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# A Historical Perspective on Development of Systems Engineering Discipline

## A Review and Analysis

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# Preface

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# A Historical Perspective on Development of Systems Engineering Discipline: A Review and Analysis

**Abstract.** Since its inception, Systems Engineering (SE) has developed as a distinctive discipline, and there has been significant progress in this field in the past two decades. Compared to other engineering disciplines, SE is not affirmed by a set of underlying fundamental propositions, instead it has emerged as a set of best practices to deal with intricacies stemming from the stochastic nature of engineering complex systems and addressing their problems. Since the existing methodologies and paradigms (dominant patterns of thought and concepts) of SE are very diverse and somewhat fragmented. This appears to create some confusion regarding the design, deployment, operation, and application of SE. The purpose of this paper is 1) to delineate the development of SE from 1926-2017 based on insights derived from a histogram analysis, 2) to discuss the different paradigms and school of thoughts related to SE, 3) to derive a set of fundamental attributes of SE using advanced coding techniques and analysis, and 4) to present a newly developed instrument that could assess the performance of systems engineers. More than Two hundred and fifty different sources have been reviewed in this research in order to demonstrate the development trajectory of the SE discipline based on the frequency of publication.

## 1. Introduction

After World War II, there was a fundamental operational transformation in industrial and construction sectors around the world. During the war, a new engineering discipline 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 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. 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 and Hitchins 2011). While this suggests a somewhat fragmented discipline, a 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 paper is to trace the chronological development of SE from 1926-2017. To achieve this purpose, the paper 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 paper are as follows:

- To trace the history development of SE from 1926-2017 based on insights derived from a histogram analysis. This would provide a comprehensive overview of SE domain.
- To derive a set of common characteristics of SE using advanced coding techniques and analysis. This would serve as a baseline snapshot to invoke a dialogue that possibly contribute to fruitful to future advancement of SE field.
- To 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 nomenclature are embedded in SE definition.
- To present a newly developed instrument that could capture the performance level of individual system engineers. It will help individuals/ group of systems engineers to identify their weak zone and develop themselves to encounter the intricacies emanating from complex systems in where they are anticipated to be engaged.

To achieve the objectives of the paper, more than two 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


**Figure 1** Classification of SE Interval for Histogram Analysis.

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 (2007a), Ferris (2007bc), Gorod et al. (2008), Brill (1998) as a grounded references where Ferris (2007a), Ferris (2007bc) 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 the 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 250+ sources are incorporated in the analysis. Grounded Theory Coding (Charmaz and Belgrave 2012) techniques were employed with the use of Nvivo 12 (QRS International 2017) 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, the paper concludes with a discussion of the implications of the analysis for the SE discipline along with the avenue of future research.

## 2. Histogram Analysis

In this section, the design and execution of the histogram analysis are developed (results summarized in Figure 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 1 provides the interval classifications for the histogram.

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 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 are identified and discussed.

### 2.1.1 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 irrigations 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 battle ships 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 inability to effectively operate the complex electronic weapon systems (Brown 1953). The complexity of the equipment exceeded 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 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 a 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 1930's and 1940's 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 network. For instance, the Radio Corporation of America (RCA) and Bell Telephone Company aimed to expand the television transmission domain and long-distance telephone network, respectively, using new broadband technologies. However, these experimental projects failed to progress due to the interruption caused by World War II. As a consequence, in lieu 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, 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 (Kelly 1950). Bell Telephone Laboratories was perhaps the first organization to coin the phrase "systems engineering" (Schlager 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 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 endeavour 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 systems 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 of 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 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 the communication among the practitioners (Checkland, 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.

Schlager (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) 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(p.1)." 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 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 aircraft system, where the all the necessary components and comminucation 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 (Kirshner 1956). This versatility created a need for a holistic approach to integrate 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 illustrated 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 (Goode and Machol 1959) 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 prewar 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 highlights the main themes in interval I.

### 2.1.2 Interval II (1961-1989): Exploration of SE

In the 1960s-1990s, SE had significant growth along with 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 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 com-

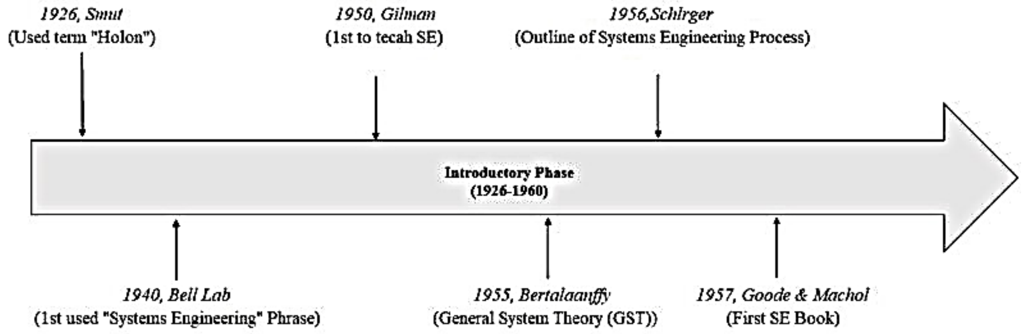



**Figure 2** Main Themes for the 1926-1960 SE Development Timeline.

posed 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 and 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 (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 shoulde 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 (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 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 and 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 a 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 MILSTD499A (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 en-

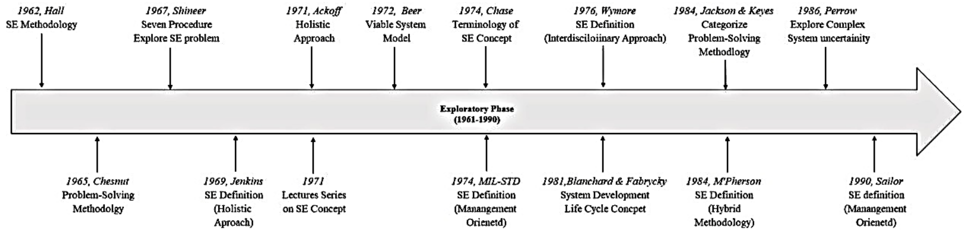



**Figure 3** Main Themes for the 1961-1989 Timeline.

gineering effort to meet cost, schedule, and technical performance objectives (Buede and Miller 2016, 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 (1991) writings in the same year underscored the importance of exploring complex system problems from different standpoints that are mutually supportive to the axioms dervied from the cybernatics. 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 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 3 shows the main themes in interval II.

### 2.1.3 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 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, symposium and journals pertaining to SE were also made available. To disseminate the SE principles and practices and to 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 for SE during this period:

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

**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 need, management processes coordinate different design and configuration control groups and encompasses 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."

**Theme II: Requirement driven process and SE process (life-cycle)**

Forsberg 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 detail 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.

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 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 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 requirements 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.

**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 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 satisfy the stakeholder need. Shenhar (1994) added another layer to the definition of SE by including the concept of interdisciplinary approach, holistic perspective, and management process. SE deals with identifying 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 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. "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.

**Theme IV: Problem solving**

Kasser (2007) developed a framework that clarifies 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 is an over-lap and correlation between systems engineering processes (SEP) and the generic problem-solving processes. However, the set of activities of SEP and problem-solving process 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 EIA 632 (1994), generic V-model and SIMILAR (Bahill and 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 B (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 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: *exploration of initial problem* and *development of technological solution*. The model consists a set of activities that addresses the background of the problem and develops the technological solution by considering the systems from a holistic perspective.

Another contribution came from Vencel and Cook (2005, p.8). They explore the

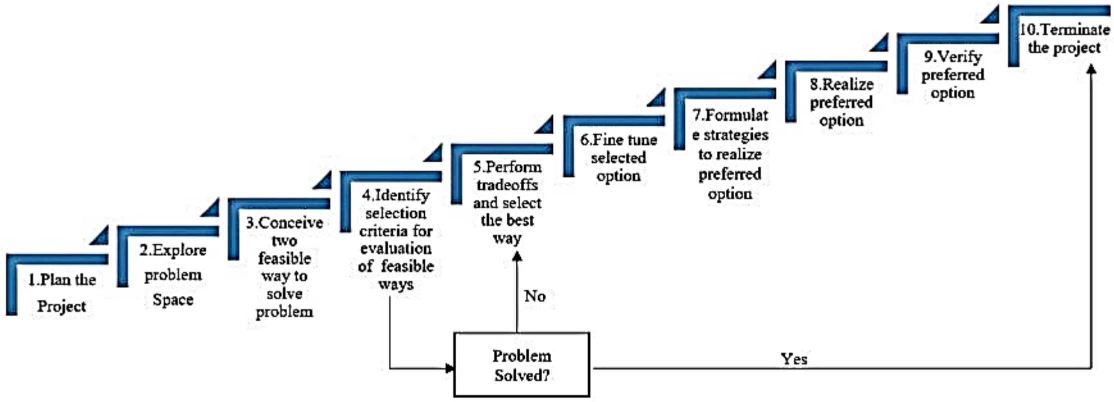



**Figure 4** 10-step Problem Solving Process.

typology of complex system problems, defined the entire problem space and categorized it based on seven-dimensional problem attributes: 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 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 Forsberg (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.

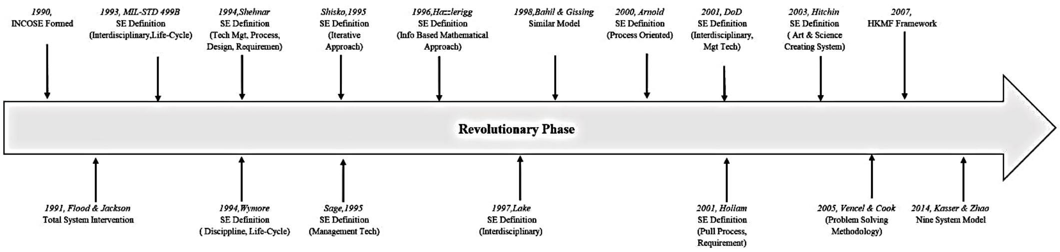



**Figure 5** Main Contributions of 1990-2017 Timeline.

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 economic 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 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 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 5.

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, main characteristics of SE are derived. 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* (reformulation of coding into higher level core categories) to derive the central theme from 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 of different types of research documents from variety of publication houses.

## 3. Histogram Analysis

Figure 6 shows the histogram analysis of SE. The horizontal axis in the histogram signifies the time line 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

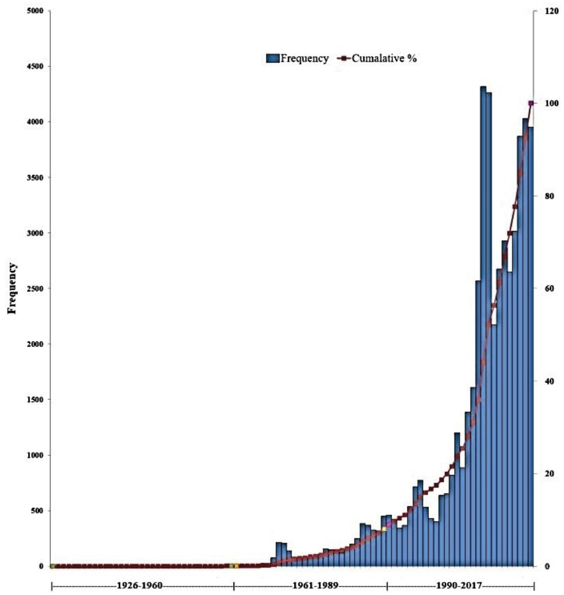



**Figure 6** Histogram Analysis of SE.

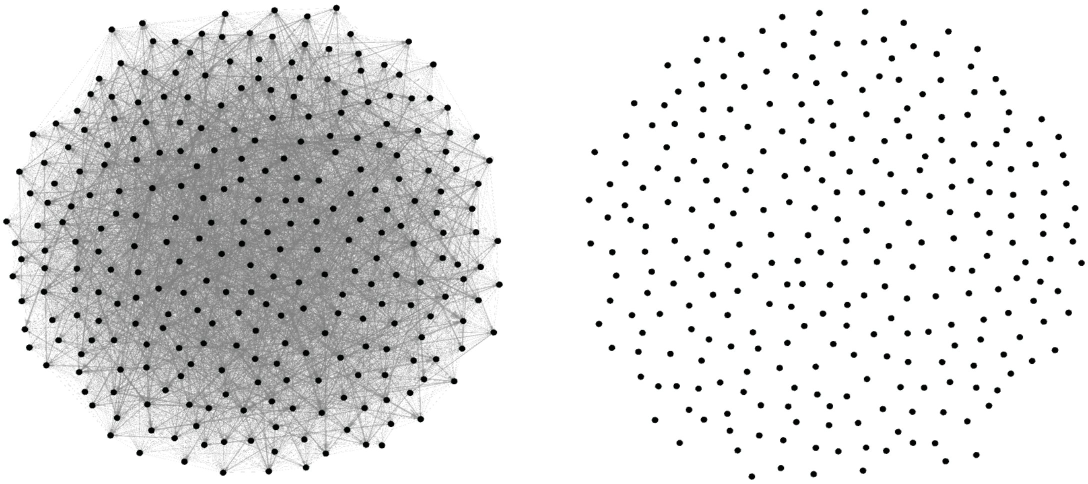
to unite the research germane to diversified branches of SE under the same umbrella and to disseminate knowledge from the field of SE. Many universities and schools introduced systems engineering into their academic curriculum as well. There will be many future opportunities where the knowledge and information 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 obvious. 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.

### 3.1 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 the 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 report) and a set of edges signifying the co-occurrence 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, .NET file contained of 278 sources was developed and imported in 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



(a) with Edges (b) without Edges

**Figure 7** The Force Atlas Layout of the 278-Node Network.

embedded graphical properties. Fort Atlas driven algorithm is well known for its clear and legible graphical output. Figure 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).

### 3.2 Data Clustering: Literature Classification

The nodes in the map can be further clustered by using data clustering technique. Data clustering technique is conduced 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 modularity tool is anchored in Louvain algorithm. The modularity index of a partition ranges from -1 to +1 that 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 following equation (Fahimnia et al. 2015).

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

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

$$(p_i = \sum_b X_{ab}),\ r_a$$

is the clusters 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 node, three major clusters were identified, as reported in Figure 8. The description of each cluster provided in Table 1.

### 3.3 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 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 total percentage value of the bar chart 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 10

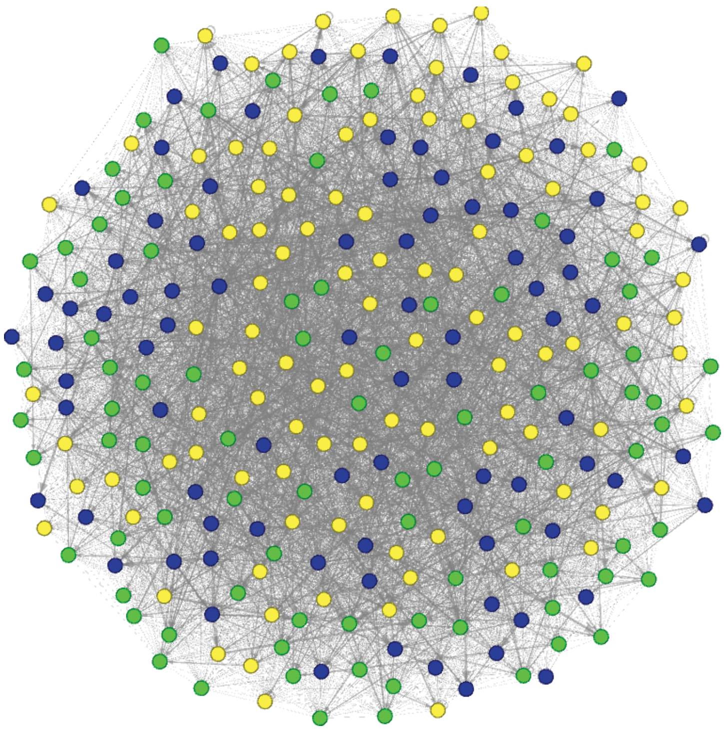


**Figure 8** Structure of the Network with Three Clusters.

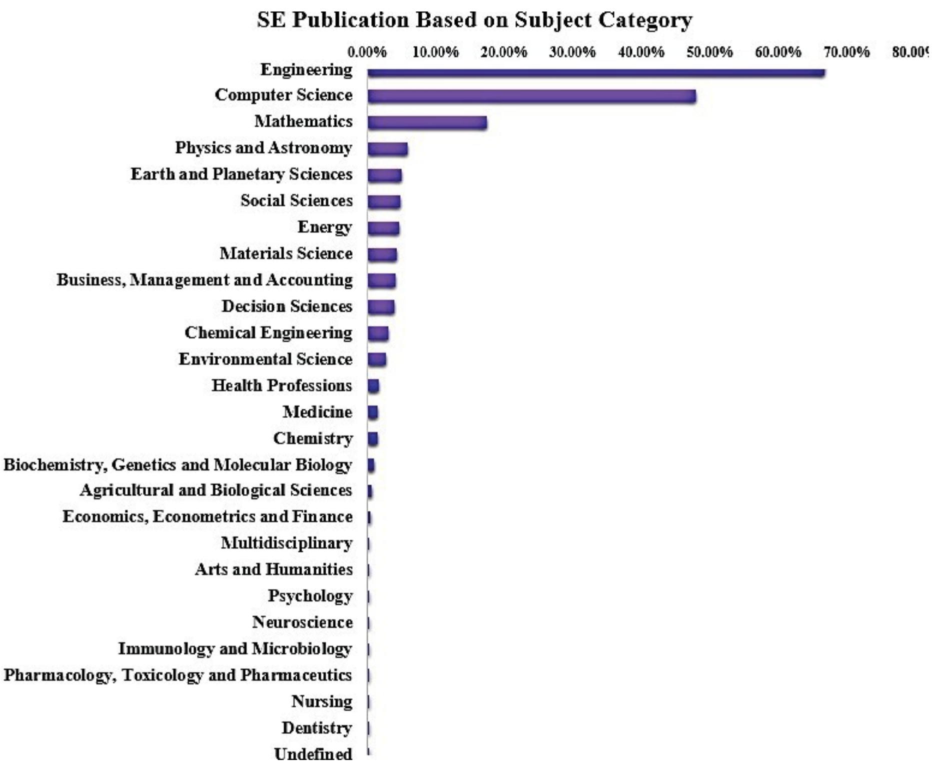



**Figure 9** Discpline wise SE Publications.

**Table 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 |

shows the interconnectivity between the generated eight common themes and the pertinent definitions stated by several researchers.

Beside the above areas, SE have been applied to multifarious problems, including risk management, critical infrastructure management,production process, cognitive science, risk and reliability engineering, economic analysis, quality management, supply chain management, and several others. To delve further into the application of SE in different disciplinary areas, readers should examine the works of Peugeot (2014), Hosseini and Barker (2016), Choi (2016), Hossain et al. (2019ab), Alfaqiri et al. (2019), Nagahi et al. (2019a), Valerdi (2008), Abdallah et al. (2014), Soleimani et al. (2018), Shepherd (2014), Stirgus et al. (2019), Hollnagel and Woods (2005).

## 3.4 Grounded Theory Coding

Grounded theory coding is an established qualitative data analysis methodology that generates a theory from the unstructured large data set including surveys, interviews, literature reviews and others (Charmaz and Belgrave 2012). After an extensive analysis of the literature of SE from 1926-2017, a set of SE attributes was derived based on grounded theory coding. Grounded theory coding was used: 1) to conduct the data collection and analysis concurrently, 2) to develop analytical codes from the available data sources, not from predefined rationally inferred hypotheses and 3) to construct pertinent theory based on the coding during each step of data collection and synthesis. In this research, three main stages of coding were conducted to analyze and code the literature from 1926-2017, including *Phase I: open coding, Phase II: axial coding and Phase III: selective coding*.

**i) Open coding (891 codes)**

At this phase, we engaged coding to assign codes to distinct elements considered to be logical expressions of the concept being expressed. Categories were created based on the classification of information (qualitative data from the literature) that best fits to a concept or any theoretical possibility (Corbin and Strauss 1990). Open coding could be word by word coding, line-by-line, paragraph by paragraph or whole document coding. In our analysis, 891 codes were generated during this coding stage. A sample of the generated nodes in open coding is captured in Figure 11 and Figure 12 provides a sample 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. The Flip-flop technique helps to answer six Ws: who, what, when, where, why, and how in the analyzing text. It also helped to perform "what-if" analysis and "imagine the opposite." The waving red-flag technique helps to avoid the use of sensitive phrases like rarely, never, and always. Saturation is another technique which occurs when the coding of the data reaches a certain point such that there are no new codes or patterns suggested from analysis of new information.

**ii) Axial coding (24 categories)**

Axial coding explores the underlying attributes of a category to show the intercon-

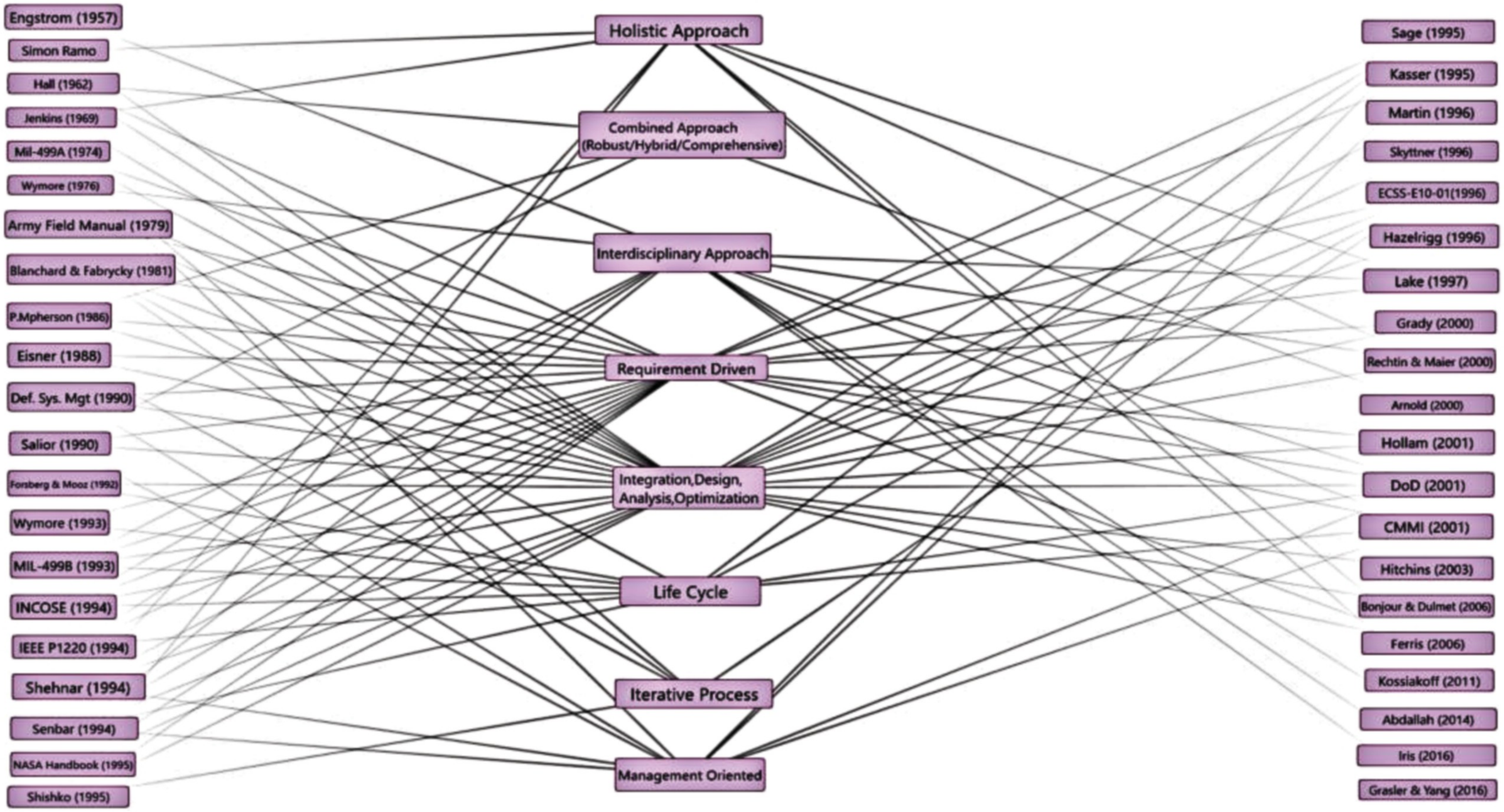
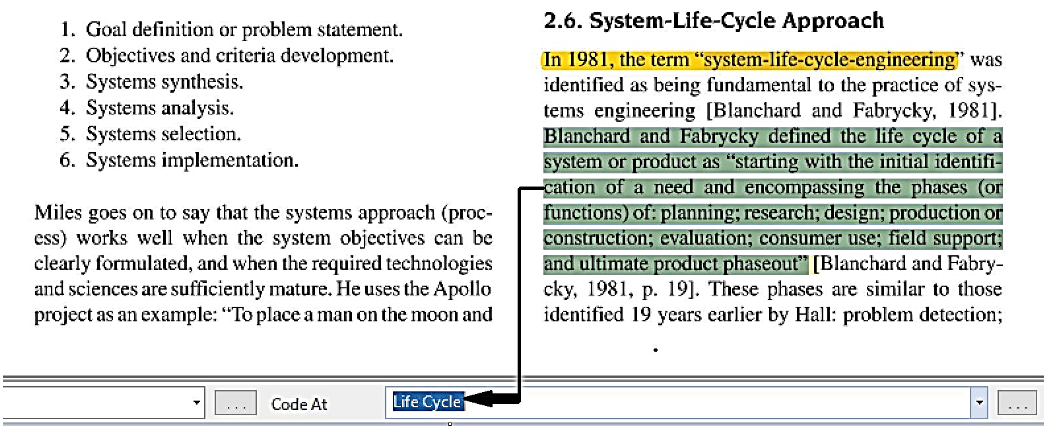



**Figure 10** Synthesis of SE Definition (Common

**Nodes**

| Name | Files | References |
|---|---|---|
| Iterative process | 6 | 9 |
| Area of SE | 8 | 10 |
| integration | 8 | 10 |
| evalution | 6 | 10 |
| life cycle | 4 | 10 |
| system design | 8 | 10 |
| systems life cycle process | 9 | 11 |
| Design and analysis | 9 | 12 |
| customer need | 8 | 13 |
| Origin of SE | 10 | 14 |
| Systems Engg & Project Management Comparison | 4 | 14 |
| Requirment completeness test | 1 | 14 |
| problem solving | 9 | 15 |
| Requirements of customer | 13 | 16 |
| Process of systems engineering | 14 | 22 |
| Interdisciplinary approach | 17 | 25 |
| Role of systems engineers | 16 | 25 |
| Defination of SE | 19 | 42 |

**Figure 11** Sample of Open Coding.



1. Goal definition or problem statement.
2. Objectives and criteria development.
3. Systems synthesis.
4. Systems analysis.
5. Systems selection.
6. Systems implementation.

Miles goes on to say that the systems approach (process) works well when the system objectives can be clearly formulated, and when the required technologies and sciences are sufficiently mature. He uses the Apollo project as an example: "To place a man on the moon and

**2.6. System-Life-Cycle Approach**

In 1981, the term "system-life-cycle-engineering" was identified as being fundamental to the practice of systems engineering [Blanchard and Fabrycky, 1981]. Blanchard and Fabrycky defined the life cycle of a system or product 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 phaseout" [Blanchard and Fabrycky, 1981, p. 19]. These phases are similar to those identified 19 years earlier by Hall: problem detection;



**Figure 12** Demonstration of Line by Line Coding.

nections and causality and specifies the plausible relationships. In this research, axial coding was used to: (1) analyze the fragmented data, 891 codes to assign them to categories and subcategories, (2) interconnect the categories to subcategories, (3) organize the categories based on the characteristic of their interconnection and (4) develop a theory based on the relationship. During the axial coding, connections between the 891 codes in the dataset were drawn and 24 main categories (parent nodes) were identified. A "causal condition" and "central phenomena" were used to create the interconnection between categories (parent nodes) and sub categories (child nodes). The 891 codes were connected to the parent node in a way that the implication of the parent nodes better described the accumulated meaning of every child node. In this stage a model coding analysis, coding query analysis, and project map analysis were performed. The intent was to compare and explore the interrelation between different categories and subcategories. In Figure 13, a snapshot of axial coding (project map) is illustrated where "Holistic approach" is considered as a main category (parent node) and "big picture perspective," "Holistic thinking," and "General systems theory" are some of the subcategories (child nodes).

**iii) Selective coding (6 main attributes)**

Selective coding conceptualizes the entire idea. The objective of selective coding is to summarize all the nodes, categories and memos and reduce them into a core category

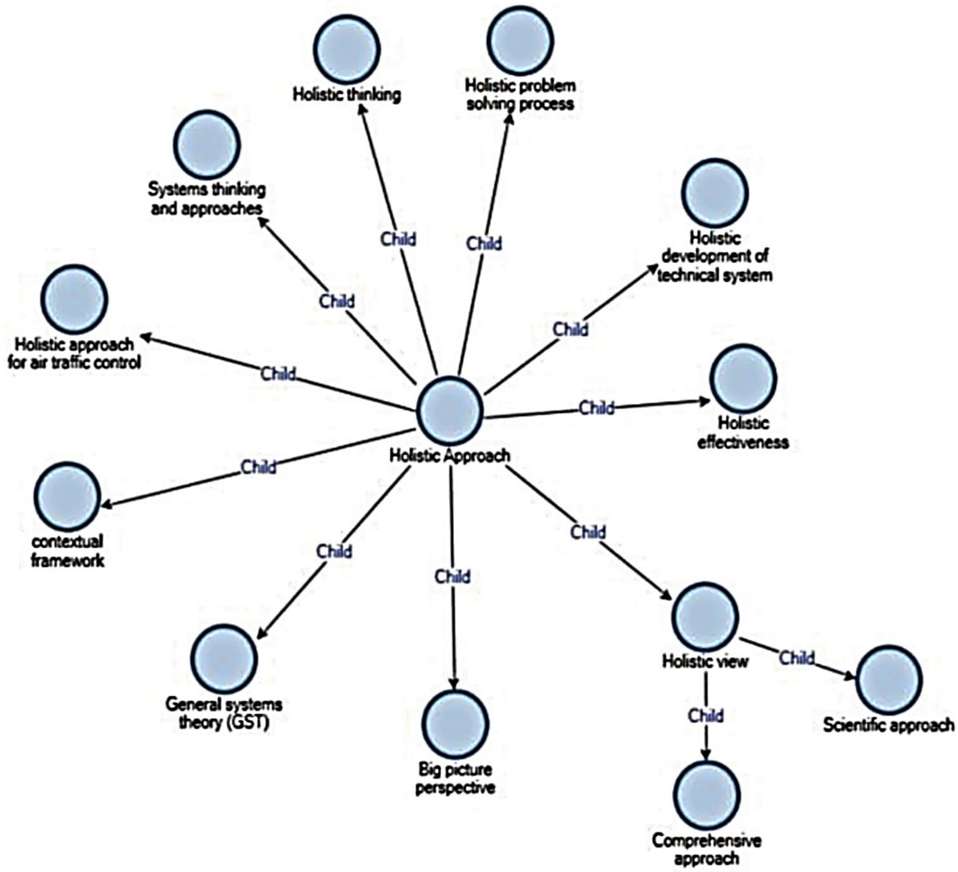



**Figure 13** Sample of Axial Coding (Project Map Analysis)

**Nodes**

| Name | Sources | References |
|---|---|---|
| Requirement Engg | 38 | 344 |
| Requirements of customer | 29 | 65 |
| customer need | 8 | 13 |
| Need identifiction | 4 | 4 |
| need satisfaction | 4 | 5 |
| customer requirement | 3 | 8 |
| practice needs | 1 | 1 |
| operational need | 1 | 3 |
| technical needs | 1 | 1 |
| business need | 1 | 1 |
| requirement negociation | 1 | 1 |
| designer need | 1 | 1 |
| requirement shell | 1 | 1 |
| Stakeholder and requirements engineer ch | 1 | 3 |

**Figure 14** Sample of Selective Coding.

**Table 2** Total Number of Coding Reference of Core Codes.

| Nodes | Number of times coded (aggregate from child nodes) |
|---|---|
| Nodes\\Interdisciplinary | 184 |
| Nodes\\Holistic | 166 |
| Nodes\\Requirement Eng. | 344 |
| Nodes\\Integration, Design & Optimization | 496 |
| Nodes\\Life Cycle | 160 |
| Nodes\\Management | 243 |

**Table 3** Summary of All Coding Techniques.

| Attributes | Open coding | Axial coding | Selective coding |
|---|---|---|---|
| Purpose | Development of categories of information | Development of interconnections and plausible relationships among the nodes generated during Axial coding. | Developments of core categories |
| Treatment of the dataset | Deconstruct the raw data into pieces by assigning several codes | Look for causal condition (compare and contrast) | Formulation of central themes |
| Approaches used | word by word coding, line-by-line, paragraph by paragraph | Causal conditions =>Central phenomenon =>Context exploration =>Intervening conditions =>Action/interaction strategies =>Consequences. | Conceptualization of the entire analysis |
| Techniques used | Flip-flop, Waving the red-flag, and Saturation | Matrix coding, coding query, model-coding analysis. | Tree map, cluster analysis, coding strip |
| Output | 891 codes | 24 categories | 6 main attributes |

that represents the central theme of a particular research and link all other appropriate codes to that category. For instance, if "requirement engineering" is selected to be code number 1 and "requirements of customer" is labeled 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 (see Figure 14).

In this final coding procedure, a theoretical model was developed. The model contains the set of systems engineering attributes (6 core-codes) that epitomize the fundamental core characteristics of a systems engineering approach. These six core codes were identified as Interdisciplinary, Holistic, Requirement Engineering, IDO (Integration, Design & Optimization), Life-Cycle Focused & Management(see Figure 15). During the GTC analysis, six fundamental systems engineering attributes were recognized based on the highest frequency of coding from the literature (see Table 2). A summary of all coding technique is presented in Table 3.

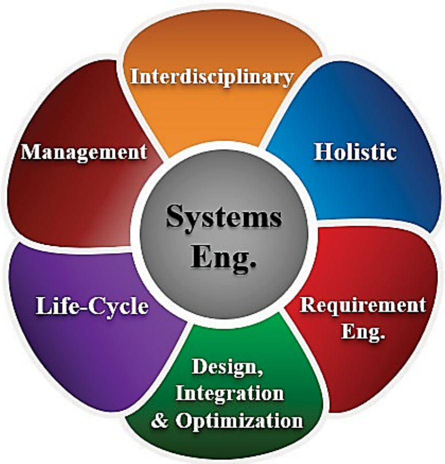



**Figure 15** Attributes of SE.

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

**i) Interdisciplinary**

Interdisciplinary approach is one of the fundamental attributes of SE. Systems engineering encompasses a number of varied disciplines to form a well-structured, process-oriented approach. To deal with complexity, a combination of different disciplines work together simultaneously, which implies that people from diverse backgrounds and varying knowledge can work collaboratively, share their understanding, and progress towards a common objective.

**ii) Holistic**

Basically, traditional SE disciplines employ a bottoms-up approach, whereas recent advances in SE suggest use of a more holistic top-down approach. Systems engineering emphasizes looking at a system problem in its entirety rather than concentrating on a distinct part of a system. It analyzes, synthesizes and designs the whole, considering the wider range of possible facets, dimensions, and related aspects of the problem, its context, and the system solution being generated. However, there is a controversy concerning the degree of holistic perspective and nature of SE. At the center of this controversy is the level of compatibility between positivist/reductionist and antipositivism/holistic based paradigms.

**iii) Requirement Engineering**

The success of SE depends primarily on how adequately it meets the intended purpose. Requirement engineering is a human-centered process that traces the stakeholder's need and transforms the need into feasible solutions. Thus, requirement engineering is captured as one of the basic attributes of SE. Requirement engineering encompasses several stages, including: identification of stakeholder need, eliciting requirements, modeling and analyzing the requirement and communicating the requirements. Often the term "requirement traceability" is used to track the artefact (specification, design, model, and test) of the requirement engineering process (Gotel and Finkelstein 1994).

**iv) Sub-elements integration, design & optimization**

A major purpose of SE is to integrate and design the sub-elements of the system to achieve optimal system performance. It integrates the possible technical parameters and assures compatibilities among the different interfaces of the system to support optimized system performance to the greatest degree possible (however, for truly complex systems it can never be known that optimal performance has been reached). The physical construction and integration of the individual components must be consistently balanced to accrue greater benefits from better systems engineering practice.

**v) Life-cycle**

Similar to other engineering disciplines, SE is life-cycle focused in movement from product inception through disposal. SDLC is split into two parts: i) acquisition phase and ii) utilization phase. The acquisition phase includes conceptual design, detail design and production phases, while the utilization phase ranges from product use through disposal. The primary goal of the acquisition phase is to enable effective system design in an economically efficient way so that full life-cycle cost can be minimized. A system spends the majority of its life in the utilization phase which includes ending with reusability, recyclability and disposability.

**vi) Managament / Systems Engineering Management**

Although SE deals with technical activities, it still plays a significant role in management. There is an overlap between systems engineering and project management. Like project management, SE is cognizant of business aspects and prescribes critical management pro-

Table 4 Summary of SE Features.

| Features | Description |
|---|---|
| Origin | System theory |
| Focus | Individual complex system |
| Objective | Design, integration, optimization and management |
| Approach | Iterative process oriented |
| Boundary | Static |
| Address | Specific need |
| Problem Domain | Pre-defined and well-bounded |
| Methodology | Structured & life-cycle based |
| Solution | Technical dominance |
| Goal | Unitary |


Figure 16 Sample Profile of a Systems Engineer.

cesses, including planning, organizing, coordinating, controlling, and directing to accomplish the objective of the system.

However, traditional systems engineering (TSE) failed to embrace high degree of uncertainty in complex systems problems. Moreover, traditional systems engineering, which is entrenched in linear pattern of concept, often unsuccessful to provide complete system solutions. As TSE's, problem domain is predefined, TSE often ignore the contextual influence of the multifaceted problem and focuses more toward technical dominant solutions. Based on the extensive review of literature, summary of SE features are listed in Table 4.

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 (Keating and Katina 2011, Keating et al. 2003). Groupings of SoS can be further characterized by Federations of system (FoS)(Adcock 2015). In the past decade, model based systems engineering (MBSE) has been appeared as modern SE tool that cover 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 (Hallqvist and Larsson 2016).

### 3.5 Development of SE Performance Measurement Instrument

From the existing SE literature, we further investigate the performance indicators pertaining to each systems engineering attribute. This set of indicators would serve as a baseline to develop a new system engineering instrument that assesses the performance of systems engineers. This instrument could assess the current state of the systems engineering skills for a systems engineer and indicate developmental areas to enhance the underlying system skills (see Table 5). The outcome of the proposed instrument will generate a profile that represents the systems engineering skill held by an individual. Each profile comprises of six letters that represents the level of skill for each individual systems engineers, and thus determine their level of performance to deal with problems emanating from complex systems domain. The development of this instrument is based on Jaradat's work. Jaradat et al. (2017) developed an instrument using 7 systems engineering dimensions that measure individuals' level of systems thinking skills. In the SE performance instrument, the focus will be on the performance. A sample individual systems engineer's profile is illustrated in Figure 16. Based on the profile depicted in Figure 16, an individual has strong knowledge (more than average) on hierarchical view, design and integration, management aptitude whereas his/her proficiency level is below par in interdisciplinary dimension. Additionally, there is a scope of improvement for the requirement engineering and life cycle attributes. The maturation and implementation of this instrument is currently in progress, interested readers are referred to study (Hossain et al. 2019c).

Appreciation of this instrument will also serve as a foundational snapshot to figure out the weakness of each individual systems engineers so that they can retrospect the scope of improvement and develop new outlooks and ways of thinking to understand and solve multifaceted system engineering problems in a productive manner. In summary, the set of performance measure would consider as "a point of comparison" to inform the development of individual and organizational development and training programs to increase systems skills in systems engineering. Table 5 illustrates the anatomy of the SE performance measurement instrument.

## 4. Conclusion

In this paper, 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 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 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 are 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 sev-

**Table 5** Anatomy of SE Performance Measurement Instrument (Hossain et al. 2019c).

| 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 providetop-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<br>- Coordination and Collaboration<br>- Hybrid Thinking<br>- Common understanding of core problems<br>- Tolerance of ambiguity<br>- Application<br>- Adaptability<br>- Leadership<br>- 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 entiresystem 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<br>-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<br>- Flow-down activities (requirement elicitation, analysis, definition (define constraint) and specifications, modelling, validation and verification)<br>- 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)<br>-System design and integration<br>- Subsystem design and integration<br>-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"<br>-Broader knowledge of "engineering development"<br>-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<br>-Risk management<br>-Configuration management<br>-Decision management<br>-Project management<br>-Quality management<br>-Information management |

eral important aspects from this beginning. First, the history of SE during this period has shown the originat- ing 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 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:

- *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.

- *The holistic nature of the SE discipline.* As SE evolved over time, so too did the types of problems considered. 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.
- *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.
- *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.
- *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.

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### 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, Pinto A (2019). A systemic approach for disruption risk assessment in oil and gas supply chains. *International Journal of Critical Infrastructure* 15(3).

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

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

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

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

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

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

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 D E, Scherer W T(1998). A comparison of systems engineering programs in the United States. *IEEE Transactions on Systems, Man, and Cybernetics, Part C* 30(2):204-212.

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

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.

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

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

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

Choi T M (2016). *Service Supply Chain Systems: A systems engineering approach.* CRC Press.

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

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

Corbin J M, Strauss A (2000). Grounded theory research: Procedures, canons, and evaluative criteria. *Qualitative Sociology* 13(1):3-21.

Defense Systems Management College (1990). *Systems Engineering Management Guide*. US Government Printing Office.

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

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

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

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(2007a). Some early history of systems engineering - 1950's in IRE publications (Part 1): The problem. *INCOSE International Symposium*:1080-1095.

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.

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.

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

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

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

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.

Gotel O C, Finkelstein C W(1994). An analysis of the requirements traceability problem. In Requirements Engineering. *Proceedings of the First International Conference on IEEE*.

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

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

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.

Haskins C, Forsberg K, Krueger M, Walden D, Hamelin D (2006). *Systems Engineering Handbook*. INCOSE.

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

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 (2007). *Systems Engineering - A 21st Century Systems Methodology*. Wiley & Sons Ltd.

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

Hitchins D K (2005). Systems methodology. *Conference on Systems Engineering Research*.

Hollnagel E, Woods D (2005). *Joint Cognitive Systems: Foundations of cognitive systems engineering*. CRC Press.

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

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

Hossain N U I, Jaradat R, Hossein S, Marufuzzaman M, Buchanan R K (2019b). 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, Nagahi M, Jaradat R, Keating C (2019c). Development of an instrument to assess the performance of systems engineers. *Proceedings of the International Conference on Industrial Engineering and Operations Management.*

Hosseini S, Morshedlou N, Ivanov D, Sarder M D, Barker K, Al Khaled A (2019d). Resilient supplier selection and optimal order allocation under disruption risks. *International Journal of Production Economics* 213:124-137.

Hosseini S, Al Khaled A, Sarder M D (2016). A general framework for assessing system resilience using Bayesian networks: A case study of sulfuric acid manufacture. *Journal of Manufacturing Systems* 41:124-137.

Hosseini S, Barker K (2016). Modeling infrastructure resilience using Bayesian networks: A case study of inland waterway ports. *Computers & Industrial Engineering* 93:252-266.

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

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 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, Bradley J M (2017). Individual capacity and organizational competency for systems thinking. *IEEE Systems Journal* 12(2): 1203-1210.

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

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

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

Kasser J E (2007). The Hitchins-Kasser-Massie (HKM) Framework for Systems Engineering. *INCOSE International Symposium*, pages 946-968.

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

Keating C, Rogers R, Unal R, Dryer D, Sousa-Poza A, Safford R, Rabadi G (2003). System of systems engineering. *Engineering Management Journal* 15(3):36-45.

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.

Kelly M J (1950). The Bell Telephone Laboratories - an example of an institute of creative technology. *Proceeding R. Soc. Lond. B*: 419-433.

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.

Kossiakoff A, Sweet W N, Seymour S J, Biemer S M (2011). *Systems Engineering Principles and Practice*. John Wiley & Sons.

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

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 (1997). *Systems Engineering Guidebook: A Process for Developing Systems and Products*. CRC Press.

MilesRF Jr (1973). *Systems Concepts*. Wiley.

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

MIL-STD-499B (1992). *MIL-STD-499B. Military Standard, Systems Engineering Draft*. United States Department of Defense (USAF).

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

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

Nagahi M, Hossain N U I, Jaradat R, Grogan S (2019b). Moderation effect of managerial experience on the level of systems-thinking skills. *Proceeding of the 13th Annual IEEE International Systems Conference.*

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.

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

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

Peugeot T (2014). *System Engineering, for a Cognitive Sciences Approach.* CSDM posters.

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

Qiqqa QRS International (2017). Available from: web.mit.edu/esd.83/www/notebook/syseng.doc.

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.

Roe C L (1995). The role of the project manager in systems engineering. *The 5th Annual International Symposium of the INCOSE.*

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

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

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

Scopus (2017). Scopus database. Available from: www.scopus.com.

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

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.

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.

Shepherd C C (2014). A systems engineering approach to quality assurance for aerospace testing. Available from: https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20140010105.pdfl.

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.

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

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

Soleimani N, Nagahi M, Nagahisarchoghaei M, Jaradat R (2018). The relationship between personality types and the cognitive-metacognitive strategies. *Journal of Studies in Education* 8(2):29-44.

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

Speaks 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.

Spiegel J, Bennett E M (1957). Military system reliability: Department of defense contributions. *Electrical Engineering* 9(3):1-9.

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.

Stirgus E, Nagahi M, Ma J, Jaradat R, Strawderman L, Eakin D (2019). Determinants of systems thinking in college engineering students: Research initiation. *Proceeding of the 126th Annual Conference & Exposition American Society for Engineering Education*.

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

Valerdi R (2008). Systems engineering economics. Available from: http://seari.mit.edu/documents/summit/2008/07-SEAriSummit08_RP_Valerdi.pdfl.

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

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

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

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

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**14. ABSTRACT**

Since its inception, Systems Engineering (SE) has developed as a distinctive discipline, and there has been significant progress in this field in the past two decades. Compared to other engineering disciplines, SE is not affirmed by a set of underlying fundamental propositions, instead it has emerged as a set of best practices to deal with intricacies stemming from the stochastic nature of engineering complex systems and addressing their problems. Since the existing methodologies and paradigms (dominant patterns of thought and concepts) of SE are very diverse and somewhat fragmented. This appears to create some confusion regarding the design, deployment, operation, and application of SE. The purpose of this paper is (1) to delineate the development of SE from 1926-2017 based on insights derived from a histogram analysis, (2) to discuss the different paradigms and school of thoughts related to SE, (3) to derive a set of fundamental attributes of SE using advanced coding techniques and analysis, and (4) to present a newly developed instrument that could assess the performance of systems engineers. More than Two hundred and fifty different sources have been reviewed in this research in order to demonstrate the development trajectory of the SE discipline based on the frequency of publications.

**15. SUBJECT TERMS**

Systems Engineering (SE), history, development, systems engineering attributes, performance measures

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