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THESIS

IDENTIFYING THE KEY MISCONCEPTIONS IN SYSTEMS ENGINEERING

by

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13. ABSTRACT (maximum 200 words)

Systems engineering (SE) is a field of study filled with various topics, and professionals enter the field along different educational pathways. Some system engineers have formal education, while others rely on prior background studies or on-the-job training. Although past studies highlight the core competencies needed to perform in an SE position adequately, they do not address the core concepts learned by students in a foundational SE course. This research identified the core concepts employing a qualitative data analysis method using subject matter experts. The research team selected subject matter experts from Naval Postgraduate School (NPS), Massachusetts Institute of Technology (MIT), NAVSEA, and industry. The team determined the core concepts by comparing the SE literature and contrasting the findings from the subject matter expert interviews. Additionally, this research identified problems in systems engineering design and issues students have with understanding core concepts. This research is designed to improve student learning in an educational environment. This research can be developed further by exploring other SE subfields in similar ways to find the concepts that exist in other SE subfields and how they overlap. Furthermore, the core concepts could be applied to create a concept inventory that would increase student knowledge transfer in the SE concepts.

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IDENTIFYING THE KEY MISCONCEPTIONS IN SYSTEMS ENGINEERING

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ABSTRACT

Systems engineering (SE) is a field of study filled with various topics, and professionals enter the field along different educational pathways. Some system engineers have formal education, while others rely on prior background studies or on-the-job training. Although past studies highlight the core competencies needed to perform in an SE position adequately, they do not address the core concepts learned by students in a foundational SE course. This research identified the core concepts employing a qualitative data analysis method using subject matter experts. The research team selected subject matter experts from Naval Postgraduate School (NPS), Massachusetts Institute of Technology (MIT), NAVSEA, and industry. The team determined the core concepts by comparing the SE literature and contrasting the findings from the subject matter expert interviews. Additionally, this research identified problems in systems engineering design and issues students have with understanding core concepts. This research is designed to improve student learning in an educational environment. This research can be developed further by exploring other SE subfields in similar ways to find the concepts that exist in other SE subfields and how they overlap. Furthermore, the core concepts could be applied to create a concept inventory that would increase student knowledge transfer in the SE concepts.

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LIST OF ACRONYMS AND ABBREVIATIONS

ABET	Accreditation Board of Engineering and Technology
CERDEC	Communications, Electronics, Research, Development, and Engineering Center
COMPOSE	Competency of the Profession of Systems Engineering
CONOPS	Concept of Operations
DAWIA	Defense Acquisition Workforce Improvement Act
DOD	Department of Defense
DoDAF	Department of Defense Architecture Framework
EMMI	energy, matter, material wealth, and information
GAO	Government Accountability Office
GRCSE	Graduate Reference Curriculum for Systems Engineering
FCI	Force Concept Inventory
INCOSE	International Council on Systems Engineering
KSAs	knowledge, skills, and abilities
LHD	Landing Dock Helicopter
M&S	Modeling and Simulation
NASA	National Aeronautics and Space Administration
NAVSEA	Naval Sea Command
NPS	Naval Postgraduate School
SE	systems engineering
SEBoK	Systems Engineering Body of Knowledge
STEM	science, technology, engineering, and mathematics
SysML	Systems Modeling Language
TRL	Technology Readiness Level
UML	Unified Modeling Language
USN	U.S. Navy
USG	United States government

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EXECUTIVE SUMMARY

Systems engineering (SE) emerged as a field in the 1940s with varying definitions of what systems are and the role and benefits of SE (Shahriari 2019). Multiple definitions of SE exist, which makes defining the fundamental concepts of the field challenging. The lack of a universal definition also makes it challenging to identify what should be understood by someone that has completed an entry-level SE class. In the physics community, Hestenes, Wells, and Swackhamer (1992) developed the Force Concept Inventory (FCI) to identify the misconceptions associated with Newtonian concepts after students have taken an introductory physics course. The result of their work launched a vein of research that aimed to improve physics instruction. Savinainen and Scott (2002) identified how a better understanding of many students' misconceptions about Newtonian concepts could enhance student learning. Through the FCI, other concept inventories have been developed and utilized to improve the way other subjects are taught (Reed-Rhoads and Imbrie 2008). Concept Inventories exist for engineering education, chemistry, biology, and management, but not yet for systems engineering.

In SE, there have been several efforts to identify the requisite knowledge, skills, and abilities for a systems engineer. Whitcomb and colleagues (2015) highlighted that the Department of the Navy did not have an SE career field. The goal of his research was to develop a competency model for the profession of SE. Similarly, organizations such as the MITRE Corporation (2007) and NASA (2019) have developed competency models that define the core knowledge, skills, and abilities needed to perform the job. Additionally, each organization provides a subjective way to measure proficiency associated with each of the competencies.

While all three of these studies highlight the core competencies needed to perform in a system engineering position adequately, they do not address the core concepts learned by students in a foundational systems engineering course. This research aims to identify the core concepts taught in a graduate-level class. Rather than identifying all of the core concepts, this research will focus on system design core concepts because they are unique to SE and different from identifying competencies. Stakeholder Expectation Definition and

Management and Technical Requirements represent System Design competency areas that NASA expects (NASA 2019). MITRE (2007) describes competencies as behaviorally based capabilities that allow the system engineer to participate in design reviews and contribute to design decisions. By contrast, a core concept in system design uses models to develop systems, hierarchical/top-down design, and development methodologies (Bahill and Botta 2008). Another critical difference between the competencies and the core concepts is that the core concepts provide the background, tools, and theory needed to contribute to the competencies.

To explore the core concepts of SE design, the research team used literature and subject matter expert interviews to determine the core concepts. While also pointing out common problems in SE design and issues that students have with understanding the concepts. As a result of this work, the research has established the SE design concepts with the problems, challenges, and complications that typically arise in a design. To continue this research, the research team recommends that the other subfields of SE be explored in similar ways to find the remaining concepts and how they overlap with the concepts identified in this research. Another suggestion is to use the concepts identified to create a concept inventory to measure and increase student knowledge transfer in the SE concepts.

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I. INTRODUCTION

Who gets to be called a systems engineer? Many engineers, scientists, and mathematicians in designated systems engineering (SE) positions in the civilian Navy commands have no formal SE education. Sheard (1996) discussed the role of systems engineers and "whether INCOSE [The International Council on Systems Engineering] is about systems engineers or about SE" (Sheard 1996, 1). Engineering institutions offer formal SE education as undergraduate and graduate-level degrees. As part of civilian training and continuing education programs provided by the Navy, engineers can pursue SE graduate degrees to enhance their career field knowledge. Although on-the-job training is an option for learning the skills and abilities needed for a given role, formal education has to have some advantages; otherwise, why is SE education deemed beneficial for engineers in the workforce? In answer to this, it is vital to understand the difference between a systems engineer and SE.

Sheard (1996) describes the subtle difference between SE and systems engineers. In Sheard's characterization, a systems engineer is a title applied to an individual who works on a larger system, not the subsystems or other elements, whereas SE is the process that the systems engineer uses. Sheard identified twelve roles that are typical in SE organizations. They are requirements owner, system designer, system analyst, validation/ verification engineer, logistics, glue among subsystem, customer interface, technical manager, information manager, process engineer, coordinator, and classified ads SE (Sheard 1996). Each of these roles requires different traits and backgrounds to be successful in the positions. To be successful at most of them would need some prerequisite SE knowledge.

Have you ever taken a class and asked yourself what the purpose was? The research team has stumbled across this question multiple times in systems engineering (SE), which sparked the interest in this topic. Often in SE courses, the intended learning objectives or core concepts are missed by the students.

This research aims to identify the core concepts taught in system design, which would likely be taught in a graduate-level SE class. The idea for this research was based on work in other fields related to concept inventories in the physics community. We wondered why a concept inventory did not exist for SE. However, to generate a concept inventory for SE, the research team believes that the SE community has not fully realized the primary concepts that separate SE from other disciplines. Additionally, we observed that SE is split into numerous specializations, as displayed in Figure 1. The research team used literature from online resources, textbooks, and subject matter expert interviews to determine the core concepts to explore SE design's core concepts. Furthermore, we attempted to identify common problems in SE design and issues students have with understanding the concepts.

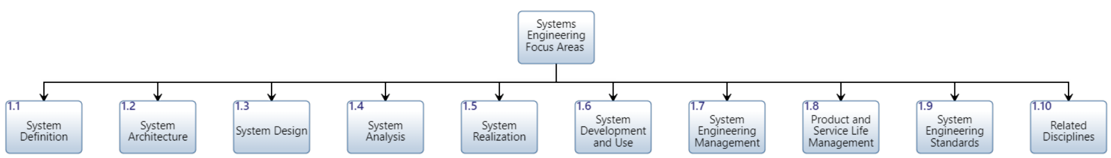

Figure 1. Systems Engineering Specialization Areas. Adapted from SEBok contributors (n.d.).

This chapter will discuss what SE is and differentiates between a core concept and a competency. The purpose of explaining the difference between the two helps define SE's concepts, the misconceptions that exist within the field, and to the ways to address them in SE education. SE design is the focus of this research due to its uniqueness in SE and the impacts of design influence in terms of system cost, sustainment, and other life cycle elements (Boehm, Valerdi, and Honour 2008).

A. BACKGROUND SE CONCEPTS, AND CONCEPT INVENTORIES

It can be beneficial to identify concepts unique to SE to enable the field's development and education. The Graduate Reference Curriculum for Systems Engineering (GRCSE) offers recommendations for the development of SE curriculums. The GRCSE states that despite the importance of SE graduate education, there is no community-accepted guidance on what to teach about SE (Pyster et al. 2015). The lack of an agreed-upon curriculum combined with SE's unestablished concepts makes assessing effective learning difficult for SE. As part of the recommendations for developing a curriculum, GRCSE discusses establishing educational objectives and measuring the goals achieved through assessments (Pyster et al. 2015).

A tool that would help measure the identified concepts' level of understanding would be a concept inventory. A concept inventory is a test to assess conceptual understanding in a subject area. The concept inventory consists of multiple-choice questions to evaluate each concept's understanding (Hestenes, Wells, and Swackhamer 1992). This research looks to identify key concepts in SE design for future educational benefits.

In the physics community, Hestenes, Wells, and Swachamer (1992) developed the Force Concept Inventory (FCI) to identify the misconceptions associated with Newtonian concepts after students have taken an introductory physics course. Their work launched a vein of research that aimed to improve physics instruction to overcome common student misconceptions. Savinainen and Scott (2002) identified how a better understanding of many students' misconceptions about Newtonian concepts could enhance student learning. Through the FCI, other concept inventories have been developed and utilized to improve the way other subjects are taught (Reed-Rhoads and Imbrie 2008).

Evans et al. (2003) discussed the development of concept inventories for various engineering disciplines and subspecialties and their importance to relating teaching techniques to student learning. They also discussed the consequence of misconceptions. Misconceptions block the connections between concepts and produce further learning problems. For example, in mathematics, addition and subtraction are fundamental concepts. When a student has issues with addition and subtraction fundamentals, the student will later have problems with multiplication and division since they both build upon the ideas of adding and subtraction. Concept inventories exist for fluid mechanics (Martin, Mitchell, and Newell 2003), chemistry (Krause et al. 2004), biology (Klymkowsky and

Garvin-Doxas 2008), and mathematics (Epstein n.d.), to name a few (Evans et al. 2003), but not yet for SE.

Simoni et al. (2004) also referenced the prior work done with concept inventories and how they point out common misconceptions in a specific body of knowledge. Their research focused on the development of an electronics concept inventory. An important note from their research is how concept inventories are accepted as valid data for the Accreditation Board of Engineering and Technology (ABET) accreditation process by showing proof of student learning (Simoni, Herniter, and Ferguson 2004). Another interesting point from work done by Simoni et al. was the purpose of the research: to inform and spark debate about the content of the electronics concept inventory, which is also the purpose of this research but in the case of SE.

The signals and system concepts inventory created by Wage et al. (2005) used a similar method as the FCI to cover the fundamental concepts taught in a signals and systems class, which is a specialty of electrical engineering. Wage et al. explain the development process for their concept inventory and the lessons learned from the development. The signals and systems concept inventory was developed as an assessment tool on problem-solving performance. From the FCI usage, an evaluation was given to 6000 students, and the research found that the students only learned about 25% of the concepts using traditional lecture methods (Hake 1998). Early evaluation of the signals and systems concept inventory displayed that only 20% of the concepts taught in a conventional lecture are mastered by students (Wage et al. 2005). The studies conducted by Hake (1998) and Wage et al. (2005) revealed that students were not grasping the core concepts and were instead relying on problem-solving skills to pass the exam. Mastering the core concepts helps generalize topics to be applied diversely (Wage et al. 2005). Other subspecialties that have concept inventories are heat transfer (Jacobi et al. 2003), fluid mechanics (Martin, Mitchell, and Newell 2003), statics (Steif and Dantzler 2005), control systems (Bristow et al. 2012), along with many others that support the development of students learning core concepts. The exploration into concept inventories is not an original idea of the research team, and we are not the first to attempt to create one for SE (SEBoK contributors n.d.).

B. CORE CONCEPTS VERSUS COMPETENCIES

Both core concepts and competencies are useful elements for understanding professional preparation, but they are different. Core concepts provide the background, tools, and theory needed to contribute to the competencies. A system design competency is stakeholder expectation definition and management or technical requirements definitions (NASA 2019). The core concepts that underlie that example would be the development of requirements or identifying the stakeholders. While core concepts may sound very similar to competencies, concepts focus on the prerequisite knowledge needed to be proficient in any given area, and competencies concentrate on areas of a given career field requiring specialized skill and expertise that use the core concepts. A technical report prepared by researchers at MITRE (2007) describes competencies as behaviorally based capabilities that allow the system engineer to participate in design reviews and develop the design. By contrast, examples of core concepts in system design, as stated by Bahill and Botta (2008, 9), are "using models to design systems, hierarchical/top-down design, or development methodologies" (9). Whitcomb et al. created a model known as the Competency of the Profession of Systems Engineering (COMPOSE) to assist with career development modeling, creating position descriptions for the DOD, and specifying SE's academic objectives. His research focused on the knowledge, skills, and abilities (KSAs) needed to perform a particular job. His contributions to the development of competency models helped lays the framework for part of this research.

The Systems Engineering Body of Knowledge (SEBok) and INCOSE have broken down SE into different specializations; however, the defined domains do not point directly to the core concepts. For this research, system design is the specialization of interest. Figure 1 identifies the 10 specialization areas identified by the SEBok and INCOSE. An example of a core concept in systems design is developing requirements. Having the ability to solicit the stakeholders and turn those wants and needs into feasible solutions is essential to the design's success. For example, in the Navy, the warfighter desires a new capability onboard a submarine to help enhance operator awareness in recognizing obstacles to avoid collisions. That desire could lead to several solutions; however, the requirement needs to be clear. Some questions need to be posed to the stakeholders: What type of obstacles are they trying to avoid? What kind of awareness does the operator currently possess? How should the operator be alerted to avoid causing a distraction? Once the need is more clearly defined, the system engineer can write a formal requirement. Then, the systems engineer can proceed to the next phase of the design process.

C. RESEARCH OBJECTIVE

This research aims to identify the core concepts of system design and any misconceptions novices may harbor when learning SE design. In addition to identifying the core concepts, the research will also attempt to identify areas where students struggle and problem areas in the design process. Identifying the core concepts, misconceptions, struggles, and problem areas can help determine how classes should be taught and increase the transfer of knowledge expected from the educational experience.

D. RESEARCH QUESTIONS

1. Primary Research Question

What concepts are unique to SE design?

Identifying the core concepts of systems design may seem straightforward. However, they are not easily defined by browsing the internet or looking at guidance from professional organizations such as INCOSE, SEBoK, NASA, MITRE, and other well-known organizations. By identifying the SE design concepts the research team will be able to determine the concepts that are unique to SE design.

2. Secondary Research Question

What are the problems, challenges, and struggles that novices encounter while learning SE design fundamentals?

Understanding the problems, challenges, and struggles in SE design can help identify SE education areas that SE professors and SE organizations can examine for improvement. Changes to engineering education can include focusing on topic areas longer or using different examples to stress the concept. The problems, challenges, and struggles link to the misconceptions by establishing the foundation of the preconceived notions.

Without understanding the problems, challenges, and struggles, the misconceptions of SE will be more difficult to identify through the concept inventory.

E. PURPOSE / BENEFIT

The benefit of this research validates that SE concepts are well established and understood by professionals entering the field. The study helps to bring together the ideas taught at a collegiate level to evaluate SE design's key topics. Once this research establishes the concepts of SE design, future research can create a concept inventory to determine the concepts students struggle with and help instructors identify which topics need more focus. Furthermore, the Navy civilian training curriculum can include the concept inventory to test misconceptions in SE methodologies to verify that up to date standards are used and identify areas where more SE expertise is needed. Identifying the misconceptions and the Navy design areas that need further evaluation could lead to cost-saving and performance improvements to naval systems.

F. METHODOLOGY

The research team assessed scholarly publications, books, and online material to determine the underlying concepts. After the research team collected the concepts, the research team interviewed SE professors and professionals to assess the concepts' validity and determine the misconceptions, problems, and complications affecting SE students or young professionals' learning. Next, the research team transcribed the interviews for usage in qualitative analysis software and analyzed the data. Further details on the qualitative analysis, members of the interview, and software are in Chapter III.

G. REPORT ORGANIZATION

Chapter I comprises the background, research objectives, scope, and methodology. Chapter II focuses on breaking down the core concepts found in the literature, scholarly publications, and online resources before performing the subject matter expert interviews. Chapter III discusses how the interviews were selected by the research team and the data analysis tool used for the analysis data. Chapter IV provides the data analysis and interpretation of the interviews. Chapter V shares the conclusions and suggestions for future research efforts.

H. CHAPTER SUMMARY

This chapter defined the background, research questions, purpose, and benefits of the research. This chapter's focus was to explain the need for identifying the core concepts and the motivation behind the research. An overview of the methodology is introduced in this chapter but discussed further in Chapters III and IV. The next chapter is the literature review of concepts that the research team has identified as a preliminary collection of the core concepts in SE design.

II. LITERATURE REVIEW

This chapter identifies SE design concepts and provides a brief background into the ideas the research team believes are essential to SE. The research team selected the concepts by reviewing literature online and examining content from SE textbooks. The research team did this before interviewing participants to gain familiarity with the range of SE topics and help guide the interviews' establishment of questions. This section describes the SE process, the idea of complexity, emergence, simplicity, modeling and simulation (M&S), early design decisions, requirements, stakeholder needs, and modular design.

A. SYSTEMS ENGINEERING PROCESS

SE teams use process models to describe the work that the team must accomplish. Development processes are unique to SE and not taught thoroughly in other engineering disciplines. Knowing which process to use and the benefit and consequence are essential to the design process. As part of the effort to explain the concept of a SE process, we reviewed the literature to determine the type of development processes and components associated with each procedure.

Each process has differences in terms of speed, completion of phases, and cost. Each of the methods starts with a need and ultimately yields an implementation. The most common SE processes are waterfall, "Vee," and spiral methods. The Department of Navy (DON) has often used the waterfall method. The Waterfall model was introduced by Royce in 1970 and was initially used by designers for software development (Blanchard and Fabrycky 2011). The Waterfall method works by splitting the SE into five to seven phases. The phases typically include requirements determination, design, implementation, verification, and maintenance. Each phase depends on the previous phase's success and provides feedback for any corrections needed for either stage. Feedback is an essential component of the waterfall model.

Boehm (1988) created the spiral process model to introduce a risk-based system development approach rather than a document or code-driven approach. Like the waterfall approach, the spiral is split into phases that include planning, requirements identification, risk analysis, and validation. The spiral model was adapted from the waterfall model and used an iterative approach that allows the designer to evaluate the risk before moving on to the next phase (Blanchard and Fabrycky 2011). Using this approach, the design team tests the system and validates incrementally to verify that the design meets the design goals before getting too far off course from the requirements. The spiral model evolved from lessons learned with the waterfall model to address the problems associated with code fixes, delivery speed, and development cost (Boehm 1988). The spiral design methodology also allows flexibility for requirements to change and the continuous evaluation of each phase. However, the spiral process is more expensive and complicated than the waterfall method (Rouse 2020). Since the spiral process involves an iterative approach, the process adds more complexity and phases. The iterative approach allows for identifying risk that would alternatively not be realized by the systems engineer until later using the waterfall approach. Rouse (2020) notes high cost, dependency on risk analysis, complexity, and time management as limitations of the spiral model.

Dr. Kevin Forsberg and Harold Mooz created the "Vee" model in 1991. The "Vee" model addressed deficiencies that the Waterfall method did not address in terms of verification and validation. The "Vee" is an extension of the waterfall model and adds a testing phase for each corresponding development stage (Mohammed, Munassar, and Govardhan, n.d.). Although the "Vee" model is also based on the Waterfall model, the "Vee" model has a focus on the user, implying that the users are involved in all aspects of the development cycle (Font Jr. 2020). The "Vee" is read from left to right, starting with the user needs and ending with a user validated system on the right side (Blanchard and Fabrycky 2011). The model's left side also accounts for decomposition and definition activities, which resolve the system architecture and design elements. The right side focuses on integrating and verifying system development activities (Blanchard and Fabrycky 2011).

Other design methodologies from the software development community are based on agile design concepts (Highsmith 2001). These development methodologies are rooted in the process formed by spiral development and the "Vee" model. The agile design methodologies are known for meeting stakeholders' needs regarding speed, security, and support. The agile methods are not based on the waterfall model and allow the system designer to complete processes without dependence on the previous step.

B. COMPLEXITY

According to the SEBok, “complexity is a measure of how difficult it is to understand how a system will behave or to predict the consequences of changing it” (Adcock, Sillitto, and Sheard n.d., 1). This concept is vital to systems design because it can help measure how effectively the operators will use the system. Complexity can also help identify how hard it will be to maintain and update the system. Langford (2012) states that complexity results from the emergent properties of a system’s integrated components. The complexity concept is challenging to understand and affects system designs in different ways based on the users, configuration, and elements or parts (Adcock, Sillitto, and Sheard n.d.). An example of complexity would be choosing a new operating system to replace an aging operating system no longer supported by the original manufacture. Replacing the operating system may be the best idea to continue to support the fielded system. However, making the system changes would not fully reveal the stakeholders’ consequences unless the system design team conducted a study.

C. EMERGENCE

Emergence is the consequence of interactions between system elements due to the individual components’ contributions and the environment (Adcock et al. n.d.). Langford (2012) notes emergence as an effect of combining objects through the processes of energy, matter, material wealth, and information (EMMI) is emergence. Emergent properties have lasting effects on a given system that other objects or combinations of the system elements cause by adding complexity to the system. In SE, emergence is a property that the systems engineer seeks to build this property into their systems design to prevent problems and complications.

Individuals working in SE positions who have not had SE-specific training will likely not know SE concepts such as emergence. For example, emergence is not taught in electrical engineering; teaching it in SE is unique in educational programs. In designing a circuit, the electrical engineer does the math to determine the desired voltage and resistance needed for the design. The designer can model the circuit to verify the circuit's input and output characteristics, but after that, the electrical engineer job is complete. The electrical engineer has designed and characterized the circuit.

In contrast, a systems engineer would be looking at the bigger picture of how all the parts fit together. When the systems engineer integrates the circuit into a more extensive system, the next electrical engineer develops the system based upon a specification and still not looking for emergence. Although the electrical engineer would look for voltage drops, impedance, and signal attenuation, these attributes are focused on the electrical engineer's specialty and not the larger picture. Emergence is a unique concept to SE design because it relates to understanding risk and the consequence of systems interacting with different components, environments, and users for the overall system.

D. SIMPLICITY

Simplicity offers a measure of simplification not present in competing alternatives. Simplicity is not merely the absence of complexity, but instead encouraging it demands a deep understanding of the system's inherent nature (Watson 2013). This concept highlights the importance of focusing on the user needs and not overcomplicating the design. For example, if a user needs a way to track the inventory they have stored in a warehouse, current tools exist to meet the user's needs. They don't need to implement a new design. During the design process, the system engineer should evaluate the existing pool of available resources and tools to determine if a solution already exists. In the DOD, a Government Accountability Office (GAO) report (2011) found duplicative efforts due to lack of collaboration and commonality in warfighter systems. Enforcing simplicity in DOD systems can lead to standard design in similar systems across the agencies and reduce the cost of designs.

E. MODELING AND SIMULATION

The concept of modeling and simulation (M&S) has improved with the advancement of computers and other technological increases. System engineers have established several modeling techniques for designing systems that focus on the decomposition of systems, system connections, and interactions with other systems.

Although M&S are viewed by most as SE tools, they are also concepts. The concept component of M&S helps systems engineers describe the connections, layout, and configuration of designs without providing a physical prototype. Understanding the utility of M&S can help prevent costly design decisions and produce design efficiencies. Some of the most common modeling techniques are the Unified Modeling Language (UML), Department of Defense Architecture Framework (DoDAF), and Systems Modeling Language (SysML) (Buede and Miller 2016).

Another component of models that help describe system interactions is the usage of viewpoints. Viewpoints are models that describe systems and interconnections of systems to help define the data exchanges, functions, external interfaces (Dam 2015). Using viewpoints in the design process can help stakeholders understand the system's design and intent related to the other components that make up the system. The system engineer typically displays the viewpoints in terms of operational, functional, and physical views. Combining the three viewpoints helps define and understand the customers' needs and reduces the likelihood of systems that do not achieve the stakeholders' needs (Defense Acquisition University 2000). The Defense Acquisition University describes each of the views as follows:

- Operational View: The Operational View addresses how the system will serve its users. It is useful when establishing requirements of "how well" [emphasis in original] and "under what condition" [emphasis in original].
- Physical View: The Physical View focuses on HOW [emphasis in original] the system is constructed. It is key to establishing the physical interfaces among operators and equipment and technology requirements.
- Functional View: The Functional View focuses on WHAT [emphasis in original] the system must do to produce the required operational behavior. It includes required inputs, outputs, states, and transformation rules. The functional requirements, in combination with the physical requirements shown below, are the primary sources of the requirements that will eventually be reflected in the system specification. (Defense Acquisition University 2000, 38–39)

F. EARLY DESIGN DECISION INFLUENCE VS. LATE CHANGES

Whether changes are made to the design early in the design process versus later on in the design heavily impacts the changes cost. This concept is vital to the system engineer in the design process when determining a new user requirement or a design change. The systems engineer must identify how far the design has progressed and discuss the consequences with their management. Buede and Miller (2016) state that roughly 55% of the cost is committed by the end of the conceptual and preliminary design phase during the design process. Followed by 80% of the price committed by the time the design and integration efforts are completed (Buede and Miller 2016). Determining that the design is correct is feasible for the stakeholders and end-users as early as possible is essential to the development proceeds.

G. REQUIREMENTS/ STAKEHOLDER NEEDS

Requirements are an essential concept in system engineering design because they define the users' needs and determine what will be design and built. System engineers have to understand how to pick out the user needs and translate them into requirements. Hook (1993) identifies converting user "needs" into clear, concise, and verifiable system requirements as an important part of the SE process. Furthermore, he states that a good requirement has characteristics that are necessary, verifiable, and attainable. Since requirements are such an important aspect of the design process, the end product's quality is related to the requirements' characteristics. Wiegers (1999) describes quality requirements as correct, feasible, necessary, prioritized, and unambiguous. Wiegers summarizes each of the qualities as follows:

- Correct: Each requirement must accurately describe the functionality to be delivered.
- Feasible: It must be possible to implement each requirement within the known capabilities and limitations of the system and its environment.
- Necessary: Each requirement should document something the customers need or something required for conformance to an external requirement, an external interface, or a standard.

- Prioritized: Assign an implementation priority to each requirement, feature, or use case to indicate how essential it is to include it in a particular product release.

- Unambiguous: The reader of a requirement statement should be able to draw only one interpretation of it. Also, multiple readers of a requirement should arrive at the same understanding. (Wiegers 1999, 2–3)

Some of the common issues found with requirements as indicated by Hook are:

- making bad assumptions

- writing implementation (HOW) [emphasis in original] instead of requirements (WHAT) [emphasis in original]

- describing operations instead of writing requirements

- using incorrect terms

- using incorrect sentence structure or bad grammar

- missing requirements

- over-specifying. (Hook 1993, under "Common Problems")

Defense Acquisition University also agrees with the attributes of good requirements described by Wiegers and Hook. Defense Acquisition University describes the characteristics to include the following:

- Achievable: It must reflect the need or objective for which a solution is technically achievable at costs considered affordable.

- Verifiable: that is, not defined by words such as excessive, sufficient, resistant, etc. The system engineer expresses the expected performance and functional utility to allow verification to be objective, preferably quantitative.

- Unambiguous: It must have but one possible meaning. The systems engineer must express the requirement in terms of need, not the solution; that is, it should address the "why" and "what" of the need, not how to do it.

- Consistent with other requirements: Requirements must resolve conflicts upfront.

- Appropriate for the level of system hierarchy: It should not be too detailed that it constrains solutions for the current level of design. (Defense Acquisition University 2000, 36)

Faisandier, Roedler, and Adcock in the SEBok state, "stakeholder needs and requirements represent the views of those at the business or enterprise operations" (2020). Stakeholders usually fall into the categories of users, acquirers, and customers. To determine the desired characteristics for system stakeholders, go through a structured process to determine the requirements. Faisandier, Roedler, and Adcock further state that stakeholder requirements play a significant role in SE as they:

- form the basis of system requirements activities
- form the basis of system validation and stakeholder acceptance
- act as a reference for integration and verification activities
- serve as a means of communication between the technical staff, management, finance department, and the stakeholder community. (Faisandier, Roedler, and Adcock 2020)

H. MODULAR DESIGN

Modular design enforces the usage of standard interfaces and common parts. This concept is vital to the system design because the modular design allows the system to be maintained more efficiently and has economic benefits due to the allowance for reuse, customization, and incremental upgrades (Spacey 2016). Enabling separate components or modules to replace the entire unit can significantly impact cost-saving and prolong a system's lifespan. For example, an automobile is an example of a modular design. Standard cars include an engine, battery, radiator, alternator, axles, and breaks. Each of the components can be services individually and upgraded as needed. Just because the breaks go bad on the vehicle does not mean that the entire system needs to be replaced by the owner. This same idea applies to DOD systems, and designers should use this concept to verify the system components' maximum reuse and easy replacement of failed parts.

I. CHAPTER SUMMARY

The concepts in this section describe SE's core concepts based upon the researcher team observation of the text, scholarly publication, and online resources. Each idea discussed provides the definition and background of the concepts identified by the research team. Chapter III introduces the members of interviews, and Chapter IV provides the analysis from the subject matter experts to compare with the researcher team's findings in this chapter.

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III. PRESENTATION OF DATA

This chapter discusses the method used to conduct the research. How the research team selected the interviewee's is described and introduces the participants along with their backgrounds. The chapter also discusses the process the research team used to extract the concepts from the interviews.

A. SUBJECT MATTER EXPERT INTERVIEWS

To conduct this research, the research team sent interview requests out to professors and professionals at Naval Postgraduate School (NPS), Massachusetts Institute of Technology (MIT), and NAVSEA to start the search for the interview members. The process of choosing the committee had two phases. The first phase consisted of inviting NPS professors to participate in the research. The second phase consisted of asking the NPS interviewee's for references that could further contribute to the topic and invite them to participate. The interviewee's consisted of six members identifying the core concepts of SE design and the underlying misconceptions, problems, and struggles students and young professionals encounter. Each of the interview members was interviewed using a web-based teleconference service and transcribed the interviews for analysis. The research team completed the analysis using NVIVO, a qualitative data analysis software that helps collect themes and draw conclusions about the selected research topic. The researcher questions are in Appendix A.

1. Participant Descriptions

Below is a description of the participants to explain how their background fits the research questions under exploration. Each of the participants has been identified below with a summary of their experience.

Participant 1

Participant 1 has been teaching SE for over 21 years and at NPS for more than 15 years, with over 100 classes taught related to system design. His focus has been on systems acquisition and design, submarine systems design, and advanced systems design. He has a

Ph.D. in Mechanical Engineering from the University of Maryland, an Electrical Engineering and Computer Science degree from MIT, and a B.S. in Nuclear Engineering from the University of Washington. He is a member of INCOSE and part of the former regional Board of Directors. His prior efforts on competencies were essential to the background work related to developing the concepts and has been referenced in this research.

Participant 2

Participant 2 has been teaching for 13 years between Virginia Tech and NPS and has taught about 59 system design classes. Before teaching, he was the chief architect for the National Reconnaissance Office Ground Enterprise. Before that, he was the chief of the architectural analysis division at the National Reconnaissance Office. He has a Ph.D. and M.S. in Industrial & Systems Engineering from Virginia Tech. He received his undergraduate from the State University of New York Maritime College with a B.S. in Meteorology & Oceanography. Participant 2 is a retired Navy Surface Warfare Officer and worked in industry as a specialist in systems architecture, M&S, and systems-of-systems engineering.

Participant 3

Participant 3 has 25 years of teaching experience, with the last 18years focused on teaching SE. This experience spans academic and industry contexts, including academia and teaching classes related to system design to industry professionals at IBM. Her industry career started at IBM Federal Systems, which was IBM's defense business. Participant 3 received her Ph.D. in Systems Science from the T.J. Watson School of Engineering at Binghamton University. She is a principal research scientist at the Massachusetts Institute of Technology in the Sociotechnical Systems Research Center. She has been very involved in the evolution of the systems engineering field, is a Past President and Fellow of the International Council on Systems Engineering (INCOSE). Her contributions in the systems field have been recognized by numerous publication and journal awards, such as IBM Outstanding Innovation Award, Lockheed Martin NOVA Award, and INCOSE Founders Award.

Participant 4

Participant 4 has been teaching SE at NPS for 11 years. She has taught courses in systems architecture, system integration, and model-based SE and researches the use and development of formal methods for systems architecture modeling. Participant 4 has a Ph.D. in Software Engineering, an M.S. in Systems Engineering Management, a Certificate in Advanced Systems Engineering from NPS, and a B.S. in Electrical Engineering from Stevens Institute of Technology. She researches system and software behavioral modeling and architectural patterns. Her research also focuses on improving techniques for teaching graduate-level courses in a distance learning environment. Before coming to NPS, she worked at U.S. Army, Communications, Electronics, Research, Development, and Engineering Center (CERDEC) at Fort Monmouth, New Jersey, for 10 years, where they built and designed communication systems.

Participant 5

Participant 5 taught SE at George Mason for 10 years and the Stevens Institute of Technology for two years. Participant 5 has years of industry experience during which he practiced SE outside of teaching. He has a Ph.D. and M.S. in Engineering-Economics Systems from Stanford University and a B.S. in Aerospace Engineering. Participant 5 is also the author of several SE books used in the NPS curriculum. He is also a member of INCOSE and the president of his own company, which uses quantitative analysis to support decision-makers in assignments related to SE, management, resource allocation, and risk management.

Participant 6

Participant 6 has been in acquisition and design for 29 years. He is a 1983 graduate of the Naval Academy. Participant 6 received a B.S. in Electrical Engineering, an M.S. in Naval Engineering, and then a Ph.D. from MIT in Naval Power Systems. His professional experience includes a combination of military experience as an officer and a civilian for Naval Sea Command (NAVSEA). At NAVSEA, he spent time working with the landing helicopter dock (LHD) program, as the ship design manager and as a technical director for the technology group. His experience also includes details with the Marines at Quantico to be the design manager for the impervious combat vehicle and as the Small Surface Combatant Task Force's design manager. Though this participant does not have experience as an educator, his experience with young professionals in the workforce gives him valuable insight into what is required to enter the field.

2. Qualitative Data Analysis

The research team used a qualitative approach to analyze the interviewee's responses. Using the software NVIVO, the interview data was closely reevaluated and coded to search for themes in the interview related to system design. Coding is the process of categorizing the topics of interest into different groupings. The research team used the literature review concepts for the "coding" the initial focus concepts. The final list of interest topics was established by reading through the interviews and creating new "coding" for the concepts that were not previously identified by the research team in the literary review.

The research team used the software to gather the concepts into the nodes based on the direct correlation of a given concept stated in the interviews. However, some interview members would use other words or descriptions that fit into the theme of a larger concept and were "coded" as such. For example, one of the concepts of systems design is requirements, so if any of the interviews discussed requirements, the research team coded that section to match the theme. Additionally, other interviews discussed defining capabilities and objectives, which can be part of the requirements theme by analogy.

B. CHAPTER SUMMARY

This chapter discussed how the interview members were selected, their backgrounds, and the research methodology. The research team explained the analysis technique along with the software used to perform the analysis. The research result of all the interviews will be discussed in further detail in Chapter IV.

IV. DATA ANALYSIS/INTERPRETATION

This chapter discusses some trends and findings from the application of the NVIVO software on the transcribed interviews. This chapter will also discuss the key findings as they relate to SE design. One of the exciting finds of the interviews was the variety of input received from the conversations. Initially, the interviews appeared to have no consensus because each of the participants discussed the concepts differently. However, the research team found similar concepts among the interviews. Some of the consistent issues found in each of the concepts were related to preconceived solutions, understanding the bigger picture, and a system engineering career field missing in the DOD.

A. INTERVIEW RESULTS

In the interviews, the interview members identified concepts, problems, and SE design themes. Based on the interview members' experiences with students or young professionals in system design, the participants highlighted some of the material students have difficulty with and topics that are hard to teach without real-world experience.

B. ANALYSIS

The analysis section below will highlight some of the significant findings in terms of problems in systems design, items that students struggle with in systems design, concepts that can be considered problematic, and a collection of all of the concepts identified during the process.

1. Collection of Concepts in Systems Design

The research team coded each of the concepts into NVIVO to measure each topic's convergence. Figure 2 displays a heat map of the core concepts that were collected. The boxes' size portrays how often each of the concepts appears in the interviews. The 10 concepts from the research with the highest amount of references are displayed in Table 1. The research team was able to establish a comprehensive list of concepts and extract the concepts that are unique to SE. Table 2 displays the concepts that the research team found as unique to SE.

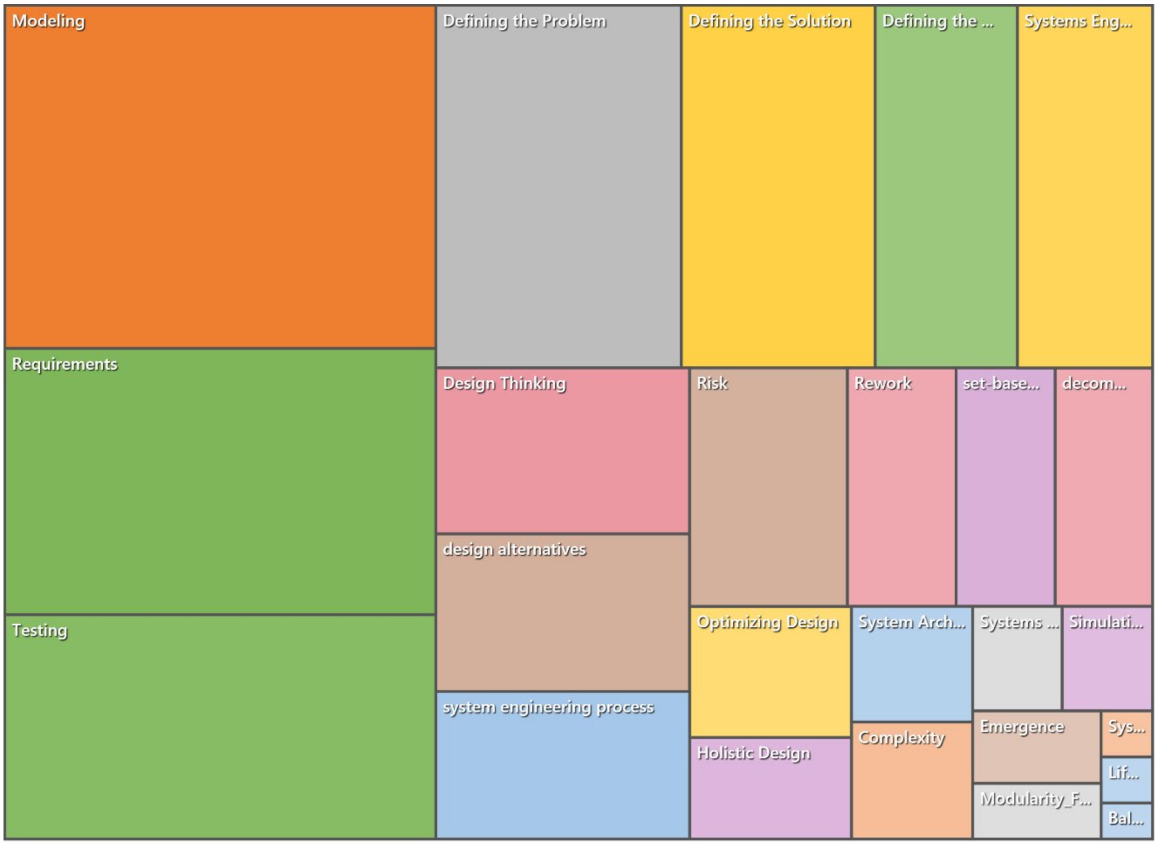

Figure 2. Heat Map of Systems Engineering Concepts

Table 1. Concepts Collected by Amount of References

Concepts of SE	# of References
Modeling and Simulation (M&S)	63
Requirements	49
Testing	41
Defining the Problem	38
SE Process	36
Defining the Solution	30
Stakeholders	23
Defining the System	22
Design Thinking	18
Design Alternatives	17

Table 2. Concepts Unique to SE

Concepts Unique to SE
SE Process
Defining the System
Design Thinking
Emergence
Modular Design
Complexity
Design Thinking
Set Based Design

M&S was the concept with the highest number of references from the interviews. An overview of the concept of M&S was explained in Chapter II by the research team. The M&S issues revolve around how and what the systems engineer needs to model, such as modeling the problem before modeling the solution, using the model to extract requirements and behavior modeling. The interview emphasized that students and professionals struggle with structuring models that can evolve with the changes in requirements and development evolutions. Using the M&S tools should help save valuable time in the development process by providing accurate models that can portray the program's capabilities, development time frames, and scheduling needs.

The interviewees identified several issues learners experienced with understanding or applying knowledge of *requirements*, such as separating them between functional and non-functional requirements, ensuring the requirement is testable, and eliciting them from the stakeholders. System engineers should write requirements at both the input and the output levels from a functional and non-functional perspective. Cristancho (2019) states that requirements should be specific, measurable, attainable, realistic, time-bound traceable. Similarly, Wiegers (1999) expresses ideas such as requirements being correct, feasible, necessary, prioritized, and unambiguous.

The U.S. Navy Zumwalt Class is an excellent example of how requirements can make a significant difference in a system's outcome. One interview member talked about his experience with the U.S. Navy Zumwalt Class Program. The interview member discussed how the system engineering was done on the Zumwalt Class Program according to the latest acquisition standards at the time. However, the requirements experienced requirements risk, meaning the requirements were incorrect. The needs changed, and the requirements were no longer relevant. This example could happen for any system under development. The requirements for any given system can change over the service life. It is up to the system engineers and program managers to handle the changes in mission profiles and modernization efforts to keep the system out in the field and relevant.

Another vital part of the requirements discussion is quantifying the value of a requirement or capability. As discussed in the interviews, if all requirements cannot be achieved, then the value to the stakeholders associated with the requirement needs to be placed on the capabilities. Assigning the value to the requirements helps the systems engineer to determine the priority when issues arise with timing or budget constraints.

Testing was a concept that caught the research team by surprise. The research team noticed testing as a necessary process for system development but not as a SE concept before the interview conversations. The parts of testing that students and professionals struggle with are: planning for testing as part of the design process, allocating time into all phases of the design, and having the necessary equipment to support the testing events. As part of the testing concept, the system engineer must plan for a test system as part of the design. The testing may be destructive or non-destructive, and additional assets have to be in place to support the test event and prevent program slowdowns. Budgeting for the testing is also an essential part of the concept. The testing phase is in the later stage of the development effort and is often cut in the budget due to earlier cost overruns by the program manager. The SE process should verify that time and money are allocated to testing by the systems engineer. Ensuring resources for testing is very important to the projects' success.

Defining the problem is simply the process of identifying what issue or gap in capability exists. The interviewee's identified one problem with defining the problem as separating the problem and solution. The interviewee's believes that students and professionals struggle not to jump straight to a solution and stay solution-natural during the problem definition phase. The interviewee's also stressed that system engineers spend insufficient time on developing the problem definition. Thinking of the system holistically and figuring out what stakeholder means with particular needs are also areas of concern for defining the problem.

The *SE process* was discussed in Chapter II by the research team to explain the typical SE processes used in the DOD. The interviewee's indicated that students and professionals struggle most with knowing which development process to use. For example, the SE Vee model is a bottom-up design methodology that flows from the concept of operations (CONOPS), requirements, implementation, testing, verification, operations, and maintenance phases. One interview participant mentioned that, in a well-known system, the SE team knows the CONOPS and many of the requirements. However, each time the Navy designs a ship, Navy system engineers start back at the SE Vee's beginning, when some information is already known. In this case, the SE Vee may not be the correct development methodology, and a more agile approach may be appropriate.

During the discussion of *defining the solution*, the interviewee's named similar reasons for defining the problem. The interview members offered advice to resolve those issues by picking the optimum solution using prototypes and continuous interaction with the stakeholders. In the interview members' experience, the technology readiness level (TRL) of solutions proposed by young professionals is often not mature enough to move forward. Suppose prototypes were able to be used to vet a technology that exhibited risk in terms of TRL. In that case, the systems engineer could evaluate the item for maturity through a prototype. Understanding that particular technology is not ready for integration into the more extensive system could save the program from other problems and costs by allowing another solution to be chosen by the design team over the immature technology. Additionally, continuously interacting with the stakeholder helps verify that the end-users will use the capabilities.

The concept of s*takeholders* is not unknown to students and professionals. Still, the interviewee's identified stakeholders as a concept that causes design problems due to not using the proper stakeholders to determine what is needed or desired. Additionally, the interviewee's noted that system engineers tend not to use diverse users to collect the requirements. The group should consist of a representative from the operators, maintainers, developers, and industry. System engineers struggle with determining the stakeholders but also think that the process ends in one cycle. The conversations with the stakeholders should be continuous and reevaluated as the system develops and adds additional capability. The procedure of seeking feedback is known as eliciting the stakeholder's needs. Another issue that stems from the lack of representation at the DOD level is the lack of engineering specialties. Engineers, scientists, physicists, mathematicians, and artists must cover the spectrum of design needs. However, only select disciplines are available in the DOD arena.

Defining the system requires understanding the need for the design, performance characteristics, and physical attributes. Defining the system has overlap with the processes of defining the problem and defining the solution. However, defining the problem and the solution helps build up the system's qualities and characteristics. Therefore, the process is threefold. Leydon (n.d.) describes defining the problem as translating the sponsor's needs into the product, service, or system requirements. "Defining the solution is the task of specifying the components that will meet those needs by becoming accepted deliverables" (Leydon n.d.). Defining the system is the process that transitions all the information from defining the problem and defining the solution into a total system. Stressing the difference in these three phases of system synthesis can help students better understand the design's purpose and enable better systems. As a result of the interviews, the interviewee's identified that students struggle with defining the system because theoretical solutions do not always translate into practical solutions. The problems that arise in the real world do not always allow the necessary time, and hypothetical examples typically do not discuss budget constraints associated with stopping a program and starting back at a particular point.

Design thinking focuses on the process of problem-solving and meeting the needs of the stakeholders. Dam and Siang (n.d.) define design thinking as an iterative process where the system engineer seeks to understand the users, challenge assumptions, and redefine the problem to identify alternative solutions that the stakeholders may not initially understand. Design thinking's overall intent is to improve the end-product by asking questions and challenging assumptions to understand better how the end-users will use the system (Dam and Siang n.d.). The interviewee's focused on design thinking details that help the system engineer look at the design holistically and how design thinking tools can help solve a design problem. The primary method of design thinking is empowering the designer to question requirements and prioritize them appropriately.

Finally, the interviewee's discussed *design alternatives* as concepts that students and professionals struggle with due to rushing into a solution based on a limited set of requirements. The discussion around design alternatives emphasized using concept generation tools such as the Pugh method and concept generation matrixes. The problem with jumping to a solution too fast is that it limits the system's capabilities and may prevent the system from meeting the stakeholder's needs.

The interview interviewee's also named other concepts that did not gain many references but are necessary to systems design. The interviews discussed training as a problem area for the DOD due to insufficient training resources for SE. Currently, the DOD offers employees the opportunity to receive training through DAWIA. However, the focus is more on program management and does not go in-depth about systems design. DOD employees are put into SE positions with only the DAWIA training and on-the-job training to prepare them for the role, adding to SE design issues.

C. CHAPTER SUMMARY

In summary, the interviewee's referenced numerous SE design concepts that are the core focus area of SE design and can be areas of weakness for SE learners. The interviews also helped identify the problems, challenges, struggles, and ways to measure SE's student learning. Now that the research team has identified SE design problem areas, SE professors can address the problems by refining how they teach them in classes. Or organizations can provide additional resources or on-the-job training to enable more efficiencies and lessen the burden of some issues.

V. CONCLUSIONS

This thesis addressed the identification of the core concepts of SE design. This chapter will present the findings and results of the search for core concepts by comparing the SE literature and contrasting the subject matter expert interviews' discoveries.

A. PRIMARY RESEARCH FINDINGS

The preliminary findings of this research were alarming after conducting the first three interviews. After completing the first three interviews, it was hard to find any correlation between what the interviewee discussed; however, after transcribing the interviews and carefully reading what the participants said, there was an overlap in the interviewees' responses. In some cases, the participant would identify requirements specifically as a concept, whereas in other interviews, the participant would refer to requirements as a capability. After further analysis, the research team discovered that both responses were essentially the same and named differently depending on the service branches. Looking for areas of overlap and similarity in terms helped to collect the concepts and find the correlation.

B. OTHER FINDINGS

The list of concepts provided in Table 1 is not an all-inclusive list of all the systems design concepts. The research team acknowledges that other concepts remain that the interviewee did not mention or did not agree sufficiently across the participants to rank among the core concepts. Other things to consider that were not mentioned during the interviews related to successful design are using open-standards, building in time for procuring long-lead items, relaxing high-risk items as early as possible, and testing as the development progresses.

C. RESEARCH QUESTIONS FINDINGS

Primary

- What concepts are unique to SE design?

The group of interviewee's established the core concepts of SE design as shown in Table 1. INCOSE, SEBoK, NASA, and MITRE also define and discuss most of the concepts provided in Table 1; however, the literature does not establish them as core concepts. For example, the interviewee's identified testing as a core concept. At the same time, the literature discusses testing as more of a process or life cycle phase that has to be completed by the design team during the design of a system. The concepts of testing, such as looking into planning, allocating testing time, and use the testing results to refine a design, should be taught and enforced in DOD systems.

Secondary

- What are the problems, challenges, and struggles that novices hold while learning SE design fundamentals?

Table 3. Problem, Challenges, Difficult Concepts, and Student Struggles in SE Design

Problems/Challenges	**Difficult Concepts**	**Student Struggles**
Rushing requirements	Defining the problem	Learning on the job without formal education
Finding a solution before looking at alternatives	Allocating time into all phases of the design	Separation of the problem from the solution
Starting to design a single solution when the problem hasn't been defined well enough.	Modeling use cases	Structuring system models
Allocating tasks appropriately to a human or to a machine.	Write requirements well	Understand the concept of operations and how it relates to the design
Applying constraints such as cost and technology readiness in a classroom environment	Separation of problem and solution	Relating basic research to real world problems
Lack of sufficient training resources in DOD environments	Decomposition	Understanding the needs of the stakeholder
DOD training offered via DAWIA mostly teaches Program Management	Understanding the needs of the stakeholder	

Problems/Challenges	Difficult Concepts	Student Struggles
Inexperienced personnel or individuals with little to no design experience in leadership roles.	Design trade-off	
Adjusting from bottom-up design mentality to top-down design mentality.	Quantifying the value of requirements or capabilities	
Quantifying the value of requirements or capabilities		

The research has identified numerous problems, challenges, and struggles in Chapter IV. The research team establisted Table 3 to reference the problems/challenges, difficult concepts, and student struggles in SE. The issues in systems design reflect overlap in students' challenges and struggles in SE education. The most frequently mentioned SE design problems were the idea of a preconceived notion for the solution and starting a design with an incomplete set of requirements. The DOD escalates the issues by misidentifying SE professionals without formal education. The expectation for a related science, technology, engineering, and mathematics (STEM) discipline to accomplish a completely different field of study is not a recommended practice. Formal SE education is essential in systems design, and DOD SE positions should be filled by practitioners who have appropriate formal training or formally measured skills. The core concepts identified in this research need reinforcement to verify the student understands the material in the education space. Additionally, the research team found that theory does not always translate to what is practical.

D. FUTURE RESEARCH

To further this current research, as part of the literature review, the research team identified that there are multiple branches of SE that INCOSE and the SEBoK have defined. Figure 1 displays the various focus area of SE. This research only focused on SE design. However, it would be fascinating to see the other concepts in any of the remaining SE branches and how they overlap with the concepts identified in this research.

The research team has completed the necessary footwork to establish an IRB protocol and highlight SE design's core concepts. One of the early goals of the research team was to create a concept inventory for SE design. However, there was not enough time to identify the core concepts and then poll students with questions about the core concepts. An example of the concept questions has been created and provided in Appendix B. Moving forward with this research can help students learn the core concepts or SE design more efficiently and help teachers identify the areas they should focus on during the course.

E. RECOMMENDATIONS

This thesis is recommended for usage in educational environments to improve SE design education. Organizations could also use the research team's concepts to monitor the professional development goals of individuals who move into SE roles without prior SE training. Applying this research to DAWIA educational objectives can help facilitate the proper usage of SE methods, tools, and techniques.

APPENDIX A. INTERVIEW QUESTIONS

Part 1: Questions related to students learning System Design

- What are the concepts that makeup system design?
- Which concept is most difficult for students/professionals to comprehend?
- How does the material taught in a System Design class prepare students for real-world experience?
- If you were to write an exam question related to System Design that no one would get correct, what would it be, and why would no one get it right?
- How do you know students have gained insightful knowledge that helps them develop better systems?

Part 2: Questions related to Systems Design

- What are the essential tools used by system engineers in the design process?
- What all goes into the design of a system? What resources are needed?
- How much does the design of a system influence the cost, performance, and schedule?
- What sources of information do you use in preparation for designing a system?

Part 3: Demographics/Background

- How many classes have you taught related to SE design or architecture? (Plus the number of times, i.e., two times a year for two years, four years, etc.)
- Describe your professional experience with System design or system architecture

Part 4: Final Thoughts:

- Is there anything else you would like to add or that you think we should know?
- Is there anyone else you recommend I interview?

APPENDIX B. CONCEPT INVENTORY STUDENT QUESTIONNAIRE

The below questions are a collection of questions generated from the literature review and student material from previous classes related to system design. The purpose of these questions is to gauge the students understanding of the core concepts and allow the professor to realign what is taught:

1. Which of the following is a good definition of Systems Engineering?
   A. An interdisciplinary approach and means to enable the realization of successful systems.
   B. A discipline that concentrates on the design and application of the whole (system) as distinct from the parts.
   C. A methodical, multi-disciplinary approach for the design, realization, technical management, operations, and retirement of a system.
   D. An iterative process of top-down synthesis, development, and operation of a real-world system that satisfies, in a near-optimal manner, the full range of requirements for the system.
   E. All of the above

2. What are among the benefits of good system design?
   A. Increased rework in design, production, and planning.
   B. Increased product variability and decrease in quality.
   C. Improved quality; improved operation and support; increased customer satisfaction.
   D. Increased system downtime leading to frustrated users and maintainers.

3. What are the results of poor system design?
   A. Poor system performance, unreliable and incorrect operation, high maintenance resource expenditure.
   B. Systems engineering accolades.
   C. High user and maintainer satisfaction.
   D. High interface reliability with a commensurate reduction in high failure items.

6. The two major aspects or efforts of integration are:
   A. Combining elements into a whole and concurrent development of support, production, user processes.
   B. Planning test resource utilization and executing test events.
   C. Operating within budgetary constraints and tracking personnel actions.
   D. Identifying underlying problems for which solutions are proposed and copying existing business or operational processes.

7. Resolving an obsolescence issue on a legacy weapon system on a class of commissioned warships is . . . .

A. A clean slate – Predecessor is replaced or non-existent
B. Incorporation of new elements into existing ones
C. True System-of-Systems

8. When is the System Engineering design executed?

A. As early in the System Life cycle as possible.
B. During verification and validation.
C. Left hand side of the SE Vee model.
D. Right hand side of the SE Vee model.
E. All of the above are correct.

9. Emergence means . . . .

A. Complex behaviors arise from relatively simple interactions
B. There is some self-organization and spontaneity
C. May or may not be predictable
D. All of the above

10. Requirements integration means

A. Because requirements come from different sources and cover the spectrum from "-ilities" to very precisely defined physical measures, they must be organized and controlled as a baseline.
B. The users must work independently of the engineering team to noodle through their extravagant list of wants before approaching a developer.
C. Management must lock down a set of requirements and not allow any change during development.
D. Information flow between users, clients, developers happens on a completely ad hoc basis.

11. Stakeholder needs are typically expressed in…

A. The language of the customer
B. The dialect of the developer
C. The concerns of the end-user
D. The interest of the designer

12. The process of identifying is an integral part of the larger design process.

A. key components
B. customer needs
C. primary capabilities
D. risk areas

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