, particularly with the customer. Technology managers need to have outstanding listening skills and the ability to skillfully negotiate tradeoffs between competing priorities when necessary. Once the strategic plan is created, tactical and operational plans can be developed to execute day to day activities in support of the strategic plan. Key decisions during operational planning include who does what, when, how, and accountability measures that will be used to measure conformance to these requirements. The ability to plan for contingencies is also a critical skill needed to address potential deviations that may occur from the strategic plan.

Another key management responsibility is organizing, which involves the identification and categorization of key activities and tasks into logical sub-groups to facilitate the assignment of the technical staff. A major part of organizing is the recruitment of staff with the appropriate skillset to perform the technical work and support organizational goals in the short and long term. The technology manager must be capable of identifying skill gaps among existing employees to determine which skills need to be acquired to build strong, competent, and cohesive teams. The technology manager is also responsible for effective delegation of responsibilities and supervision of the work performed without excessively micro-managing technical support staff. Along with hiring, the technology manager must be instrumental in motivating and training staff to deliver results on time, within budget, and to the required specifications with the minimum amount of conflict. Above all, technology managers need to be proficient in motivating staff and project teams and keeping the momentum to achieve desired outcomes, sometimes under long hours of intense activity to meet deadlines. Occasionally, the technology manager might be faced with the difficult task of employee termination if performance fails to meet expectations after attempts at training and coaching become futile.

Documentation and control are other vital tasks performed by technology managers. Documentation of technology solutions, operational processes, maintenance procedures, tasks, and methods used to resolve recurring problems provide standard references for maintaining the ongoing operations of a technological system. The control process is provided through a feedback mechanism that allows the identification and evaluation of deviations from defined plans. As mentioned previously, complex technological systems may display unintended emergence properties in response to unforeseen external shocks or interactions of the sub-units. Technology managers must be capable of applying a methodological approach to address these problems with creativity, agility, and decisiveness.

The organizational framework within which a technology manager operates is not uniform across organizations and will vary based on the mission of the organization and the type of technology involved. Having a strong managerial skillset to navigate the organizational structure and collaborate effectively with unit managers, stakeholders, and staff is indispensable for effective technology management. A balanced set of technical, business, managerial, and interpersonal skills are crucial. Interpersonal skills, in particular, have been recognized as one of the most essential management skills for superior technology management.

Organizations that take the lead in developing their technology management talent by implementing a robust system for recruiting, training, and continually developing technology management staff in the six areas discussed above will find that they are better positioned to traverse the dynamic technological landscape and strategically negotiate a course that leads to sustained improvement in technological competitiveness.

5.4 Limitations and Future Study

The proposed instrument which is developed to assess the performance of the systems engineers is completely new in the relevant literature. In addition, some of existing tools, competency models, and seminal works in the current literature talk about one or two measures/axis to assess the performance of the individual systems engineers while our instrument capture full spectrum of the systems engineering attributes and their corresponding performance indicators to evaluate the performance of the systems engineers when they engage in systems engineering activities. This inflicts a limitation in terms of institute an external validation for the 'new' proposed instrument, since it has no other benchmark/ reference point against which it could be compared or gaged. In other words, although in this dissertation we used different kinds of techniques such as exploratory factor analysis and confirmatory factor analysis to demonstrate the level of validity and reliability of our instrument , but it is limited by the first instantiation of the instrument for the comprehensive testing.

Since this research is solely designed for the systems engineering focused group i.e., only who has knowledge on the systems engineering area, therefore sample size was limited. In light of the findings developed from this current study, it is recommended that the following aspects might be considered to improve the results of the study. A larger number of participants with a more varied field of occupations could be appraised in future studies, ensuring that each domain has an equal sample size. The equal sizing will allow for the investigator to make better comparisons among the profile domains. These expansions will also help to better distinguish between the potential significant differences in the SE competency levels.

Disclaimer: Several parts of this dissertation have already been published in different journals and conferences proceedings; and relevant citations of the published works are listed in the following reference list.

REFERENCES

Abdallah, S. B., Zouari, A., Aidi, M., Maalej, A. (2014). Logistics integration in product design using a systems engineering approach. In Advanced Logistics and Transport (ICALT). *International Conference on IEEE*

Ackoff, .R. (1971).*Towards a system of systems concepts. Management Science* 17(11): 661 672.

Adcock, R.D. (2015).Guide to the systems engineering body of knowledge (SEBoK). The Trustees of the Stevens Institute of Technology (SIT), Hoboken, NJ.

Alfaqiri, A., Hossain, N. U. I., Jaradat, R., Abutabenjeh, S., Keating, C., Khasawneh, M., and Pinto, A. (2019). A systemic approach for disruption risk assessment in oil and gas supply chains. *International Journal of Critical Infrastructures*, *15*(3).

Aghalari, A., Nur, F., & Marufuzzaman, M. (2020a). A Bender's based nested decomposition algorithm to solve a stochastic inland waterway port management problem considering perishable product. *International Journal of Production Economics*, *229*, 107863.

Aghalari, A., Nur, F., & Marufuzzaman, M. (2020b). Solving a stochastic inland waterway port management problem using a parallelized hybrid decomposition algorithm. *Omega*, 102316.

Andale, S. (2017). Kaiser-Meyer-Olkin (KMO) test for sampling adequacy. *Statistics how to*.

Anderson, C. (2010). Presenting and evaluating qualitative research. *American journal of pharmaceutical education*, *74*(8), 141.

Arnold, S. (2000). Systems engineering: from process towards profession. *Proceedings of The 10th Annual Symposium of the INCOSE*.

Babbie, E. (2013). The practice of social research (International Edition). *Andover: Cengage Learning*.

Babbie, E.R. (2020). *The practice of social research*. Cengage learning.

Bahill A. T, Gissing B (1998). Re-evaluating systems engineering concepts using systems thinking. *IEEE Transactions on Systems, Man, and Cybernetics, Part C: Applications and Reviews* 28(4):516-527

Barnett G. A. (2004).Exploratory data analysis. In: LewisBeck M S, Bryman A, Liao T F (Eds.). *Encyclopedia of Social Science Research Methods*. SAGE Publications Inc.

Barnett G. A. (2011). *Encyclopedia of Social Networks*. SAGE Publications Inc.

Bay, M., Gerstenmaier, B., Griffin, M., Knight, J., Larson, W., Ledbetter, K., Lee, G., Menzel, M., Muirhead, B., Muratore, J., Ryan, B., Ryschkewitsch, M., Schaible, D., Scolese, C., & Williams, C. (2009). *The Art and Science of Systems Engineering*. 1–10.

Bazeley, P., & Jackson, K. (Eds.). (2013). *Qualitative data analysis with NVivo*. SAGE publications limited.

Beer S. (1972). *Brain of the Firm*. John Wiley & Sons.

Bellamy, N. (2014). Principles of clinical outcome assessment.

Bertalanffy L. (1968). *General Systems Theory*. Brazillier.

Blanchard B., & Fabrycky W. (1981). *Systems Engineering and Analysis*. Prentice-Hall Inc.

Blanchard, B.S., Fabrycky, W.J., and Fabrycky, W.J. (1990). *Systems engineering and analysis* (Vol. 4). Englewood Cliffs, NJ: Prentice Hall.

Brehl, A. & Leroux, M. (2000). Optimizing technology innovation in manufacturing. Proceedings of the 2000 IEEE Engineering Management Society. EMS-2000 (Cat. No. 00CH37139), Albuquerque, NM. Pp. 81 – 87.

Brill J. H. (1998). Systems engineering: A retrospective view. *Systems Engineering* 1(4):258-266.

Brown A. S.(1953).Reliability of airborne electronic equipment and our ability to maintain it for war. *Transactions of the IRE Professional Group on Aeronautical and Navigational Electronics* 9:3-9.

Brown, T. A. (2015). *Confirmatory factor analysis for applied research*: Guilford publications.

Brunner, M., & SÜβ, H.-M. (2005). Analyzing the reliability of multidimensional measures: An example from intelligence research. *Educational and Psychological Measurement, 65*(2), 227-240.

Buckle-Henning, P., Wilmshurst, J., & Yearworth, M. (2012). Understanding systems thinking: an agenda for applied research in industry. In Paper presented at the 56th meeting of the international society for the systems sciences. San Jose, USA.

Buede D. M., Miller W. D. (2016). *The Engineering Design of Systems: Models and methods*. John Wiley & Sons.

Campbell, D.T., & Fiske, D.W. (1959). Convergent and discriminant validation by the multitrait-multimethod matrix. *Psychological bulletin, 56*(2), 81.

Caracelli, V. J., & Greene, J. C. (1997). Crafting mixed-method evaluation designs. *New directions for evaluation*, *74*, 19-32.

Carmines, E.G., & Zeller, R. A. (2008). Reliability and validity assessment,[Nachdr.]. *Newbury Park, Calif.*

Charmaz, K., Belgrave L (2012). Qualitative interviewing and grounded theory analysis. *The SAGE Handbook of Interview Research: The Complexity of the Craft* 2:347-365.

Charmaz, K., & Belgrave, L. L. (2007). Grounded theory. *The Blackwell encyclopedia of sociology*.

Chase, W.P. (1974).*Management of Systems Engineering.* Robert Krieger Malabar.

Checkland, P. (1981*). Systems Thinking*, Systems Practice.Wiley.

Checkland, P., & Holwell, S. (1993). Information management and organizational processes: an approach through soft systems methodology. *Information Systems Journal*, *3*(1), 3-16.

Chenhall, R.H. (2005). Integrative strategic performance measurement systems, strategic alignment of manufacturing, learning and strategic outcomes: an exploratory study. *Accounting, Organizations and Society*, 30, 395– 422.

Chestnut, H. (1965). *Systems Engineering Tools*. Wiley.

Churchill Jr, G.A., & Peter, J.P. (1984). Research design effects on the reliability of rating scales: A meta-analysis. *Journal of marketing research, 21*(4), 360-375.

Churchill, G.A., & Iacobucci, D. (2006). *Marketing research: methodological foundations*: Dryden Press New York.

Clark, L.A., & Watson, D. (2016). Constructing validity: Basic issues in objective scale development.

Clemson, B. (1991). *Cybernetics: A new management tool*. CRC Press.

CMMI(2001). *Appraisal Requirements for CMMI*, Version 1.1 (ARC, V1. 1)

CMMI(2001).Retrieve from (http://resources.sei.cmu.edu/asset_files/TechnicalReport/2001_005_001_14012.pdf)

Cohen, R. J., Swerdlik, M. E., & Phillips, S. M. (1996). *Psychological testing and assessment: An introduction to tests and measurement*: Mayfield Publishing Co.

Cook, S.C. & Ferris, T.L.J. (2006) 'The bounds of systems engineering', Proceedings of the 12th ANZSYS Conference – Sustaining Our Social and Natural Capital, Katoomba, NSW,Australia, Paper 81, 3–6 December, pp.432–449.

Corbin, J. M., & Strauss, A. (1990). Grounded theory research: Procedures, canons, and evaluative criteria. *Qualitative sociology*, *13*(1), 3-21.

Corbin, J., Strauss, A., & Strauss, A. L. (2014). *Basics of qualitative research*. Sage.

Creswell, J. W., & Creswell, J. D. (2017). *Research design: Qualitative, quantitative, and mixed methods approaches*. Sage publications.

Creswell, W.J. (2005). *Educational Research Planning, Conducting and Evaluating Qualitative and Quantitative.* Pearson: Merrill Prentice Hall.

Cronbach, L.J., & Meehl, P.E. (1955). Construct validity in psychological tests. *Psychological bulletin, 52*(4), 281.

Croxton, F.E., & Cowden, D.J. (1939). Applied general statistics.

Davidz, H. L., Nightingale, D. J., & Rhodes, D. H. (2005). *Accelerating the development of senior systems engineers*.

Dayarathna, V., Karam, S., Jaradat, R., Hamilton, M., Nagahi, M., Joshi, S., Ma, J., Ashour, O., & Driouche, B. (2020). Assessment of the Efficacy and Effectiveness of Virtual Reality Teaching Module: A Gender-Based Comparison. International Journal of Engineering Education.

De Vaus, D. (2001). *Research design in social research*. Sage.

de Weck, O.L., Roos, D., & Magee, C.L. (2011) Engineering Systems: Meeting Human Needs in a Complex Technological World, MIT Press, Cambridge, Massachusetts.

Derro, M.E., & Williams, C.R. (2009). Behavioral competencies of highly regarded systems engineers at NASA. *IEEE Aerospace Conference Proceedings*. https://doi.org/10.1109/AERO.2009.4839712

Derro, M.E., & Williams, C. R. (2009, March). Behavioral competencies of highly regarded systems engineers at NASA. In 2009 IEEE *Aerospace conference* (pp. 1-17). IEEE.

DeVellis, R.F. (2016). *Scale development: Theory and applications* (Vol. 26). Sage publications.

Dowdy, S., Wearden, S., & Chilko, D. (2011). *Statistics for research* (Vol. 512): John Wiley & Sons.

Duan, G., Nur, F., Alizadeh, M., Chen, L., Marufuzzaman, M., & Ma, J. (2020). Vessel routing and optimization for marine debris collection with consideration of carbon cap. *Journal of Cleaner Production*, 121399.

ECSS-E-10-01 (1996). *System Engineering Process*. European Cooperation for Space Standardization.

EIA 632(1994).*EIA 632 Standard: Processes for engineering a system*.

Elakramine, F., Hossain, N. U. I., Jaradat, R., Kerr, C., Nagahi, M., Banghart, M., ... & Goerger, S. (2020). The application of system modelling language (sysml) in an aviation structure and maintenance system.

Ellwood, S., Pallier, G., Snyder, A., & Gallate, J. (2009). The incubation effect: hatching a solution? *Creativity Research Journal, 21*(1), 6-14.

Engstrom E.W. (1957). Systems engineering: A growing concept. *Electrical Engineering* 76(2):113-116.

Epstein, M., and Manzoni, J. (1998). Implementing corporate strategy: from tableaux de bord to balanced scorecards. *European Management Journal*, 16, 190–203.

Fahimnia, B., Sarkis J., & Davarzani H. (2015). Green supply chain management: A review and bibliometric analysis. *International Journal of Production Economics* 162:101-114.

Ferris, T. L. (2007b). Some early history of systems engineering - 1950's in IRE publications (Part 2): The solution. *In INCOSE International Symposium*:1080-1095.

Ferris, T. L. (2007c). History of Systems Engineering (Part 3) - 1950's in Various Engineering Sources. *In INCOSE International Symposium*: 46-57

Ferris, T. L.(2007a). Some early history of systems engineering - 1950's in IRE publications (Part 1): The problem. *INCOSE International Symposium*:1080-1095.

Field, A. (2013). *Discovering statistics using IBM SPSS statistics*. sage.

Flood R. L., Jackson M C (1991). *Systems Engineering Coping with Complexity*. Wiley.

Ford W. (2010).Learning and teaching math. Available from: http://mathmaine.wordpress.com/2010/01/09/problemsfall-into-four-categoriesl.

Fornell, C., & Larcker, D. F. (1981). Structural equation models with unobservable variables and measurement error: Algebra and statistics.

Forsberg K, Mooz H. (1992). The relationship of systems engineering to the project cycle. *Engineering Management Journal* 4(3):36-43.

Forsberg, K., & Mooz, H. (1992). The relationship of systems engineering to the project cycle. *Engineering Management Journal*, *4*(3), 36-43.

Frampton, K., Carlo, T. Di, & Frank, M. (2007). Characteristics of Successful Systems Engineers, Systems Architects and IT Architects. *Knowledge Creation Diffusion Utilization*.

Frank, M. (2006). *Excellence in Systems Engineering: What Characterizes Successful Systems Engineers?* 7–8.

Frank, M., Frampton, K., & Carlo, T.D. (2007). Characteristics of successful systems engineers, systems architects and IT architects. In *Asia-Pacific Software Engineering Conference (APSEC), Nagoya, Japan* (pp. 1-12).

Frank, M.. (2000). Cognitive and Personality Characteristics of Successful Systems Engineers. *INCOSE International Symposium*, 10(1), 718–726. https://doi.org/10.1002/j.2334-5837.2000.tb00447.x

Gardy, J.O. (2000). *Systems Engineering Deployment*. CRC Press.

Gasparatos, A., El-Haram, M., & Horner, M. (2009). The argument against a reductionist approach for measuring sustainable development performance and the need for methodological pluralism. In *Accounting Forum* (Vol. 33, No. 3, pp. 245-256). Taylor and Francis.

GDRC(2009). The Problem Solving Process. Available from: http://www.gdrc.org/decision/problemsolve.Html.

Gelfand, D. M., Hartmann, D.P., Cromer, C.C., Smith, C. L., & Page, B. C. (1975). The effects of instructional prompts and praise on children's donation rates. *Child Development*, 980-983.

Ghauri, P., & Gronhaug, K. (2005). Research Methods in Business Studies, Edinburgh Gate, Harlow. In: Pearson Education Limited.

Glaser, G., & Straus,s L. (1967). The discovery of grounded theory: strategies for qualitative research. *New York, Adline de Gruyter*.

Glaser, B.G., & Strauss, A.L. (1967). *Discovery of grounded theory: Strategies for qualitative research*. Routledge.

Goode, H.H., & Machol R.E. (1959). *Systems Engineering*. McGraw-Hill

Gorod, A., Sauser B., Boardman J. (2008). System-of-systems engineering management: A review of modern history and a path forward. *IEEE Systems Journal* 2(4):484-499.

Goulding, C. (2002). *Grounded theory: A practical guide for management, business and market researchers*. Sage.

Grady, J. O. (2016). *System management: planning, enterprise identity, and deployment*. CRC Press.

Grasler I., Yang X. (2014). Interdisciplinary development of production systems using systems engineering. *Procedia CIRP*.

Gräßler, I., & Yang, X. (2016). Interdisciplinary Development of Production Systems Using Systems Engineering. *Procedia CIRP*, *50*, 653-658.

Greene, J.C., Caracelli, V.J., & Graham, W.F. (1989). Toward a conceptual framework for mixed-method evaluation designs. *Educational evaluation and policy analysis*, *11*(3), 255-274.

Gregory, A.J. (2007). Target setting, lean systems and viable systems: a systems perspective on control and performance measurement. *Journal of the Operational Research Society*, 58(11), 1503-1517.

Hall A.D. (1962). *A Methodology for Systems Engineering.* Nostand Ed. Princeton.

Hall, M. (2008). The effect of comprehensive performance measurement systems on role clarity, psychological empowerment and managerial performance. *Accounting, Organizations and Society,* 33(2-3), 141-163.

Hallam, C.R.A. (2001). An overview of systems engineering. Available from:web.mit.edu/esd.83/www/notebook/syseng.doc

Hallqvist, J., Larsson J. (2016). Introducing MBSE by using systems engineering principles. INCOSE International Symposium: 512-525.

Hawley, M.E. (1956). Speech communications in aircraft. *Transactions of the IRE Professional Group on Communications Systems* 4(2):173-174

Haynes, S. N., Nelson, K., & Blaine, D. D. (1999). Psychometric issues in assessment research.

Hazelrigg, G. A. (1996). *Systems Engineering: An approach to information-based design*. Pearson College Division.

Hitchins, D.K. (2003). *Advanced Systems Thinking, Engineering, and Management*. Artech House.

Hitchins, D.K. (2005). *Systems Engineering - A 21st Century Systems Methodology*. Wiley & Sons Ltd.

Hitchins, D.K.(2007). *Systems Engineering*. Wiley.

Kasser, J. E. (2007, June). 6.4. 1 The Hitchins-Kasser-Massie (HKM) Framework for Systems Engineering. In *INCOSE International Symposium* (Vol. 17, No. 1, pp. 946-968).

Hossain, N.U.I. & Jaradat, R. (2018). A synthesis of definitions for systems engineering. In *Proceedings of the International Annual Conference of the American Society for Engineering Management.* (pp. 1-10). American Society for Engineering Management (ASEM).

Hossain, N.U.I., Nur, F., & Habib, M. A. (2013). Achieving competitive advantage through practicing TQM tools in pharmaceuticals company. *Journal of Mechanical Engineering*, *43*(2), 103-109.

Hossain, N.U.I., Nur, F., & Jaradat, R. M. (2016). An analytical study of hazards and risks in the shipbuilding industry. In *Proceedings of the international annual conference of the American society for engineering management* (pp. 1-8).

Hossain, N.U.I., Debusk, H., & Hasan, M. M. (2017). Reducing patient waiting time in an outpatient clinic: a discrete event simulation (DES) based approach. In *IIE Annual Conference. Proceedings* (pp. 241-246). Institute of Industrial and Systems Engineers (IISE).

Hossain, N.U. I. & Jaradat, R. (2018a). Leveraging six sigma approach to reduce clinic patient waiting time. In *Proceedings of the International Annual Conference of the American Society for Engineering Management.* (pp. 1-6). American Society for Engineering Management (ASEM).

Hossain, N.U.I., Jaradat, R., Hosseini, S., Marufuzzaman, M., & Buchanan, R. K. (2019a). A framework for modeling and assessing system resilience using a Bayesian network: A case study of an interdependent electrical infrastructure system. *International Journal of Critical Infrastructure Protection*, *25*, 62-83.

Hossain, N.U.I., Jaradat, R., Marufuzzaman, M., Buchanan, R., & Rianudo, C. (2019b). Assessing and enhancing oil and gas supply chain resilience: A Bayesian network based approach. In *IIE Annual Conference. Proceedings* (pp. 241-246).

Hossain, N.U.I., Nagahi, M., Jaradat, R., & Keating, C. (2019c). Development of an instrument to assess the performance of systems engineers. In *Proceedings of the International Conference on Industrial Engineering and Operations Management, Toronto, Canada, October 23-25*.

Hossain, N.U.I., Nur, F., Hosseini, S., Jaradat, R., Marufuzzaman, M., & Puryear, S. M. (2019d). A Bayesian network based approach for modeling and assessing resilience: A case study of a full service deep water port. *Reliability Engineering & System Safety*, *189*, 378-396.

Hossain, N.U.I., Nur, F., Jaradat, R., Hosseini, S., Marufuzzaman, M., Puryear, S. M., & Buchanan, R. K. (2019e). Metrics for assessing overall performance of inland waterway ports: A bayesian network based approach. *Complexity*, *2019*.

Hossain, N.U.I., Jaradat, R. M., Hamilton, M. A., Keating, C. B., & Goerger, S. R. (2020). A historical perspective on development of systems engineering discipline: a review and analysis. *Journal of Systems Science and Systems Engineering*, *29*(1), 1-35.

Hossain, N.U.I., El Amrani, S., Jaradat, R., Marufuzzaman, M., Buchanan, R., Rinaudo, C., & Hamilton, M. (2020a). Modeling and assessing interdependencies between critical infrastructures using Bayesian network: A case study of inland waterway port and surrounding supply chain network. *Reliability Engineering & System Safety*, *198*, 106898.

Hossain, N.U.I., El Amrani, S., Nagahi, M., Jaradat, R., & Buchanan, R. (2020b). Modeling and Assessing Social Sustainability of a Healthcare Supply Chain Network-Leveraging Multi-Echelon Bayesian Network.

Hossain, N.U.I., Kerr, C., Jaradat, R., Dadi, K. K., Nagahi, M., & Georger, S. (2020c). How to develop effective system engineers? In proceeding of the American Society for Engineering Management 2020 International Annual Conference and 41st Annual Meeting, Denver, Colorado, USA, Oct. 28-31.

Hossain, N.U.I., Nagahi, M., Jaradat, R., Shah, C., Buchanan, R., & Hamilton, M. (2020d). Modeling and assessing cyber resilience of smart grid using Bayesian network-based approach: a system of systems problem. *Journal of Computational Design and Engineering*.

Hossain, N.U.I, Nagahi, M., Jaradat, R., Stirgus, E., & Keating, C. B. (2020e). The effect of an individual's education level on their systems skills in the system of systems domain. *Journal of Management Analytics*, 1-22.

Hossain, N.U. ., Jaradat, R., Nagahi, M., Dadi, K., & Rinaudo, C.(2020f). Development of New Systems Engineering Instrument using Text Mining Technique.

Hossain, N.U.I., Dayarathna, V. L., Nagahi, M., & Jaradat, R. (2020g). Systems thinking: A review and bibliometric analysis. *Systems*, *8*(3), 23.

Hoyle, R. H. (1995). *Structural equation modeling: Concepts, issues, and applications*: Sage.

Huck, S. W., Cormier, W. H., & Bounds, W. G. (1974). *Reading statistics and research*: Harper & Row New York.

IEEE P1220 (1994*). Standard for Application and Management of the Systems Engineering Process*. IEEE.

INCOSE (2015). Systems Engineering Handbook: A Guide for System Life Cycle Processes and Activities, version 4.0. Hoboken, NJ, USA: John Wiley and Sons, Inc, ISBN: 978-1-118-99940-0

International Council for Systems Engineering, INCOSE (2014). A World in Motion Systems Engineering Vision 2025. https://www.incose.org/docs/default-source/aboutse/se-vision-2025.pdf

Jackson, M. C, & Keys, P. (1984). Towards a system of systems methodologies. *Journal of the Operational Research Society* 35(6):473-486.

Jansma, P. A., Derro, M. E. (2007). If you want good systems engineers, sometimes you have to grow your own! *IEEE Aerospace Conference Proceedings*. https://doi.org/10.1109/AERO.2007.352993

Jaradat, R., & Katina P (2011). A synthesis of definitions for system of systems engineering. Proceedings of the 32nd National ASEM Conference: 589-596.

Jaradat, R. (2014). An instrument to assess individual capacity for system thinking.

Jaradat, R. M. (2015). Complex system governance requires systems thinking-how to find systems thinkers. *International Journal of System of Systems Engineering*, *6*(1-2), 53-70.

Jaradat, R. M., Keating, C. B., & Bradley, J. M. (2014). A histogram analysis for system of systems. *International Journal of System of Systems Engineering*, *5*(3), 193-227.

Jaradat, R. M., Keating, C. B., and Bradley, J. M. (2018). Individual capacity and organizational competency for systems thinking. *IEEE Systems Journal*, *12*(2), 1203-1210.

Jaradat, R., Adams, F., Abutabenjeh, S., & Keating, C. (2017). The complementary perspective of system of systems in collaboration, integration, and logistics: a value-chain based paradigm of supply chain management. *Systems*, *5*(4), 50.

Jaradat, R., Hamilton, M., Dayarathna, V.L., Karam, S., Jones, P., Wall, E., El Amrani, S., & Hsu, G. (2019). Measuring Individuals' Systems Thinking Skills through the Development of an Immersive Virtual Reality Complex System Scenarios. In Proceedings of the ASEE Annual Conference and Exposition, Tampa, FL, USA, 15–19 June 2019.

Jaradat, R. M., Keating, C. B., & Bradley, J. M. (2017a). Individual capacity and organizational competency for systems thinking. *IEEE Systems Journal*, *12*(2), 1203-1210.

Jaradat, R., Stirgus, E., Goerger, S. R., Buchanan, R. K., Hossain, N. U.I., Ma, J., & Burch, R. (2020). Assessment of Workforce Systems Preferences/Skills Based on Employment Domain. *Engineering Management Journal*, *32*(1), 61-73.

Jenkins G. M. (1969). *The Systems Approach in Systems Behaviour*. Harper and Row.

Jolliffe, I. T., & Cadima, J. (2016). Principal component analysis: a review and recent developments. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 374*(2065), 20150202.

Kaplan, R. M., & Saccuzzo, D. P. (2017). *Psychological testing: Principles, applications, and issues*: Nelson Education.

Kaplan, R. S., & Norton, D. P. (1996). *Translating strategy into action: the balanced scorecard.* Boston: Harvard Business School Press

Kaplan, R. S., & Norton, D. P. (2001). *The strategy focused organization: how balanced scorecard companies thrive in the new business environment*. Boston: Harvard Business School Press.

Kapurch, S. J. (Ed.). (2010). *NASA systems engineering handbook*. Diane Publishing.

Karam, S., Nagahi, M., Dayarathna, L., Ma, J., Jaradat, R. & Hamilton, M. (2020). Integrating systems thinking skills with multi-criteria decision making to recruit employees. Expert Systems with Applications.

Kasser, J.E., Zhao Y.Y., Mirchandani C. J. (2014). Simplifying managing stakeholder expectations using the ninesystem model and the holistic thinking perspectives. *INCOSE International Symposium*.

Kasser, J. (2002).Systems engineering: An alternative management paradigm? *Doctoral Dissertation*. Systems Engineering Society of Australia.

Kasser, J. E, Hitchins D. K. (2011). Unifying systems engineering: Seven principles for systems engineered solution systems. *Proceedings of the 20th International Symposium of the INCOSE.*

Kasser, J. (2007). Eight deadly defects in systems engineering and how to fix them. INCOSE.

Kasser, J.E., Frank, M. (2010). A maturity model for the competency of systems engineers. 20th Annual International Symposium of the International Council on Systems Engineering, INCOSE 2010, 1, 37–50.

Kasser, J., Hitchins, D., & Huynh, T. V. (2009, July). Reengineering systems engineering. In *The 3rd Annual Asia-Pacific Conference on Systems Engineering (APCOSE)*.

Katina, P.F ., Keating, C. B., and Jaradat, R.M. (2014). System requirements engineering in complex situations. *Requirements Engineering*, *19*(1), 45-62.

Keating C. B., Katina P. F. (2011). Systems of systems engineering: Prospects and challenges for the emerging fields. *International Journal of System of Systems Engineering* 2(3):234-256.

Keating, C. B., & Katina, P. F. (2011). Systems of systems engineering: prospects and challenges for the emerging field. *International Journal of System of Systems Engineering*, 2(2-3), 234-256.

Keller, A. C. (1981). Early Hi-Fi and Stereo Recording at Bell Laboratories (1931-1932). *Journal of the Audio Engineering Society*, *29*(4), 274-280.

Kelley, T. L. (1927). Interpretation of educational measurements.

Kennerley, M. and Neely, A. (2002). A framework of the factors affecting the evolution of performance measurement systems. *International Journal of Operations and Production Management*, 22, 1222–1245.

Kerr, C., Jaradat, R., & Hossain, N.U.I. (2020). Battlefield Mapping by an Unmanned Aerial Vehicle Swarm: Applied Systems Engineering Processes and Architectural Considerations From System of Systems. *IEEE Access*, *8*, 20892-20903.

Kirshner D.R. (1956). Air traffic control in the jet age. *Transactions of the IRE professional Group on Communications Systems* 4(2):34-47

Kline S.J. (1995). *Conceptual Foundations for Multidisciplinary Thinking*. Stanford University Press, Stanford.

Kline, R.B. (2015). *Principles and practice of structural equation modeling*: Guilford publications.

Koen, B.V. (2003) Discussion of the Method: Conducting the Engineer's Approach to Problem Solving, Oxford University Press, Oxford, UK.

Kopalle, P.K., & Lehmann, D. R. (1997). Alpha inflation? The impact of eliminating scale items on Cronbach's alpha. *Organizational Behavior and Human Decision Processes, 70*(3), 189-197.

Kossiakoff, A., & Sweet, W. N. (2003). *Systems engineering: Principles and practices*. John Wiley and Sons, Inc.

Kossiakoff., A.., William, N. S., Samuel, J. S., & Steven, M. B. (2011). Systems engineering: principles and practice.

Lawrence, J. M., Hossain, N.U.I., Nagahi, M., & Jaradat, R. (2019). Impact of a cloud-based applied supply chain network simulation tool on developing systems thinking skills of undergraduate students. In *Proceedings of the International Conference on Industrial Engineering and Operations Management, Toronto, Canada, October 23-25*.

Lawrence, J. M., Hossain, N.U.I., Rinaudo, C., Buchanan, R., & Jaradat, R. M. (2020). An Approach to Improve Hurricane Disaster Logistics Using System Dynamics and Information Systems. In *18th Annual Conference on Systems Engineering Research (CSER), CA, March 19* (Vol. 21).

Lawrence, J.M., Hossain, N.U.I., Jaradat, R., & Hamilton, M. (2020a). Leveraging a Bayesian Network approach to model and analyze supplier vulnerability to severe weather risk: A case study of the US pharmaceutical supply chain following Hurricane Maria. *International Journal of Disaster Risk Reduction*, 101607.

Lee, J. & Baskerville, R. (2003) 'Generalizing generalizability in information systems research', *Information Systems Research*, Vol.14, No. 3, pp. 221-243.

Lee, J. and Mo, J. (2011). Analysis of Technological Innovation and Environmental Performance Improvement in Aviation Sector. *International Journal of Environmental Research and Public Health*. 8(9): 3777 – 3795.

Leedy, P. D., & Ormrod, J.E. (2005). *Practical research*. Pearson Custom.

Luck, D. J., & Rubin, R.S. (1997). Marketing Research. Prentice Hall. *New York*.

Lumpkin, R. (2009). *NASA SYSTEMS ENGINEERING BEHAVIOR STUDY KENNEDY SPACE CENTER*. February.

Lynch, R. L., and Cross, K. F. (1992). *Measure up – Yardsticks for continuous improvement*. Cambridge, MA: Basil Blackwell.

M'Pherson, P. K. (1986). Systems engineering: A proposed definition. *IEEE Proceedings A:Physical Science, Measurement and Instrumentation, Management and Education, Reviews:* 330-331.

Malviya, S., Vierhauser, M., Cleland-Huang, J., & Ghaisas, S. (2017). What questions do requirements engineers ask?. In *2017 IEEE 25th International Requirements Engineering Conference (RE)* (pp. 100-109). IEEE.

Mar, B. (2009). Commentary on the consensus of INCOSE fellows. Available from: http://www.incose.org/practice/fellowsconsensus.aspxl.

Martin J. N. (1996). *Systems Engineering Guidebook*. CRC Press.

Martin, J. N. (2000). Processes for engineering a system: an overview of the ANSI/EIA 632 standard and its heritage. *Systems Engineering*, *3*(1), 1-26.

Miles, R. F. Jr (1973). *Systems Concepts*. Wiley

MIL-STD-499A (1974). *Mil-STD-499A Engineering Management*. United States Department of Defense (USAF).

MIL-STD-499B (1992). *Military Standard, Systems Engineering, Draft*. Department of Defense. Keating, C. B., Katina, P. F., Bradley, J. M., Jaradat, R. E., and Hodge, R. (2018). Systemic Intervention for Complex System Governance. In *INCOSE International Symposium* (Vol. 28, No. 1, pp. 1534-1548).

Mishra D., Gunasekaran A., Papadopoulos T., Hazen B. (2017). Green supply chain performance measures: A review and bibliometric analysis. *Sustainable Production and Consumption* 10:85-99.

Mooz H., Forzberg K. (1997). Visualizing system engineering and project management as an integrated process. *INCOSE International Symposium*: 573-580.

Morgan, D. (1998). Practical strategies for combining qualitative and quantitative methods: Applications to health research. *Qualitative Health Research, 8*(3), 362-376.

Morse, J. M. (2016). *Mixed method design: Principles and procedures* (Vol. 4). Routledge.

Moser, C., & Kalton, G. (1985). Survey methods in social investigation Aldershot. *UK: Gower*.

M'Pherson, P.K. (1986). Systems engineering: A proposed definition. *IEE Proceedings A (Physical Science, Measurement and Instrumentation, Management and Education, Reviews)*, *133*(6), 330-331.

Nagahi, M., Hossain, N. U. I., & Jaradat, R. M. (2019a). Gender differences in practitioners' preferences for systems-thinking skills. In *proceeding of American Society for Engineering Management 2019 International Annual Conference and 40th Annual Meeting* (pp. 23-26).

Nagahi, M., Hossain, N. U. I., Jaradat, R., & Grogan, S. (2019b). Moderation effect of managerial experience on the level of systems-thinking skills. In *2019 IEEE International Systems Conference (SysCon)* (pp. 1-5). IEEE.

Nagahi, M., & Hossain, N. U. I. & Jaradat, R. (2019c). Classification of Individual's Systems Thinking Skills/Preferences Based on Different Organizational Ownership Structure.

Nagahi, M., Jaradat, R., Hossain, N. U. I., Nagahisarchoghaei, M., Elakramine, F., & Georger, S.R. (2020a). Indicators of engineering students' academic performance: A gender-based study. In *proceeding of the 14th IEEE international system conference, Montreal, Quebec, Canada*.

Nagahi, M., Jaradat, R., Ngahisarchoghaei, M., Hossain, N. U., Shah, C., & Goerger, S.R. (2020b). The Relationship between Engineering Students' Systems Thinking Skills and Proactive Personality: Research Initiation. *Orion*, 7.

Nagahi, M., Jaradat, R. Goerger, S., Hamilton, M., Buchanan, R., Abutabenjeh, S. & Ma, J. (2020c). The Impact of Practitioners' Personality Types on Their Level of Systems-Thinking Skills Preferences. Engineering Management journal. https://doi.org/10.1080/10429247.2020.1780817

Nagahi, M., Jaradat, R., El Amrani, S., Hamilton, M. & Goerger S.R. (2020d). Holistic and Reductionist Thinkers: A Comparison Study Based on Individuals' Skillset and Personality Types. Int. Journal of System of Systems Engineering.

Netemeyer, R.G., Bearden, W.O., & Sharma, S. (2003). *Scaling procedures: Issues and applications*: Sage Publications.

Nunnally, J. C., & Bernstein, I. H. (1994). Psychological theory.

Nur, F., Chowdhury, S., Quddus, T. B. M., Jaradat, R., & Purnell, R (2016). Assessing the Efficiency of 4-Way Stops Compared to Traditional Traffic Signals: A Simulation Approach. *methodology*, *1*, 2.

Nur, F., Marufuzzaman, M., & Puryear, S. M. (2020a). Optimizing inland waterway port management decisions considering water level fluctuations. *Computers & Industrial Engineering*, *140*, 106210.

Nur, F., Aboytes-Ojeda, M., Castillo-Villar, K.K., & Roni, M. S. (2020b). A Two-stage Stochastic Programming Model for Biofuel Supply Chain Network Design with Biomass Quality Implications. *IISE Transactions*, 1-55.

Nur, F., Alrahahleh, A., Burch, R., Babski-Reeves, K., & Marufuzzaman, M. (2020c). Last mile delivery drone selection and evaluation using the interval-valued inferential fuzzy TOPSIS. *Journal of Computational Design and Engineering*.

Nuseibeh, B., & Easterbrook, S. (2000). Requirements engineering: a roadmap. In *Proceedings of the Conference on the Future of Software Engineering* (pp. 35-46). ACM.

Okress E.C., Gleason C.H., White R.A., & Hayter W.R. (1957). Design and performance of a high power pulsed magnetron. *IRE Transactions on Electron Devices* 4(2):161-171.

Olthuis R.W. (1954). Considerations in klystron design for microwave relay systems. *Transactions of the IRE Professional Group on Communications Systems* 2:103-107.

Oluwatayo, J.A. (2012). Validity and reliability issues in educational research. *Journal of educational and social research, 2*(2), 391-391.

OVAE (2005). Problem-solving process. Available from: http://www.cpal.net/course/module3/pdf/Week3_Lesson21.pdf.

ovae D. K.(2007). *Systems Engineering*. Wiley.

Palinkas, L. A., Aarons, G. A., Horwitz, S., Chamberlain, P., Hurlburt, M., & Landsverk, J. (2011). Mixed method designs in implementation research. *Administration and Policy in Mental Health and Mental Health Services Research*, *38*(1), 44-53.

Pedhazur, E. J., & Schmelkin, L. P. (2013). *Measurement, design, and analysis: An integrated approach*: psychology press.

Perrow, C. (1984). *Normal Accidents: Living with High-Risk Technologies*. Basic Books.

Peter, J.P. (1981). Construct validity: A review of basic issues and marketing practices. *Journal of marketing research, 18*(2), 133-145.

Popham, W. . (2008). Transformative Assessment: Association for Supervision and Curriculum Development. 1703 North Beauregard Street, Alexandria, VA 22311-1714.

Pun, K. F., and White, A. S. (2005). A performance measurement paradigm for integrating strategy formulation: A review of systems and frameworks. *International journal of management reviews*, 7(1), 49-71.

Pyster, A., Dominick, P., Henry, D., Hutchison, N., Lipizzi, C., Kamil, M., & Manchanda, S. (2014). *Atlas : The Theory of Effective Systems Engineers* ,. 1–119.

Qiqqa (2017).Available from: http://www.qiqqa.com/.

Quddus, M.A., Hossain, N.U.I., Mohammad, M., Jaradat, R.M., & Roni, M.S. (2017). Sustainable network design for multi-purpose pellet processing depots under biomass supply uncertainty. *Computers & Industrial Engineering*, *110*, 462-483.

NVivo 12[software program]. Version 12. QSR International (2018). Retrieve from https://www.qsrinternational.com/nvivo-qualitative-data-analysis-software/home

Radicchi, F., Castellano, C., Cecconi, F., Loreto, V., Parisi, D. (2004). Defining and identifying communities in networks. *Proceedings of the National Academy of Sciences*.

Rechtin, E., & Maier, M.W. (2000). The Art of Systems Architecting. CRC Press. INCOSE (2006). *Systems Engineering Core Competencies Framework* (No. 2). Technical report, INCOSE, UK.

Roe, C.L. (1995). 5.1.1 the Role of the Project Manager in Systems Engineering. *INCOSE International Symposium*, 5(1), 466–474. https://doi.org/10.1002/j.2334-5837.1995.tb01899.x

Romig, H.G. (1956). Engineering and testing for reliability. *IRE Transactions on Reliability and Quality Control* 6:21-26.

Ryschkewitsch, M., Schaible, D., & Larson, W. (2009, December). The art and science of systems engineering. In Systems Research Forum (Vol. 3, No. 02, pp. 81-100). World Scientific Publishing Company.

Sage, A.P. (1995). *Systems Management for Information Technology and Software Engineering*. Wiley.

Sage, A.P. (1995) *Systems Management for Information Technology and Software Engineering*. New York:Wiley.

Sailor (1990). Identifiable capabilities expressed as performance measurable of functions that the system must possess to meet the mission objectives.

Saukko, T. (2014). *Factors Affecting Customer Profitability: A bibliometric study.* Lappeenranta University of Technology, Lappeenranta.

Schaeffer, M.D. (2005). Technical Excellence through Systems Engineering. Boeing Technical Excellence Conference.

Schlager, K.J. (1956). Systems engineering - key to modern development. *IRE Transactions on Engineering Management* 3(3):64-66.

Schoonenboom, J., & Johnson, R.B. (2017). How to construct a mixed methods research design. *KZfSS Kölner Zeitschrift für Soziologie und Sozialpsychologie*, *69*(2), 107-131.
Scopus(2017). Scopus database. Available from: www.scopus.com

SEBoK contributors, "Guide to the Systems Engineering Body of Knowledge (SEBoK)," SEBoK, Retrieved from:

https://www.sebokwiki.org/w/index.php?title=Guide_to_the_Systems_Engineering_Body_of_Knowledge_(SEBoK)&oldid=59187 (accessed July 25, 2020).

Shannon, C., Weaver W. (1949). *The Mathmatical Theory of Information*. University of Illinois Press.

Sharpe, D. (2015). Chi-Square Test is Statistically Significant: Now What? *Practical Assessment, Research, and Evaluation, 20*(1), 8.

Sheard, S.A. (1996). Twelve Systems Engineering Roles. *INCOSE International Symposium*, 6(1), 478–485. https://doi.org/10.1002/j.2334-5837.1996.tb02042.x

Shenhar, A. (1994).Systems engineering management: A framework for the development of a multidisciplinary discipline. *IEEE Transactions on Systems, Man and Cybernetics* 24(2):327-333.

Shenhar, A. J., & Bonen Z. (1997). The new taxonomy of systems: Toward an adaptive systems engineering framework. *IEEE Transactions on Systems, Man, and Cybernetics-Part A: Systems and Humans* 27(2):137-145.

Shinners, S. (1967). *Techniques of Systems Engineering*. McGraw-Hill.

Shishko, R. (1995). *NASA Systems Engineering Handbook*. US Government Printing Office.

Shishko, R., & Aster, R. (1995). NASA systems engineering handbook. *NASA Special Publication*, *6105*.

Sillitto, H.G. (2010). Design principles for Ultra-Large-Scale (ULS) Systems. In INCOSE International Symposium (Vol. 20, No. 1, pp. 63-82).

Skyttner, L. (1996). *General Systems Theory*. Trans-Atlantic.

Smuts, J. (1926). *Holism and Evaluationg*. Macmillan.

Sousa-Poza, A., Keating, C., & Kovacic, S. (2014). Systems engineering: evolution and challenges. *International Journal of System of Systems Engineering*, 5(4), 379-399.

Souza, R. De, Langford, G., & Hall, B. (2009). *Becoming a Systems Engineer. Cosgrove 2006.*

Spanke, W.F. (1954). Department of the Army command communications. *Transactions of the IRE Professional Group on Communications Systems* 2(3):43-50.

Speak,s F.A. (1956). Power amplifier klystron tubes for U.H.F. transmission. *Transactions of the IRE Professional Group on Communications Systems* 4(1):69-76.

Steiner J.E. (1959). Three models for three ranges the Boeing 707. *Mechanical Engineering* 81(5):46-49.

Stevens, R., Brook P, Jackson K, Arnold, S. (1998). *Systems Engineering Coping with Complexity*. Prentice Hall.

Stewart, P. (2016). Small or pilot study, GCRC protocols which propose" pilot studies. *Cincinnati Children's Hospital Medical Center*.

Streiner, D.L. (2003). Starting at the beginning: an introduction to coefficient alpha and internal consistency. *Journal of personality assessment, 80*(1), 99-103.

Taherdoost, H. (2016). Validity and reliability of the research instrument; how to test the validation of a questionnaire/survey in a research. *How to Test the Validation of a Questionnaire/Survey in a Research.*

Tolk A., Adams K., & Keating, B. (2011). *Intelligence-Based Systems Engineering*. Springer.

Trochim, W. (2000) *The Research Methods Knowledge Base*, Atomic Dog, Ohio.

Vencel L. S., & Cook C. (2005). Methodology selection for the engineering of defence systems. *The 15th INCOSE Annual International Symposium.*

Watson, M.D. (2019), Systems Engineering Principles and Hypotheses. INSIGHT, 22: 18-28. doi:10.1002/inst.12233

Wauben, L.S.G.L., Guédon, A.C.P., de Korne, D.F., & van den Dpobbelsteen, J.J. (2015). Tracking surgical day care patients using RFID technology. *BMJ Innovations*, 1: 59 – 66.

Westen, D., & Rosenthal, R. (2003). Quantifying construct validity: two simple measures. *Journal of personality and social psychology, 84*(3), 608.

Whitley, B. E., & Kite, M.E. (2013). *Principles of research in behavioral science*: Routledge.

Whittemore, R., & Melkus, G.D.E. (2008). Designing a research study. *The Diabetes Educator*, *34*(2), 201-216.

Williams, L.J., & Holahan, P.J. (1994). Parsimony-based fit indices for multiple-indicator models: Do they work? *Structural Equation Modeling: A Multidisciplinary Journal, 1*(2), 161-189.

Wymore A.W. (1976). *Systems Engineering Methodology for Interdisciplinary Teams*. John Wiley & Sons, 1976.

Wymore, A.W (1994). Model-based systems engineering. *The Journal of INCOSE* 1(1):83-92.

Yong-Hak J. (2013). Web of Science. Thomson Reuters. Available from: http://wokinfo.com/media/pdf/WoSFS_08_7050.pdf.

Zar, J. H. (2005). Spearman rank correlation. *Encyclopedia of Biostatistics, 7*.

Zeigler, B.P. (2016). A note on promoting positive emergence and managing negative emergence in systems of systems. The Journal of Defense Modeling and Simulation, 13(1) 133 – 136.