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Development of a New Instrument to Assess the Performance of Systems Engineers

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Abstract

Complex systems continue to confound the capabilities of systems engineers to deal with and navigate a new generation of problems. Thus, there is an emerging need to develop a cadre of effective systems engineers capable of efficiently addressing complex systems problems. This paper introduces a new system engineering instrument that assesses the performance of systems engineers. The instrument is based on the set of performance indicators examining six fundamental system engineering attributes. This instrument would provide a baseline to understand the current state of the systems engineering skills for a systems engineer and indicate developmental areas to enhance those skills. Following a brief introduction, this paper is structured to explore four primary areas. First, we examine why there is a need to develop effective systems engineers. Second, we propose a novel tool that could assess the state of systems engineering skill and support the purposeful development of skills. Third, we present an examination of the individual performance of induvial systems engineers. Fourth, a discussion is presented on the utility and implications for the proposed instrument.

Keywords
Systems engineering, systems skill, effective system engineers, performance instrument, and complex system.

1. Introduction

Modern systems are designed and develop to fulfill needs or provide solutions for bettering organizations and overcoming persistent challenges stemming from increasing complexity. However, systems and their derivative problems are not likely to be settled in the near future rather they are more likely to intensify in complexity. Perhaps, revolutions in technologies and proliferation of information are indicative of the future which must be dealt with by systems engineers. Thus, there is a need to employ a "systemic approach" to better manage and navigate these complex system problems (Alfaqiri et al., 2019; Hossain et al., 2016; Lawrence et al., 2019; Nagahi et al., 2019). In response, *Systems Engineering (SE)* has developed as a distinctive discipline to address these challenges and concerns by using a systemic approach to ensure that individual elements, sub-elements, and associated phenomena are functioning harmoniously in a given operational environment to achieve an effective performance of the overall system. From a fundamental perspective, systems engineering is an iterative process to ensure that the embedded elements and subsystems constituting the system are designed, balanced, and function in the most effective manner while integrating appropriate "ilities" (i.e, maintainability, sustainability, reliability, manability, supportability) and other attributes into the total engineering effort (Blanchard and Fabrycky, 1990; Buede, 2016; Hossain and Jaradat, 2018; Nagahi et al., 2018; Shishko and Aster,1995). The underlying role of a systems engineer ranges from the identification of the stakeholders' requirements to the conceptual design to the system development and operation to the product disposition phase. Sheard (1996) identified 12 fundamental roles of systems engineers; however, the primary role of the system engineer is to implement systems engineering activities, regardless of title. Along the same line, Frank (2002) posited thirty systems thinking laws, that could serve as a guideline to perform their work.

Over the years, many issues have complicated the tasks of systems engineers. These include evolving legacy and off-the-shelf components, contextual specificity, extensively large structures, and lack of clarity in multiple expectations and outcome (Sousa-Poza et al., 2014). Thus, there is a need to develop an effective systems engineering workforce that can efficiently work in complex system problem domains. Mark Schaeffer, the former Principal Defense Systems and Director, Systems Engineering for the Office affiliated with Secretary of Defense (ATandL) made a statement to emphasize the importance of developing qualified systems engineers. He stated that "degreed workforce is a shrinking pool" and that we "need new ways to attract and develop system engineers (Schaeffer, 2005)." He also added, "An experienced, trained workforce is in short supply (Schaeffer, 2005)." This again stresses the importance of organizations developing a cadre of skillful systems engineers. This also suggests two important questions that are not well defined in the existing body of literature: *(1) What are the fundamental attributes of systems engineering that would impact the performance of individual system engineers? (2) What are the leading indicators for appraising the performance of an individual systems engineer?* To answer the aforementioned questions, we conducted an extensive review of the literature on systems engineering to identify the fundamental attributes of systems engineering and the corresponding performance indicators that can measure each attribute. This review supports the development of a novel *systems engineering performance measurement tool* that captures and assesses the performance of individual systems engineers. This performance is based on assessing the leading indicators of the fundamental systems engineering attributes. The outcome of this instrument will generate a unique profile for individual systems engineers and allows engineers to improve their systems engineering skills to better deal with the increasing intricacies of the design and operation of complex systems. Appreciation of this framework will also serve as a benchmark to trace out the weakness of individual systems engineers. Once 'weak' areas are identified they can serve to (1) support developmental areas for an engineering, (2) identify potential vulnerabilities in performance of work assigned to systems engineers that may be performing 'systems' engineering activities for which they are not sufficiently prepared, and (3) identify where additional/different skill sets might need to be added to supplement systems engineering activities. Thus, the purpose of this research is to develop an instrument that will assess the performance of an individual systems engineer who engages across the complete systems engineering life cycle activities.

2. Performance Measurement System Tools

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

3. The Development of Instrument

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

After completion of the final stage of coding, a theoretical model has been developed, and a new theory is obtained. This theory represents the set of systems engineering attributes (6 core-codes) and the corresponding performance indicators for each attribute. The six core codes were derived after examining the patterns in the dataset using three main progressive stages of coding: open coding, axial coding, and selective coding. The anatomy of the six attributes and the corresponding performance indicators for each attribute are presented in Table 1.

Table 1. The anatomy of the six attributes and the corresponding performance indicators

Attributes	Performance Indicators
Interdisciplinary: Integration of diversified disciplines in order to deal with complex system problems and to provide top-notch solutions during the design and development stages of a system	• *Integration* • *Coordination and Collaboration* • *Hybrid Thinking* • *Common understanding of core problems* • *Tolerance of ambiguity* • *Application* • *Adaptability* • *Leadership* • *Communication and Listening*
Hierarchical View: Perception about a problem, its environment, and solution. The viewpoint of a systems engineer whether he/she is considering the entire system life cycle as a whole or only focusing on a set of disconnected parts.	• *Holistic* • *Reductionist*
Requirement Engineering: 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 fulfill customer expectation.	• *Context and groundwork* • *Flow-down activities (requirement elicitation, analysis, definition (define constraint) and specifications, modeling, validation, and verification)* • *Requirement traceability and management (Change management, evolving requirement)*
System Design and Integration: Represents design, integration, and verification of sub-elements through a logical sequence to optimize the performance of the system.	• *ConOps (the concept of operation)* • *System design and integration* • *Subsystem design and integration* • *Unit design and testing* • *Coding (V&V)*
System Life Cycle: Defines the stages involved in bringing a system from inception to phase out.	• *Knowledge of "concept development"* • *Broader knowledge of " engineering development"* • *Knowledge of "post-development" phase*

Management/Systems Engineering Management: Technical skill-set in conjunction with a broad understanding of business principles to oversee the system processes in order to enhance system performance.	• *Management planning and control* • *Risk management* • *Configuration management* • *Decision management* • *Project management* • *Quality management* • *Informantaion management*

4. Assessing the performance of Individual Systems Engineers

The proposed instrument consists of 34 scenarios with binary response question options. These scenarios were developed based on the extensive literature review of the performance indicators for each attribute. Participants engage with each scenario in order to select the best options based on their systems engineering knowledge. For our scoring purpose, we have coded one point for a systemic response and zero points for each non-systemic response. Then, the sum of the individual response points is divided by the number of total questions for each attribute to obtain the cumulative score for the respective attribute. This score represents the weighted performance for an individual systems engineers skill state for that corresponding attribute. Finally, the cumulative score will be converted into a percentage scale, which ranges from 0 to 100. The resulting score is then translated into a performance profile that contains six main letters. This translation is done based on the score obtained for the respective attribute. For instance, for the interdisciplinary attribute, if an individual scores more than 50, his/her letter tag is I^+ (I-plus), which represents that the individual possesses the above-average interdisciplinary skill. On the other hand, if an individual score less than 50, his/her letter tag is I^-(I-minus). This means that the individual has below average skill on the interdisciplinary attribute. If an individual's score is equal to 50, he/she gets the letters I (I-plain), which entails that the participant has average knowledge on the interdisciplinary attribute. The performance profiles (6-letters) represents an individual performance in the domain of system engineering. The results of the instrument's application are instructive for systems engineers as well as the organization/teams to which they are assigned. For systems engineers, the results provide a professional development framework of areas that they may need to focus on to enhance their systems engineering skill sets. For organizations/teams, the results of the team members assigned to a particular effort can suggest the diversity of skills that exist on a team. This can be compared to the particular effort to identify potential skill set vulnerabilities that may need to be 'compensated' such that the effort will have a better chance for success. While the instrument results are not the 'definitive' guide to skills, they do provide a valuable indicator to suggest areas of deeper inquiry.

4.1. Interdisciplinary

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

4.2. Hierarchical View

The hierarchical view represents the perception of a problem, its environment, and the solution. More precisely, the viewpoint of a systems engineer whether he/she is considering the entire system life cycle as a whole or only focusing on a set of disconnected parts. Jaradat (2015) defined the level of hierarchical view as a personal tendency to view complex problems from either a holistic or reductionist perspective. Keating et al. (2018) posited that "In addition to technical/technology aspects of a system, consideration for the entire influencing spectrum of human/social, organizational/managerial, policy, political, and information aspects central to a more complete (holistic) view of a system. Behavior and performance as a function of interactions in the system – not reducible or revealed by understanding individual constituents" (Keating et al., 2018, Table 1). By the same token, Gasparatos, El-Haram, and Horner (2009) stated "our recent awareness of economies, societies, and ecosystems as complex adaptive systems that cannot be fully captured through a single perspective further adds to the argument. Failure to describe these systems holistically through the synthesis of their different non-reducible and perfectly legitimate perspectives amounts to reductionism. An implication of the above is the fact that not a single sustainability metric at the moment can claim to comprehensively assess sustainability" (p. 245).

4.3. Requirement Engineering

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

4.4. System Design and Integration

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

4.5. System Life Cycle

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

4.6. Management/Systems Engineering Management

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

5. The Outcome of the Profile

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

Figure 1: An example of a systems engineer's profile.

Table 2: Two extremes of each attribute

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

5.1 Interpretation of Profiles

The first attribute*, interdisciplinary skill (I),* describes whether an individual has the ability to work on a collaborative environment or not? The second, *skill on the hierarchical view (H)*, indicates the way an individual approaches problems to solve system engineering problems. The third pair, *skill on requirement engineering (R)*, describes an individual's proficiency in the requirement engineering discipline. The fourth attribute, *systems design, and integration skill,* indicates an individual's dexterity on understanding the fundamentals of systems design and integration. The fifth attribute, skill on *system lifecycle*, describes an individual's knowledge on systems life cycle management. The final attribute, *skill in SE management*, specifies the way an individual approaches managing systems engineering problems through their business, technical, and interpersonal skill. Based on the profile depicted in Figure 1, an individual has strong knowledge (more than average) on interdisciplinary, hierarchical view, and design and integration aptitude, whereas his/her proficiency level is below par in management dimension. Additionally, there is a scope of improvement for the requirement engineering and life cycle attributes. The illustration of an example profile as depicted in Figure 1 is represented as a scale in the following Figure 2. The cross mark – "X" sign shows an individual's skill/performance on each attribute.

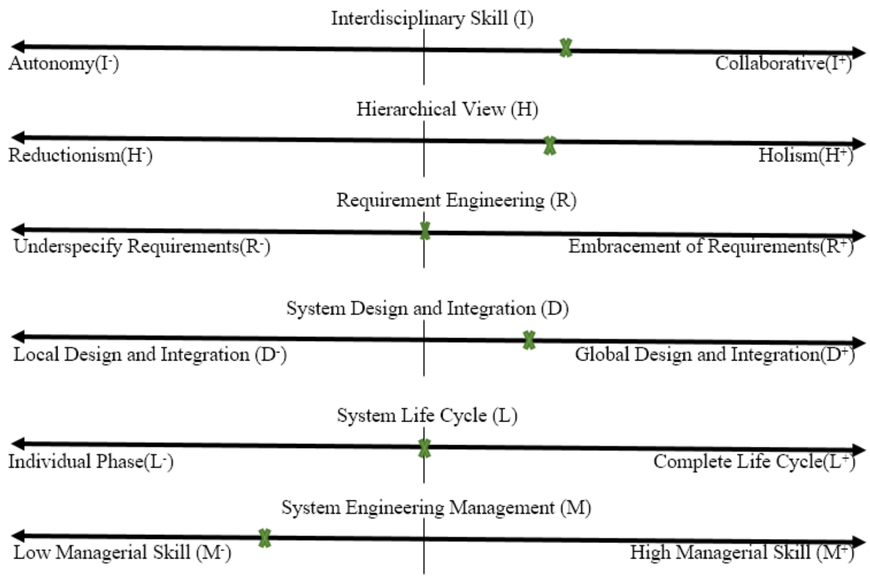

Figure 2: SE performance measurement scale

6. Implication and Conclusion

While there is a list of works that were specific to the characteristics of individual systems engineers, this study discusses how to measure the performance of individual systems engineers. The six fundamental attributes are derived based on advanced analytical technique; then, the corresponding list of performance measures are explored from the extensive review of literature for each attribute. The suitability of the individuals' systems engineering profiles might vary based on the nature, context, and circumstance of solving complex systems. This instrument will serve as a baseline to find the improvement areas for each individual so that that they can rectify and overcome their laggings and leave them behind. The implications of the research across theoretical, methodological, and practical dimensions are summarized as follows.

- This research offers a starting point to better understand the individual capacity to engage in complex multidimensional problems.

- Served as a 'baseline snapshot" to assess the performance of systems engineers measuring in complex systems and their symptomatic problems. Each profile gives a clear description of how an individual would perform complex problems.

- The systems engineering instrument can be applied at multiple levels: individuals, organizations, teams, and others. It helps individuals/ cadre of systems engineers to strengthen their weak area and fit themselves to face the complexities stemming from the problem domain in where they are anticipated to be deployed.

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

This research offers three important utilities. First, practicing managers can use the instrument to determine that state of systems engineering skills and diversity in 'thinking' that exist in a team. This permits the determination as to whether the skills should be developed within an existing team, the team should be expanded to compensate for skillset deficiencies, or the deficient skills should be 'outsourced' as necessary to perform the project. Second, individuals can better understand personal implications for the further development of skills. These skills can enhance current performance or provide extended 'career' skills to advance. Third, the skills necessary for a systems engineering effort can be examined over the systems life cycle. Necessary systems skills can and will shift over the life cycle of a system. Appreciation of this perspective, coupled with having a tool to understand the state of systems engineering skills, will provide a more informed development approach to engage throughout the system life cycle.

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