Systems Engineering Transformation: Transdisciplinary Endeavor

LynnDee Ford[1] **and A. Ertas**[2]

[1]Raytheon Technologies, McKinney, Texas
[2]Texas Tech University, Department of Mechanical Engineering, Lubbock, Texas 79409
Email: atila.ertas@ttu.edu

Received 29 November, 2023; Revised 28 December, 2023; Accepted 1 January, 2024
Available online 1 January, 2024 at www.atlas-tjes.org, doi: 10.22545/2024/00240

Abstract:*System Engineering (SE) solves the most complex problems bringing together societal issues, theoretical engineering, and transformation of theory into products and services to better mankind and reduce suffering. The research of this paper utilizes transdisciplinary engineering to develop a SE methodology for the concept stage permitting proposal generation accuracy and expediency to provide solutions to counter regional aggressive threats.*

Today's world stage is witnessing superpower dominance over neighboring less military-capable nations. The societal impact goes beyond the borders of conflict and affects the world's global market. In the deterrence of dominance, the United States' posture is providing weapon systems to the victim in our increasingly unstable geopolitical environment. The US has many reasons to make this technology available to other nations; just as it has many reasons to constrain proliferation.

The United States Government is energizing the U.S. defense industry to provide the needed weapon systems following US prescribed acquisition methods. The sale of US weapon systems to International Customers is through a US defense contractor implementing a specialized acquisition model specific for international customers acquiring exportable defense articles. These constraints in the form of export regulations, critical to this paper, are essential to account for early in the concept development. The added complexity to concept development in international defense is that in addition to the usual, "what capabilities does the customer need to accomplish their mission?" and "what are the alternative solutions?" questions, we need to address the fact that US contracts may be required to limit capabilities and/or the technical solution space in opposition to the international customer's desires. Whereas we normally turn to systems engineering processes to address such complex problems, we have found that the current SE methodology for the concept stage does not address the complexities associated with international sales.

The international customers' need for complex solutions in an expedited time frame emphasizes the prime contractor's complex and inadequate proposal concept stage. Under U.S. government procurement, the prime contractor shifts a portion of the design phase into the concept phase. This modality requires significant time and funding to fully develop the technical baseline, meanwhile, the international customer requires a solution to react to an immediate threat to their country's safety.

The main objective of this research is to develop a system engineering methodology for the concept stage to effectively understand the technical baseline maturity for proposals specific to International Customers.

Keywords:Systems Engineering Methodologies, weapon systems, complex system solutions, concept stage of traditional systems engineering methodologies, transdisciplinarity, convergence, transdisciplinary integration.

1 Introduction

Today's world stage is witnessing superpower dominance over neighboring less military-capable nations. The societal impact goes beyond the borders of conflict and affects the world's global market. In the deterrence of dominance, the United States' posture is providing weapon systems to the victim while maintaining anonymity.

The United States Government is energizing the U.S. defense industry to provide the needed weapon systems following US-prescribed acquisition methods. The sale of US weapon systems to International Customers is through a US defense contractor implementing a specialized acquisition model specific for international customers acquiring exportable defense articles. The systems engineering methodology for the concept stage does not address the complexities associated with international sales.

A major gap exists in the current SE methodologies for the concept stage. During the concept stage, prime contractors generate proposals to bid international contracts for complex systems. The proposals require an assessment of technical baseline maturity solutions in reference to the customer requirements. The current SE methodologies [1,2,3]) do not provide detail for proposal generation.

Defense article proposal generation is a complex problem and married to societal problems. Regional conflicts drive international customers to request U.S.-based exportable defense articles under distressed situations for their region [4]. The U.S. government procurement and prime contractor proposal process is insufficient to meet the real-time needs of international customers [5].

The international customer need for complex system solutions in an expedited time frame emphasizes the prime contractor's inadequate proposal concept stage [6]. Under U.S. government procurement, the prime contractor shifts a portion of the design phase into the concept phase. This modality requires significant time and funding to fully develop the technical baseline. In comparison, the international customer requires a solution to react to an immediate threat versus the U.S. government's approach of highly funded proactive procurement addressing future threats [7].

The 5th generation U.S. F-35 fighter jets required a product cycle of 20 years and $200 billion dollars [8], but the U.S. had immediate solutions for current and near-future threats with deployed 3rd and 4th generation fighters. In comparison, international customers' weapon systems are easily 25 years behind U.S. capabilities [9].

The main objective of this research is to develop a system engineering methodology for the concept stage to effectively understand the technical baseline maturity for proposals specific to International Customers.

2 Materials and Methods

2.1 Traditional Systems Engineering Methodologies

System Engineering solves the most complex problems bringing together societal issues, theoretical engineering, and transformation of theory into products and services to better mankind and reduce suffering.

Technology and processes are driven by societies' problems at large. As populations grew, the problems facing countries grew in complexity and the required solutions followed and required advancements in technology and processes. The previous solutions and processes could no longer address the issues efficiently or produce the solutions in a timely and cost-effective manner. The problems were describable, but many

Figure 1: System engineering life cycle stages.

times the entire problem set from the user's perspective through the release of a solution was never fully integrated and the stove pipe engineering disciplines processes and methods had significant gaps. The period of 1940's and WWII became one of the largest drivers demanding a new engineering discipline to solve this dilemma, [10].

System engineering is a discipline that examines a system as a whole, encompassing all its components and their individual contributions [11]. Systems engineering is a comprehensive, integrative discipline that integrates the contributions of various engineering disciplines to create a coherent whole [11]. System engineering involves a comprehensive approach to technical decisions, aiming to meet stakeholder needs within cost, schedule, and constraints throughout the system's intended use environment [11].

Since the 1940's multiple system engineering methodologies have been developed based on unique problems, advancement of system engineering discipline, system engineering education, and available technology. As shown in Figure 1, the system engineering life cycle stages namely, concept, development, production, utilization, support, and retirement are the basis for all methodologies [12].

Today, a core set of methodologies are still in practice and labeled as Traditional System Engineering Methodologies. More recently, lean methodologies and agile methodologies have been introduced based on software processes and methods to reduce cost and schedule. However, the current methods fail to fully address the concept phase in today's business environment and updates are needed to meet the needs of today's industrial complexes.

Traditional system engineering methodologies were largely sequential in nature. Each step of the process was carried out separately and completely (see Figure 1). The next step cannot be started until the previous step is completed. The direction of flow is in one direction, and each step is clearly defined without overlap. Traditional methodologies are often used when requirements are clearly defined early in the process, and planned deliverables are required at defined milestones. The process is plan-driven, and unplanned changes are not easily implemented. The summary of the process of the traditional methodologies is described in Table 1 [13,14].

Table 1: Process of traditional methodologies

• Traditional methodologies are plan-driven
• Used on high criticality projects
• For a culture that demands order
• Traditional methodologies follow a step-by-step process
• Used when the requirements are well defined early
• Works well for projects with many junior developers
• Progress is demonstrated by planned deliveries at defined milestones

Table 2 illustrates the absence or lack of focus on the concept stage of traditional systems engineering methodologies. Specifically, the system methodologies predominantly begin with the require-

Table 2: Concept stage of traditional SE methodologies

Methodology	**Concept Stage**
Waterfall	Requirements, eliciting, analysis
Vee	Concept of Operation
Spiral	Concept of Operation
Incremental	Requirements
Lean	Value - Customer definition of value
Set-Based Concurrent Engineering	Requirements
Kanban	Product Scheduling
Kaizen	Incremental Improvement
Agile	Research and Concept
Scrum	Management Methodology
Extreme Programming	Requirements
Feature Driven Development	Development
Dynamic System Development	Focus is business value

ments/development cycle. INCOSE defines systems engineering as focusing on defining customer needs and required functionality early in the development cycle, documenting requirements, and then proceeding with design synthesis [12].

The Generic life cycle as defined by ISO15288, illustrates the Concept Stage proceeding to the Development Stage as shown in Figure 1. This research will expand the methodology of the Concept stage to introduce a modified SE methodology. As prime contractors are for-profit companies, it is mandatory to understand and accurately price the technical baseline in the concept stage to avoid unfunded cost overruns during the program execution. The current methodologies do not consider the ability to meet a competitive price to win the contract and successfully complete the contract with profit for the prime contractor.

2.2 Complex Societal Problems and Transdisciplinarity

Several difficult, complex challenges have started to emerge as 21^{st} century priorities. Some of the most concerning challenges facing our globe today are challenging social issues like the environment, climate change, immigration, hunger, water crises, world population, disease, pollution, global warming, and energy. No single discipline can resolve these cross-disciplinary problems on its own: Transdisciplinary (TD) initiatives, which offer new competencies and resources targeted at creativity, invention, and collaboration across knowledge domains, can offer answers to these problems [15].

People deal with societal issues on a daily basis. Their dynamic qualities and social significance make them extremely complicated [16]. Social, cultural, political, economic, environmental, and emotional difficulties are all intertwined with technology, making societal challenges highly transdisciplinary [17]. Important societal issues like drug abuse, food insecurity, health care, climate change, and global poverty present difficult challenges and bring uncertain constraints with a high level of complexity. Cronin stated [18]:

> “There is a need for transdisciplinary research (TDR) when knowledge about a societally

> relevant problem field is uncertain when the concrete nature of problems is disputed, and when there is a great deal at stake for those concerned by problems and involved in dealing with them. TDR deals with problem fields in such a way that it can: a) grasp the complexity of problems, b) take into account the diversity of life world and scientific perceptions of problems, c) link abstract and case-specific knowledge, and d) constitute knowledge and practices that promote what is conceived to be the common good."

Rapid technological change and convergence in the globally competitive economy has and will cause upheaval in the labor market. A paradigm shift in engineering education is required to respond to these market uncertainties to mitigate unemployment and prepare engineers to tackle problems requiring a disciplinary convergence (i.e., transdisciplinary integration). The need for skilled workers in STEM industries is rapidly increasing across the United States.

Outsourcing is occurring in STEM-dominated fields due to globalization and information technology [19]. Because of this outsourcing, American students will need to acquire value-added skills, such as creativity, problem-solving and innovation, and engineering system integration [20]– specifically problem definition and innovation, engineering system integration, and creativity. They also need to be able to deal with the opportunities and challenges presented by technology in today's world, as well as the diversity of opinions. The Grand Challenges identified by the National Academy of Engineering [21] and other as-yet-unidentified challenges require U.S. students to be taught new skills for dynamically synthesizing new knowledge. According to [22]:

> "If the world of working and living relies on collaboration, creativity, definition and framing of problems and if it requires dealing with uncertainty, change, and intelligence that is distributed across cultures, disciplines, and tools–then graduate programs should foster transdisciplinary competencies that prepare students for having meaningful and productive lives in such a world."

2.2.1 Convergence – Transdisciplinary Integration

Disciplinary convergence, the ***transdisciplinary integration*** of science and technology knowledge, ideas, and practices from multiple disciplines as well as the participants in the TDR process from the scientific community, issue experts, and other sectors of civil society (community associations and private sectors), to tackle real-world complex problems from many angles, will make important contributions in scientific advances and their impact on society.

> "***Convergence:*** facilitating ***transdisciplinary integration*** of life sciences, physical sciences, engineering, and beyond is an approach to problem-solving that cuts across disciplinary boundaries. It integrates knowledge, tools, and ways of thinking from life and health sciences, physical, mathematical, and computational sciences, engineering disciplines, and beyond to form a comprehensive synthetic framework for tackling scientific and societal challenges that exist at the interfaces of multiple fields. By merging these diverse areas of expertise in a network of partnerships, convergence stimulates innovation from basic science discovery to translational application. It provides fertile ground for new collaborations that engage stakeholders and partners not only from academia, but also from national laboratories, industry, clinical settings, and funding bodies."
>
> **National Research Council of the National Academies**

A common scientific goal is achieved by integrating disciplines to address issues that are ill-defined and span a wide range of traditional disciplines. This process is known as transdisciplinary research and is defined as the ***integrated*** use of tools, techniques, and methods from various disciplines [23]. The TDR process represents the highest degree of cross-disciplinary collaboration and is superbly suitable to address the issue of convergence and its effect on the American workforce.

TDR has come to the forefront as an accepted mainstream research methodology by the OECD Global Science Forum (GSF) [24,25]. Addressing global unstructured real-world problems and associated risks and societal challenges, as embedded in the sustainable development goals (SDGs), is the main goal of transdisciplinary science and technology [24].

2.3 Transdisciplinary Systems Engineering

The transdisciplinary (TD) integrative and iterative research process facilitates the convergence of scientific disciplines and engineering knowledge in the development of innovative strategies and methods for designing and managing transdisciplinary complex systems.

Madni's profound belief was that disciplinary convergence is an enabler of *transdisciplinary systems engineering* [26]. He defined "transdisciplinary systems engineering as an integrative meta-discipline that reaches beyond systems engineering to make connections with other disciplines to develop solutions to problems that appear intractable when viewed solely through the lens of traditional systems engineering" [26].

Mokiy and Lukyanova stated that the "transdisciplinary system can act as the universal model of the system. Within this system, disciplinary knowledge about the world, the object of research, and similar and dissimilar research areas are arranged without strict boundaries between different disciplines but by objective truth, which follows the way things should be so that it is possible to ensure the unity of objects along with the unity of their diverse relations. In this capacity, the systems transdisciplinary approach acts more like a general systems theory or an academic discipline (metascience), providing opportunities to bring together all of humankind's knowledge into one integrated and consistent science, with a common set of concepts expressed in a metalanguage." [27].

However, no established and well-accepted methodology for integration fits all cases of TD issues because transdisciplinary vary in purpose, scale, and scope as well as the nature of the problems at hand. Moreover, a mix of participants' expertise, degree of management of coordination, timing, and responsibility for integration compound the outcome difficulty [28]. TD knowledge integration is an open-ended learning process without pre-determined outcomes [29]. It is a multidimensional interactive and iterative process [29,17].

Therefore, there is a need for a transdisciplinary framework as the basis for advancing transdisciplinary systems engineering [26].

3 Proposed Systems Engineering Concept Stage Methods and Theory

This research contributes by filling gaps in the current System Engineering concept stage [12], guiding prime contractors in proposal generation. As mentioned earlier, the focus of this research is to expand the Concept Stage of an existing system engineering methodology to assess the technical maturity during the bid/no bid phase in support of executive leadership decision-making during contract negotiations to better position the company for success and profit.

The key attributes drive systems engineering design, development, and implementation of complex systems. Therefore, defining the SE main attributes specific to the concept stage will be the main objective of this section. Figure 2 shows the proposed TD research process to define the attributes specific to the SE methodology in the concept stage. As shown in the figure, this process is hypothesized in six steps:

1. Identifying the complex issue and TD team building
2. Process: procedure to be followed
3. TD team communication and TD integration
4. Developing TD collective intelligence (interactive process)

5. Defining the attributes affecting the complex system design
6. Establishing attributes contextual relationships

Step 01 Identifying the Complex Issue and TD Team Building

Through subject matter experts, the diverse knowledge domain depicted in Figure 2 creates *collective impact* (CI) in the solution of difficult problems. It is a creative TD strategy that bridges the social and professional spheres to address unstructured issues. In this research, the engineers chosen for the NGT were practicing engineers with relevant experience in large proposal generation for the concept stage within the past year. They are considered subject matter experts in their discipline. CI included a focus group of 26 system engineers and subject Matter Expert (SME)s, who were available to participate. The group consisted of 12 systems engineers, 4 mechanical engineers, 2 software engineers, 3 electrical engineers, and 5 aircraft engineers. Moreover, 6 of the systems engineers described above had previous mechanical engineering experience and the other remaining 6 systems engineers had previous electrical engineering experience. Each SME had a range of 10-26 years of professional experience with at least 3 years of proposal experience and the majority having 10 years of proposal experience.

Customer requirements (needs) are an essential part of problem understanding and team building. An international Customer has significant tangible and intangible needs when procuring an airborne exportable military defense article. Typically, the international customer requires significant assistance from a prime contractor in developing an executable mission solution. The prime contractor must execute multiple meetings to educate the customer on exportable solutions. The normal circumstance is the international customer demands the highest technology, an unrealistic short delivery schedule, an unrealistic budget, and in-country acceptance requiring test ranges only available in the United States. The prime contractor must balance a technical wish list, budget, schedule, and US export laws in developing the mission solution meeting the customer's concept of operations.

Step 02 Process

The existing generic process that defines the procedures to be followed to generate a proposal will be tailored down to processes applicable to the statement of work signed by the customer. The chief engineer and program manager guide the team to modify the generic existing process.

Step 03 TD Team Communication and TD Integration

In Figure 2, the concept of TD team communication and TD integration is viewed as the heart of the TD research process. It is a key research practice in knowledge co-production. Integrating science and technology knowledge, ideas, and practices from multiple disciplines as well as the participants in the TDR process from the scientific community, issue experts, and other sectors of civil society (community associations and private sectors) to tackle real-world complex problems from many angles, to make both societal and scientific advances is not an easy task.

The following five proposed classes integrate these different types of expertise into more successful ways of addressing the problematic issues:

1. *Integration through the logic of included middle (Hidden Third)* – The Hidden Third (the logic of included middle) mediates the continuous flow of information with the simultaneous flow of consciousness such that conflicting minds can connect and share information and perspectives so as to solve societies' complex, emergent problems [30].

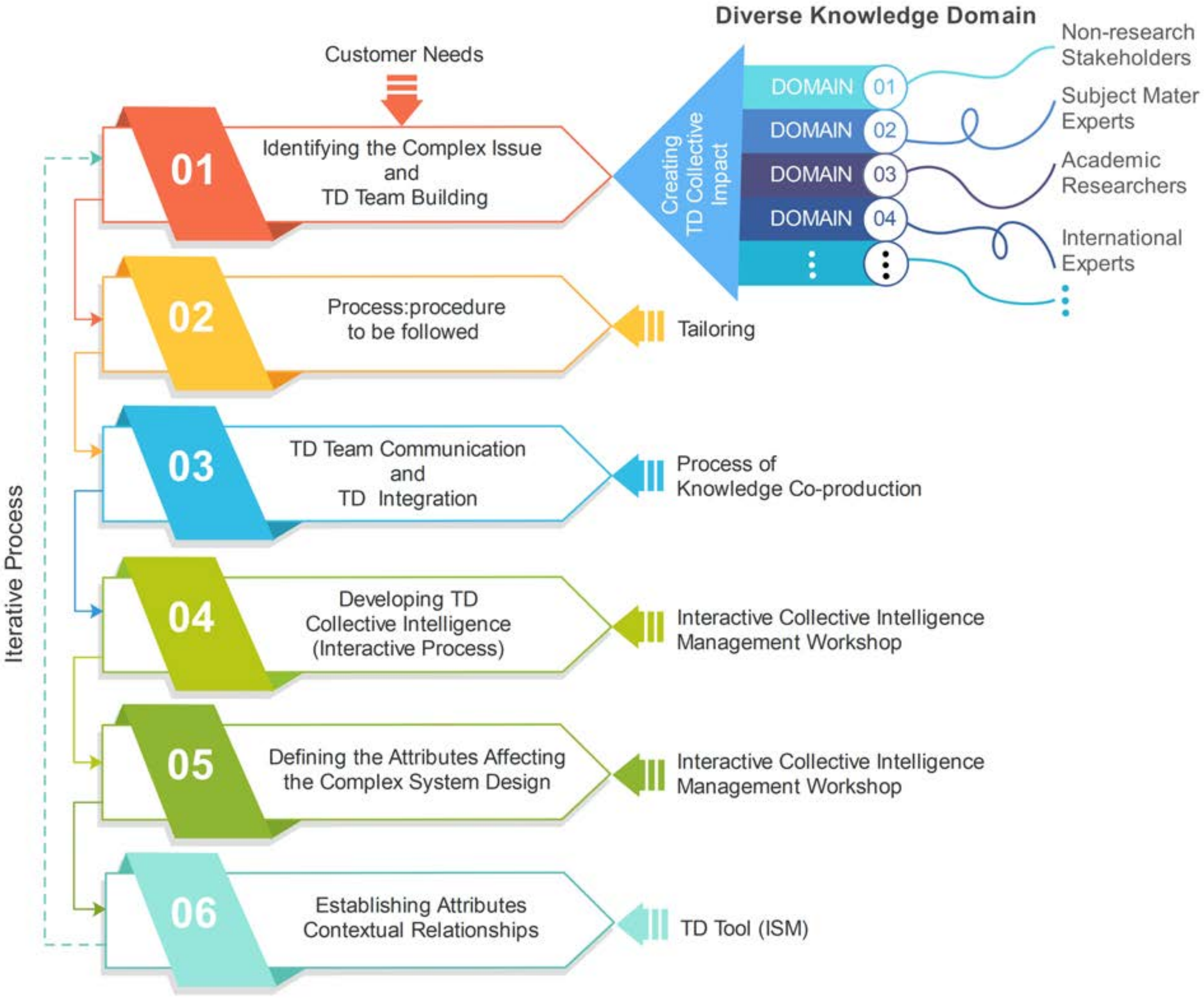


Figure 2: A TD framework defining attributes affecting SE concept development (adapted from Ertas, 2022).

2. *Integration through Boundary objects* – The concept of "boundary objects" indicates those interfaces where participants from diverse fields meet and communicate to develop common shared main points such as concepts, methods, models, and research questions [31].
3. *TD Knowledge integration through the formulation of research hypothesis* – Before starting TD research, the formulation of a research hypothesis or research question (RQ) is an essential factor for knowledge integration between scientific and societal actors. In many cases, the overall research task can only be achieved if novel scientific, problem-oriented techniques are developed to generate new transdisciplinary knowledge [25].
4. *TD Knowledge integration through conceptual clarification and theoretical framing* – A conceptual framework is an important element of TD-RI to understand the principles and concepts of the research study. The main reasons for developing an agreed conceptual framework are that it provides fundamental principles of TD research integration and a basis for resolving research disputes [25].
5. *Through coming to a consensus on a conflicted issue* – Consensus on a final understanding for

problem-solving is another kind of integration. Consensus decision-making during the TD research integration is an important element that builds trust and creates ownership and commitment to the research issue in discussion.

Any of the method(s) mentioned above can be used that we found most useful for transdisciplinary integration applied to a specific problem. In this research, *coming to a consensus on a conflicted issue* was used to make a meaningful decision.

3.1 Step 04 Developing TD Collective Intelligence

In 1980, the University of Virginia developed the idea of interactive management (IM). Since then, the practice of IM has spread to many places and a wide range of applications have been developed. IM is a system of management specifically designed to be used in complexity management. IM was created specifically to use complexity management to address problems whose scope extends beyond the typical problem type that organizations can easily resolve [32].

In order to serve as the foundational element of the Transdisciplinary Design Process, IM has been renamed Interactive Collective Intelligence Management (ICIM) [17]. ICIM is divided into three phases as follows [32]:

Planning Phase: Making all the necessary arrangements to carry out the ICIM workshop is the goal of the planning phase. This stage will involve clearly identifying the complex issues that need to be studied and carefully selecting and inviting knowledgeable experts in the field to participate. Specific, measurable, and realistic major outcome statements will be planned and defined.

ICIM Workshop Phase: The planning phase's plan is put into action during the ICIM Workshop phase. In the workshop phase, a select group of people with knowledge of the topic under study from expert domains are brought together to facilitate extensive communication among group members in order to identify the critical factors influencing an issue's complexity. As was previously mentioned, 26 SMEs were invited to participate in ICIM. Twelve systems engineers, four mechanical engineers, two software engineers, three electrical engineers, and five aircraft engineers made up the group. The professional experience of each SME ranged from 10 to 26 years, with the majority having 10 years of experience and at least 3 years of experience writing proposals.

The lead author of this paper, who also serves as the facilitator, introduced the workshop and provided some background information on the Nominal Group Technique (NGT) using flip charts. NGT is a productive technique that can be used to generate new ideas in groups, clarify those generated, edit and organize the ideas, and create a preliminary ranking of the set of ideas [33].

The NGT construction for this research followed the basic steps for NGT as described by the following: clarification of a trigger question, silent generation of ideas in writing by each group member, round-robin recording of the ideas, ongoing discussion of each idea for clarification and editing, and voting to obtain a preliminary ranking of the ideas in terms of significance [17].

In this research, the trigger question was what key attributes are required and needed for a systems engineering methodology for the concept stage for a prime contractor's proposal generation. After the trigger question was presented and discussed, the group had silent time to generate their own ideas. Each idea was recorded in a round-robin manner meaning each member provided one attribute, then the next member provided one attribute, and the process continued until all attributes were recorded. The group continued discussions through the process gaining clarifications from SMEs and making necessary edits. Ten key attributes were initially nominated, however, after discussions the key attributes were down-selected to six. Then, the working group continued to deliberate on establishing contextual relationships among the attributes to develop a structural self-interaction matrix that required fundamental knowledge to decompose the complex issue of the System Engineering Concept Stage into understandable and meaningful pieces.

NGT facilitation: NGT implementation was performed in a conference room and led by the lead author of this paper. The meeting was held and executed in a business venue and the lead author of this paper was responsible for the coordination and facilitation of the meeting, in addition to capturing and recording the group discussion points and results.

Follow-up Phase: The follow-up phase includes the iteration of the problem solution and its implementation.

Step 05 Defining the key Attributes

Through the ICIM, the six selected and non-ranked key attributes were identified and described as documented in the section below.

Customer: An international Customer has significant tangible and intangible needs when procuring an airborne exportable military defense article. Typically, the international customer requires significant assistance from a prime contractor in developing an executable mission solution. The prime contractor must execute multiple meetings to educate the customer on exportable solutions. The normal circumstance is the international customer demands the highest technology, an unrealistic short delivery schedule, an unrealistic budget, and in-country acceptance requiring test ranges only available in the United States. The prime contractor must balance a technical wish list, budget, schedule, and US export laws in developing the mission solution meeting the customer's concept of operations.

Competition: The international military procurement environment continues to experience increased competition, requesting USG's most advanced solutions, and challenging fiscal environments. The international customer desires more innovative mission solutions, with no up-front engineering development costs and shortened development/fielding schedules.

The prime contractor in this environment requires transdisciplinary collaboration to identify key attributes driving competitive solutions that successfully address the customer's needs. The key attributes must address the following to account for competition:

- understand customer needs and USG export laws,
- connect customer key care-abouts with discriminating solutions,
- shape customer perceptions and requirements toward prime contractor's strengths and discriminators,
- balances the customer's requirements and needs with the available fiscal budget and schedule.

It is critical for the prime contractor to have as much knowledge as possible about the background, experience, products, and proven deployed solutions accomplished by the competitors. The prime contractor must review and analyze the competitor's performance record, areas of expertise, customer presence, and capabilities, and derive the competitor's strengths and weaknesses.

The prime contractor competitive assessment provides information about the competitors' relative positions, advantages/disadvantages with each customer, and their most likely offered solution for proposal submission.

Architecture: Architecture refers to the planning, foresight, creativity, and overall product strategy plan that the company/group offers today as well as plans to produce in the future for all customers, and potential customers while keeping in mind the return on investments.

For the international customer, the prime contractor typically will reuse an existing developed and proven architecture tailored to meet exportability, mission and technical requirements, and fiscal constraints.

In an international market, complex systems require architecture in the concept stage prior to detailed design and implementation. The SMEs during the NGT process examined and discussed architecture reuse and tailoring required for developing complex systems. The discussion topics focused on how architecture benefits the customer and the prime contractor's team. The topic items included the necessity for customer collaboration (validating needs and requirements), establishing a tailored architecture team of cross-functional representation (i.e., systems, electrical, mechanical, software, aircraft), and system of systems development items (versus reuse items). This group's primary task is to define, document the architecture, and transition the completed architecture to the other team members to develop a proposal.

The proposal must include a defined and negotiated architecture with the customer and prime contractor program teams to provide a priced solution.

Design: For an international airborne solution, procurement is rarely a start-from-scratch activity. The prime contractor takes existing internal and external subsystem solutions to implement the developed architecture. The system engineers address the design from two viewpoints. Viewpoint one, the system design and integration team utilizes existing subsystems to populate the architecture. Viewpoint two, the system design and integration team are cognizant that a new design is required for development and another team is deployed to work on such design activities. Development may include modifying an existing product, development may include a new design, and with both viewpoints, the development will include tailored software mandatory to integrate the subsystems into the final system of systems solution. The prime contractor makes the decision to invest upfront on any new design items/subsystems or defer the design to after a potential contract award. The prime contractor's bid/no bid decision is influenced by whether the investment of the new product design or sub-system design is in the concept stage (pre-award) or after the contract award.

Process: Process refers to the structured methods and procedures a prime contractor implements to align teams to execute work in a deterministic and repeatable manner, define work products, and mission assurance standards. The prime contractor's process is critical to delivering quality products according to cost and schedule.

The prime contract must review and align processes from many stakeholders including the customer, the USG, the internal prime contractor, and subcontractors. A prime contractor's key concern is the introduction of new processes from the customer or USG requiring changes to the prime contractor's processes during the concept stage and flow down to any of the subcontractors.

As prime contractors gather lessons learned, the process is updated to ensure the same mistakes are not repeated. This action creates continual improvement in current and future programs. The process is the cornerstone of quality aligning the teams' products and services to meet the customer needs.

Reporting: Reporting is the seamless communication amongst all stakeholders and the most basic human factor. The introduction of international customers and language barriers create the opportunity for the misinterpretation of essential and critical information. Additionally, the dissemination of information to the prime contractor's internal team exhibits similar deficiencies even when no language barriers exist. The prime contractor's process implements templates, standards, and training to establish communication principles. These standards allow the sharing of information across the prime contractor's teams, USG, and customers.

During the concept stage, accurate reporting is critical in the development of the solution. Any miscommunication or dropped information most likely results in an item not being accurately bid. The prime contractor makes the decision to implement design reviews and granularity of these reviews during the concept stage to minimize missing information. The cost and design review scores are considered in the bid/no bid decision.

3.2 Step 06 Establishing Attributes Contextual Relationships

After the key attributes were identified and defined using ICIM, an exercise of determining the interrelations between each followed. The interrelationships were captured by creating the Structural Self-Interaction Matrix (SSIM), which is the first step of the Interpretative Structural Modeling (ISM) technique.

In the following section, the Interpretive Structural Modeling technique is described using a sequence of activities.

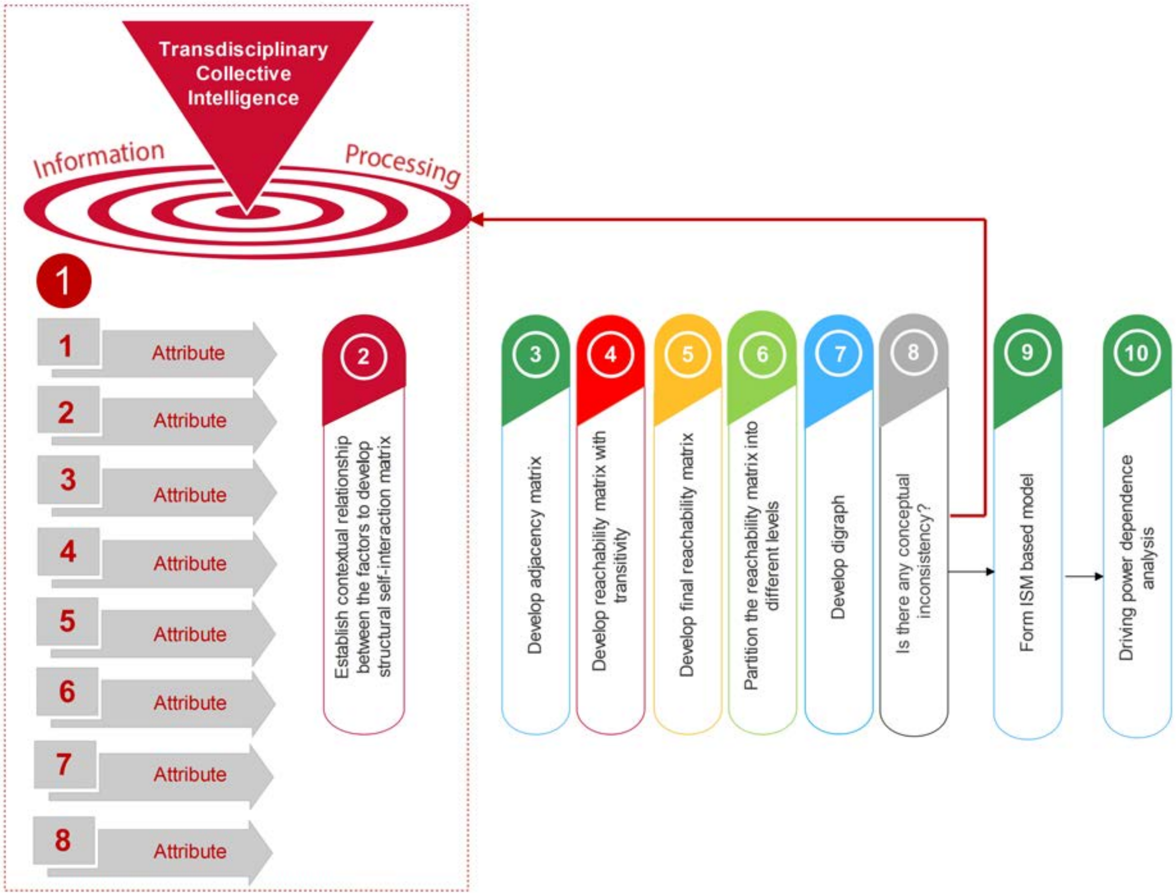


Figure 3: Sequence of activities to develop interpretive structural modeling technique.

3.3 Interpretive Structural Modeling (ISM) Technique

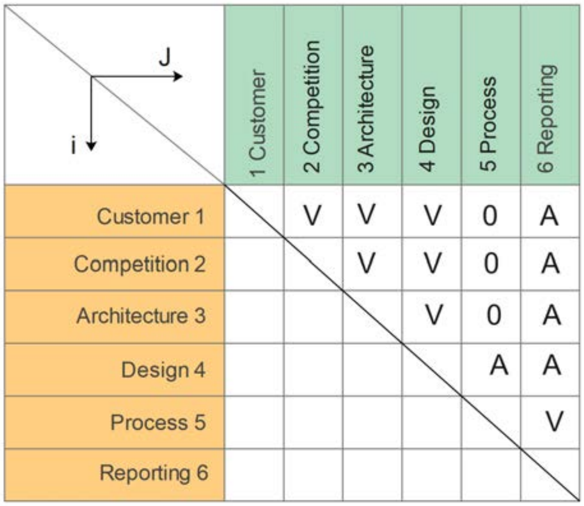
The Interpretive Structural Modeling (ISM) technique was proposed by Warfield in 1973 [34]. The ISM technique begins as illustrated in Figure 3 with the development of the Transdisciplinary Collective Intelligence step utilizing the NGT method. An Interactive Collective Intelligence Management workshop is held to identify and define the key attributes of the problem. During the workshop, a contextual relationships matrix of said attributes was developed. The results will be passed to the Decomposing Complexity developing a digraph for ISM Analysis. ISM Analysis will identify the driving power and dependencies [17]. Figure 3 illustrates the sequence of activities of the ISM technique.

3.3.1 Structural Self-Interaction Matrix (SSIM)

Following the identification and definition of the key characteristics, the SSIM (Structural Self-Interaction Matrix) was created during ICIM Workshop as shown in Figure 4.

During this stage, ICIM Workshop participants decided about the pairwise relation between attributes. The contextual relationship for each attribute, the relationship between any two attributes (i and j), and the associated direction of the relation was decided through the workshop participants' debate. The four symbols used to indicate the direction of the relationship between the factors i and j are given below:

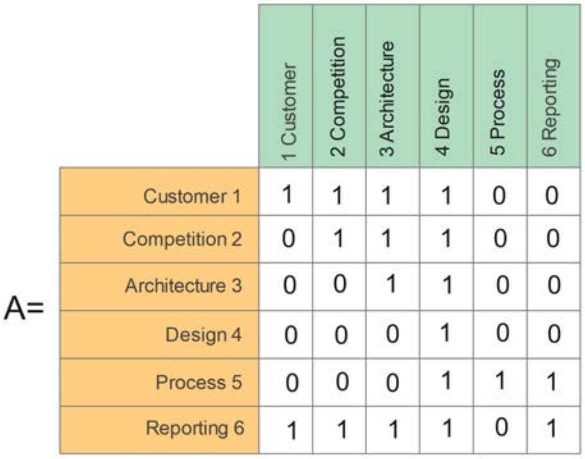
- V = for the relation from i to j but not in both directions;



	1 Customer	2 Competition	3 Architecture	4 Design	5 Process	6 Reporting
Customer 1		V	V	V	0	A
Competition 2			V	V	0	A
Architecture 3				V	0	A
Design 4					A	A
Process 5						V
Reporting 6						

Figure 4: Structural Self-Interaction Matrix.

- A = for the relation from j to i but not in both directions;
- X = for both-direction relations: from i to j and j to i; and
- O = if the relation between the elements does not appear to be valid



A=

	1 Customer	2 Competition	3 Architecture	4 Design	5 Process	6 Reporting
Customer 1	1	1	1	1	0	0
Competition 2	0	1	1	1	0	0
Architecture 3	0	0	1	1	0	0
Design 4	0	0	0	1	0	0
Process 5	0	0	0	1	1	1
Reporting 6	1	1	1	1	0	1

Figure 5: Adjacency Matrix.

3.3.2 Develop Adjacency Matrix

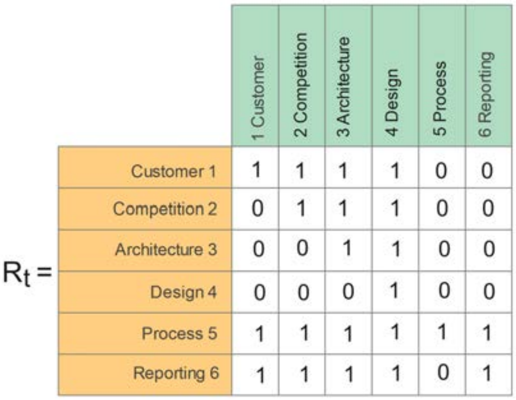
As shown in Figure 5, replace the entries V, A, X, and O of the SSIM with 1 and 0, following the below rules:

- When the (i, j) entry in the SSIM is V, then the (i, j) entry in the reachability matrix becomes 1 and the (j, i) entry becomes 0.

- When the (i, j) entry in the SSIM is A, then the (i, j) entry in the reachability matrix becomes 0 and the (j, i) entry becomes 1.
- When the (i, j) entry in the SSIM is X, then both the (i, j) and (j, i) entries of the reachability matrix become 1.
- When the (i, j) entry of the SSIM is O, then both the (i, j) and (j, i) entries of the reachability matrix become 0.

3.3.3 Develop Reachability Matrix with Transitivity

The reachability matrix with transitivity is displayed in Figure 6. The transitivity rule is checked for in the reachability matrix, and it is updated until transitivity is verified. The transitive rule is "if **A** has a relationship to **B** and **B** has a relationship to **C**, then **A** has a relationship to **C**". Following the transitivity rule a reachability matrix shown in Figure 6 is developed.



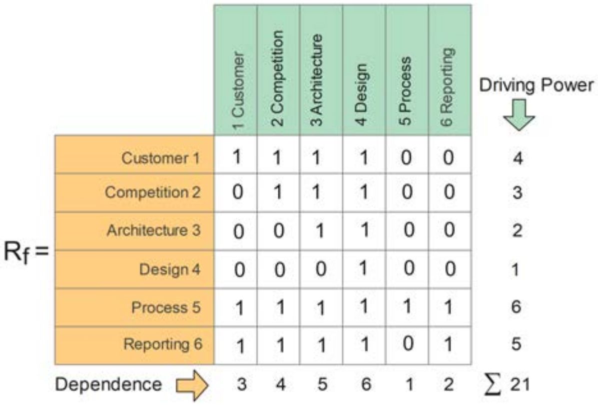
$R_t =$

	1 Customer	2 Competition	3 Architecture	4 Design	5 Process	6 Reporting
Customer 1	1	1	1	1	0	0
Competition 2	0	1	1	1	0	0
Architecture 3	0	0	1	1	0	0
Design 4	0	0	0	1	0	0
Process 5	1	1	1	1	1	1
Reporting 6	1	1	1	1	0	1

Figure 6: Reachability matrix with transitivity.

3.3.4 Develop Final Reachability Matrix

Figure 7's final reachability matrix displays the attributes' *Dependency* and *Driving power*.

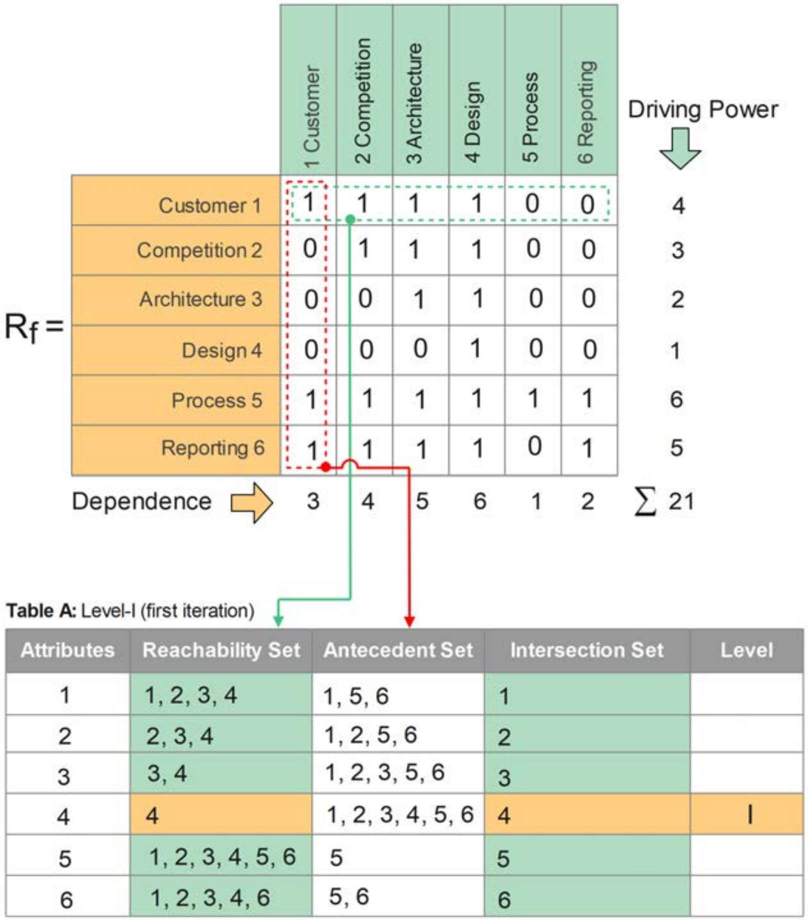


$R_f =$

	1 Customer	2 Competition	3 Architecture	4 Design	5 Process	6 Reporting	Driving Power
Customer 1	1	1	1	1	0	0	4
Competition 2	0	1	1	1	0	0	3
Architecture 3	0	0	1	1	0	0	2
Design 4	0	0	0	1	0	0	1
Process 5	1	1	1	1	1	1	6
Reporting 6	1	1	1	1	0	1	5
Dependence	3	4	5	6	1	2	$\sum$ 21

Figure 7: Final reachability matrix.

The driving force and dependence are respectively calculated as the sum of the ones in the corresponding rows and columns. The final representation of all the attributes' relationships with the problem under consideration is found in Figure 7. MICMAC analysis will make use of the driving power and dependence calculations shown in Figure 7.



R_f	1 Customer	2 Competition	3 Architecture	4 Design	5 Process	6 Reporting	Driving Power
Customer 1	1	1	1	1	0	0	4
Competition 2	0	1	1	1	0	0	3
Architecture 3	0	0	1	1	0	0	2
Design 4	0	0	0	1	0	0	1
Process 5	1	1	1	1	1	1	6
Reporting 6	1	1	1	1	0	1	5
Dependence	3	4	5	6	1	2	∑ 21

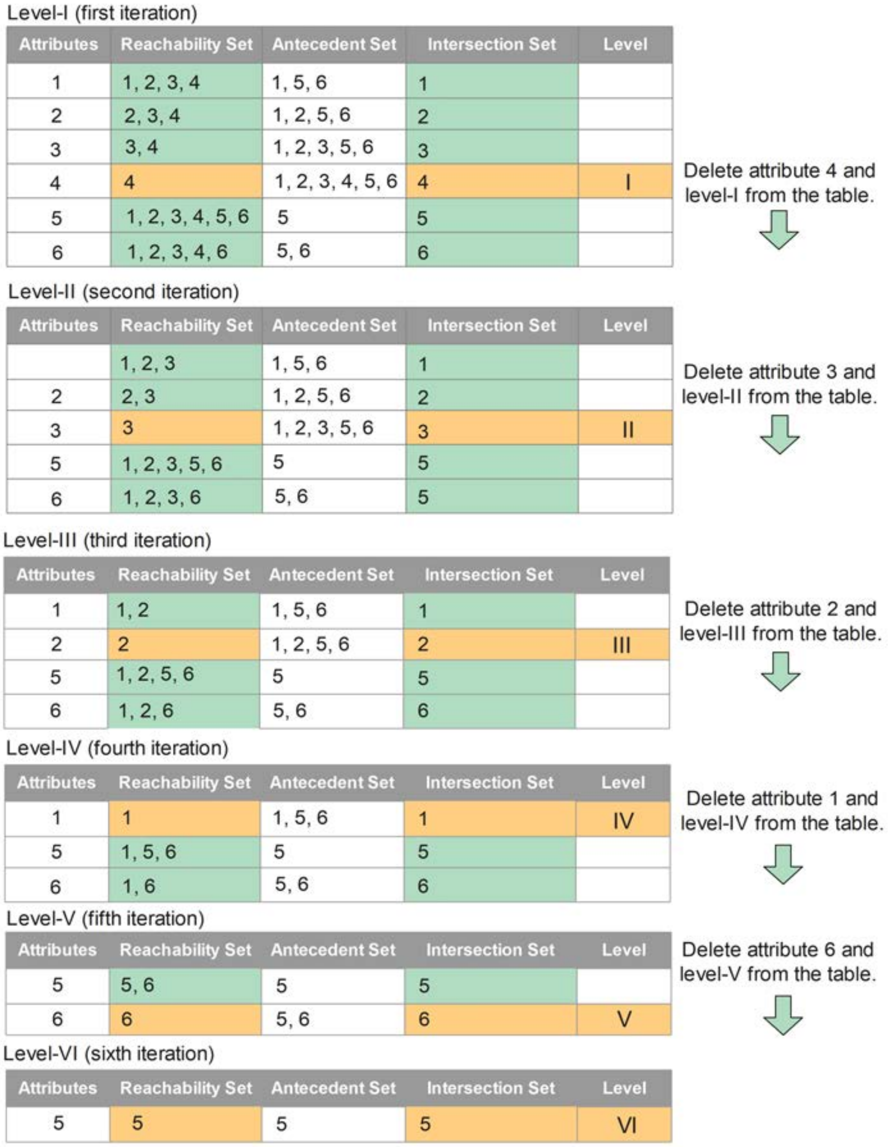
Table A: Level-I (first iteration)

Attributes	Reachability Set	Antecedent Set	Intersection Set	Level
1	1, 2, 3, 4	1, 5, 6	1	
2	2, 3, 4	1, 2, 5, 6	2	
3	3, 4	1, 2, 3, 5, 6	3	
4	4	1, 2, 3, 4, 5, 6	4	I
5	1, 2, 3, 4, 5, 6	5	5	
6	1, 2, 3, 4, 6	5, 6	6	

Figure 8: Final reachability matrix.

3.3.5 Level Partition

The final reachability matrix's driving force and dependence will be useful to us as we group the factors. An intersection set will result from the intersection of the reachability and antecedent sets, as illustrated in Figure 8. Stated differently, the intersection set consists of the elements shared by the antecedent set and the reachability set. We can determine the attribute levels with the aid of these three sets. The attribute will be recognized as the top-level group (level I group) in the ISM hierarchy when the attributes of the intersection and reachability sets match. To determine the next level, the top-level factors are removed from the set after they have been identified. This iterative process is carried out repeatedly until all of the levels are identified, as shown in Figure 9. The ISM model and digraph will be constructed using these levels.



Level-I (first iteration)

Attributes	Reachability Set	Antecedent Set	Intersection Set	Level
1	1, 2, 3, 4	1, 5, 6	1	
2	2, 3, 4	1, 2, 5, 6	2	
3	3, 4	1, 2, 3, 5, 6	3	
4	4	1, 2, 3, 4, 5, 6	4	I
5	1, 2, 3, 4, 5, 6	5	5	
6	1, 2, 3, 4, 6	5, 6	6	

Delete attribute 4 and level-I from the table.

Level-II (second iteration)

Attributes	Reachability Set	Antecedent Set	Intersection Set	Level
	1, 2, 3	1, 5, 6	1	
2	2, 3	1, 2, 5, 6	2	
3	3	1, 2, 3, 5, 6	3	II
5	1, 2, 3, 5, 6	5	5	
6	1, 2, 3, 6	5, 6	5	

Delete attribute 3 and level-II from the table.

Level-III (third iteration)

Attributes	Reachability Set	Antecedent Set	Intersection Set	Level
1	1, 2	1, 5, 6	1	
2	2	1, 2, 5, 6	2	III
5	1, 2, 5, 6	5	5	
6	1, 2, 6	5, 6	6	

Delete attribute 2 and level-III from the table.

Level-IV (fourth iteration)

Attributes	Reachability Set	Antecedent Set	Intersection Set	Level
1	1	1, 5, 6	1	IV
5	1, 5, 6	5	5	
6	1, 6	5, 6	6	

Delete attribute 1 and level-IV from the table.

Level-V (fifth iteration)

Attributes	Reachability Set	Antecedent Set	Intersection Set	Level
5	5, 6	5	5	
6	6	5, 6	6	V

Delete attribute 6 and level-V from the table.

Level-VI (sixth iteration)

Attributes	Reachability Set	Antecedent Set	Intersection Set	Level
5	5	5	5	VI

Figure 9: Identifying levels.

3.3.6 Formation of Digraph

The digraph is a visual representation that illustrates the interrelationships between the direct and indirect relationships between various attributes. The theory of digraphs can be used to translate the relationship between attributes and binary associations through matrices into graphical form, as illustrated in Figure 10(a).

3.3.7 MICMAC Analysis

Duperrin and Godet developed the MICMAC analysis in 1973 to analyze the driving power and dependence of attributes affecting an issue [36]. The attributes are categorized into four clusters based on their driving power and dependence, as depicted in Figure 10(b) [37]. The attributes are categorized into autonomous,

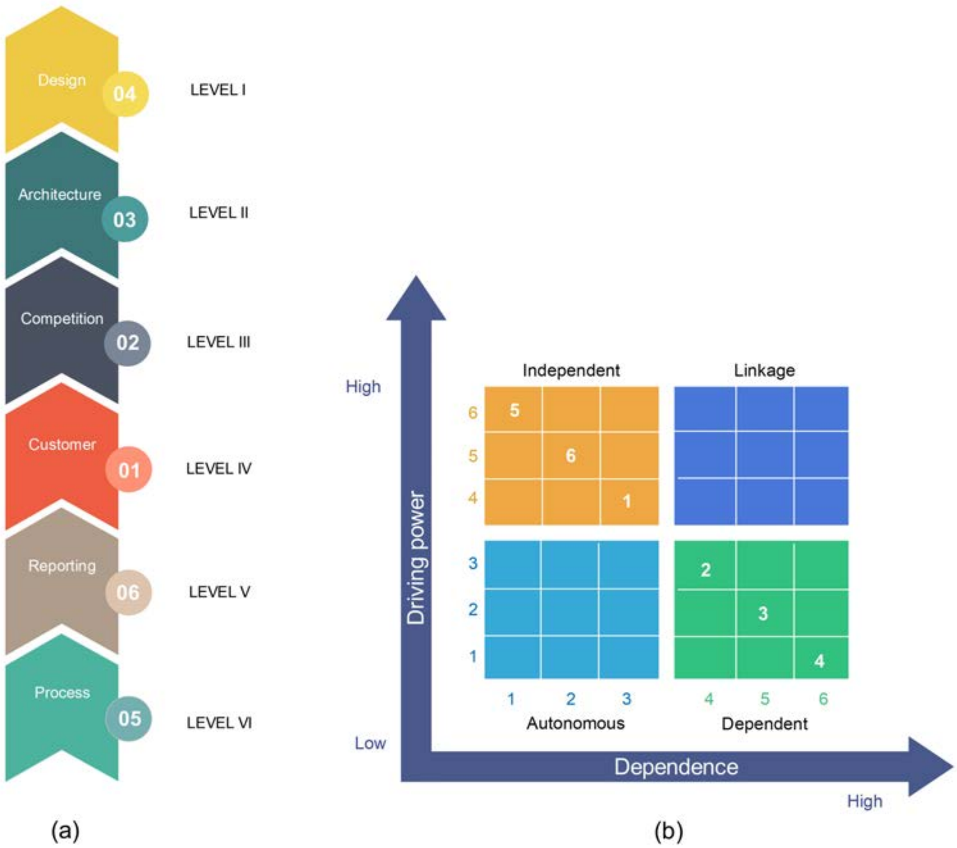


Figure 10: (a) Digraph, (b) MICMAC analysis.

dependent, linkage, and independent, with their driving power and dependence sourced from Figure 8.

Cluster I includes no attributes that are autonomous. Autonomous attributes have low driving power and low dependence. Cluster II includes three attributes (2, 3, and 4) that are dependent. Dependent attributes have low driving power and high dependence. Cluster III includes zero attributes that are linkage. Linkage attributes have high driving power and high dependence; therefore, these attributes would be of extreme importance. The fact that there are no Linkage attributes indicates that there is shared importance among the attributes that were identified. Cluster IV includes three attributes (5, 6, and 1) that are independent. Independent attributes have high driving power and low dependence. These attributes have a direct impact on the success of system performance.

3.4 Developing Three Incremental Step Modifications for SE Methodology Utilizing ISM

3.4.1 First Incremental Step Modification for SE Theoretical Methodology

The International Council on Systems Engineering (INCOSE) foundation/framework is internationally recognized and is introduced to provide a baseline for the new modified methodology. The INCOSE foundation/framework theoretically describes the entire product lifecycle of Systems Engineering as illustrated in Figure 11. However, it does not clearly define the Concept Stage where proposal generation occurs.

The INCOSE SE Handbook also describes generic life cycles for Systems Engineering. The Generic life

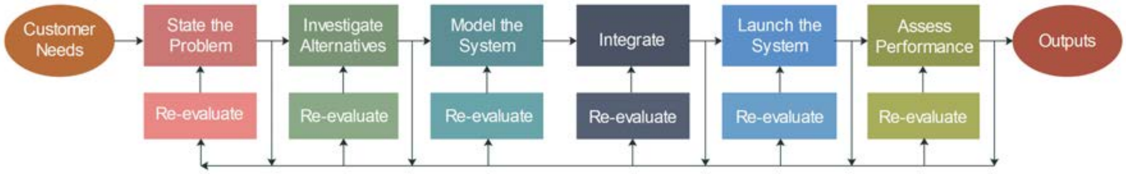


Figure 11: INCOSE foundation/framework (Bahill & Gissing, 1998).

cycle theoretically describes the entire product lifecycle of Systems Engineering as illustrated in Figure 11 but, again, it does not provide granularity to the Concept Stage.

The Concept Stage begins with the customer needs statement and concludes with an engineering solution for the proposal called outputs. The output in the Concept Stage is the prime contractor's proposal of a solution to the USG. As shown in Figure 12, inserting the INCOSE foundation/framework into the Concept Stage generic life cycle provides the theoretical granularity needed to execute the proposal generation.

Figure 12 shows the first incremental step proposed modified theoretical methodology. The next section addresses why this initial modified methodology was not sufficient to address the prime contractor's needed concept stage and requires additional modification.

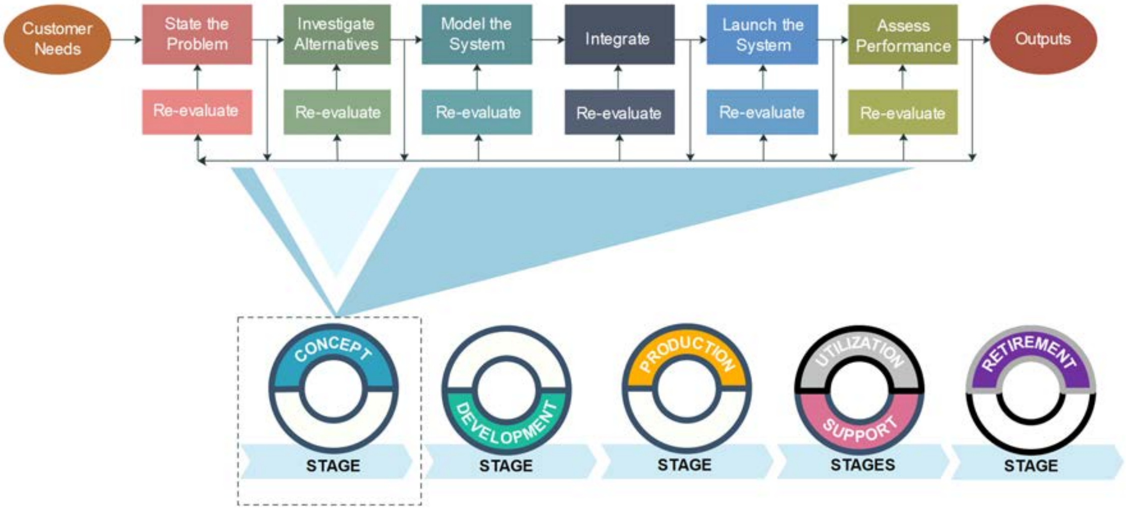


Figure 12: First incremental step modification for SE theoretical methodology.

3.4.2 Second Incremental Step Modification for SE Theoretical Methodology

As demonstrated in Figure 12, the first modified methodology provides the theoretical framework for analyzing the concept stage. This modified methodology must be aligned to the key attributes identified during the ICIM to create the second incremental modified SE methodology.

This section addresses the real-world attributes for the concept stage mandatory for proposal generation. The real-world attributes mandatory for the proposal generation were developed by the subject matter experts, developed using recognized scientific techniques, and driving power and interdependencies mapped by a digraph utilizing the Interpretative Structural Modeling. The digraph topology clearly illustrates defined building blocks aligned sequentially based on time-order events. Similarly, the theoretical INCOSE foundation/framework topology illustrates generic building blocks aligned sequentially based on time order events.

Since the INCOSE foundation/framework is solely theoretical, it does not account for a prime contractor's key *care-abouts* (customer, competition, architecture, design, process, and reporting). The concept stage output is similar to the output of the theoretical INCOSE foundation/framework; the concept stage output is a solution that must be generated to submit a proposal and the INCOSE foundation/framework output is a solution of product or services to the end user.

Including the prime contractor's key *care-abouts* in the concept stage allows the prime contractor to have the necessary information to gauge the maturity of the technical solution, to provide information to the prime contractor's executive leadership, and to assist in bid/no decision. Not having these key attributes as part of the concept stage risks bidding on immature technical solutions, not being able to meet schedule, and/or under or over-bidding losing profit or potential contracts for the prime contractor business. The theoretical INCOSE foundation/framework cannot provide the bid/no bid mandatory information.

Table 3: Alignment of the theoretical INCOSE foundation/framework to the Key Attributes

Theoretical INCOSE foundation/framework	Key attributes as defined by the SMEs	Prime Contractor's additional concept stage foundation/framework requirements beyond the theoretical INCOSE foundation/framework requirements.
State the Problem	Customer	The customers purchase a weapon's system to prevent or eliminate a significant threat. The technical requirements are a subset of the larger customer problem statement.
Investigate Alternatives	Competition	Investigate the competition's advantages and disadvantages.
Model the System	Architecture	The architecture confirms the weapon's system ability for military mission success and meeting the subset of technical requirements.
Integrate	Design	The prime contractor's proposed solution must be realizable for the weapon's system lifecycle which incorporates model the system, integrate, launch the system, assess performance, and address sustainability.
Launch the System	Process	A prime contractor must have processes for the the workforce to follow in order to competitively price a solution and the prime contractor must follow the USG governance process in order to export an international solution.
Assess Performance	Reporting	Reporting is a critical attribute in a Prime Contractor environment. The diverse workforce must share information across the proposal team and other functional groups, otherwise an accurate bid/no bid cannot be determined.

Table 3 aligns key attributes identified and defined during the ICIM workshop by the subject matter

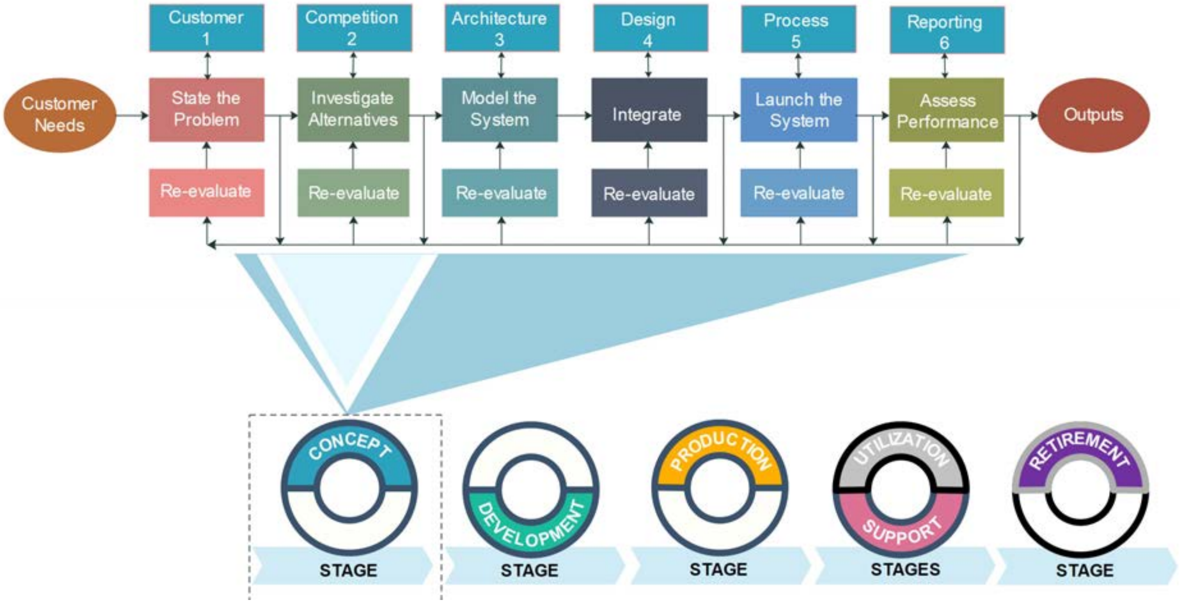


Figure 13: Second incremental step modification for SE theoretical methodology.

experts to the theoretical INCOSE foundation/framework. Figure 13 illustrates the alignment of the theoretical INCOSE foundation/framework blocks with the key attributes blocks from the ICIM workshop as described previously.

3.4.3 Third Incremental Step Modification for SE Theoretical Methodology

This research makes use of Interpretive Structural Modeling to develop the prime contractor's final modified methodology. ISM evaluated the key attributes for driving force, and interdependencies, and generated a digraph providing the steps and geometry to provide the prime contractor's accuracy in determining bid/no bid information.

Referencing the MICMAC analysis, the attributes were dispersed into two clusters along a perfect diagonal where driving power and dependency are clearly distinguishable making prioritization of the factors clearly a serial step process. The digraph and MICMAC relationship network is illustrated in Figure 10.

As provided in Figure 10(a), the digraph defined key attribute 5, "Process", as having the highest driving power and lowest dependency. Key attribute 6, "Reporting", was defined as the next highest driving power and next lowest dependency. Per the transdisciplinary generated digraph, key attribute 5 and key attribute 6 were moved to the front of the second incremental modified methodology, and the remaining key attributes followed in line as illustrated in Figure 14. Figure 15 illustrates the creation of the final modified methodology.

The digraph defined the required modification needed to the INCOSE foundation/framework for the use in real-world concept stage for a prime contractor.

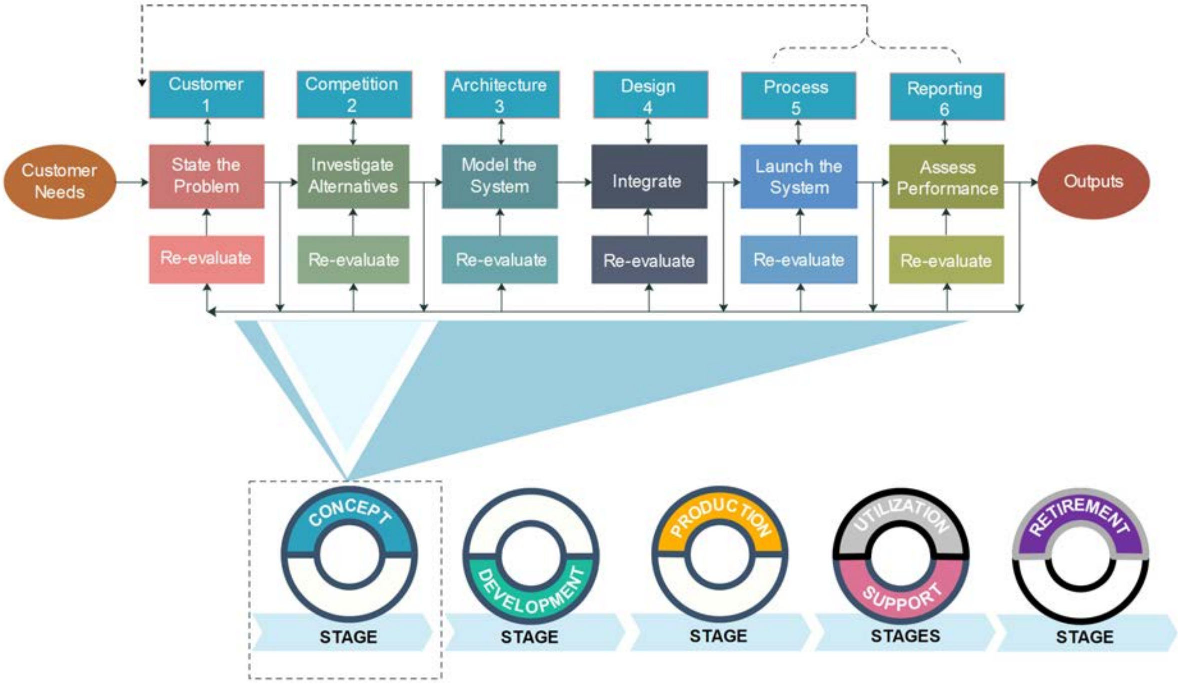


Figure 14: Third incremental step modification for SE theoretical methodology.

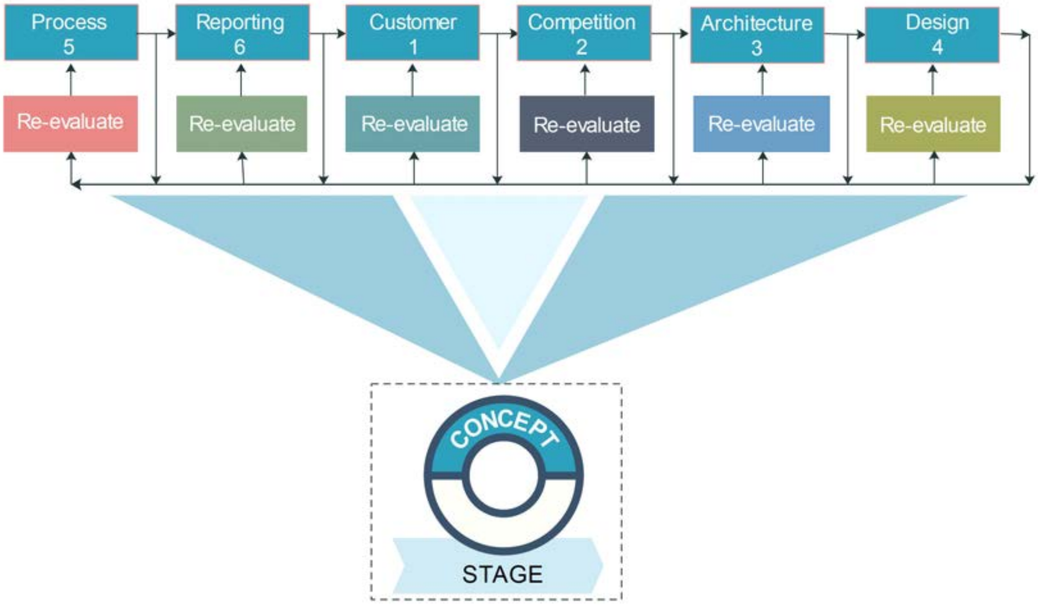


Figure 15: Final modification for SE theoretical methodology.

4 Modified Methodology for System of Systems

This research focused primarily on USG contracts where solutions are typically complex and require a system of systems (SoS) solution. A system of systems is an interoperating and integrated assembly of stand-alone systems. The system of systems generates solutions that otherwise would not be attainable from a single system [12]. Previously discussed incremental step modification was used to modify the SoS methodology as shown in Figure 16.

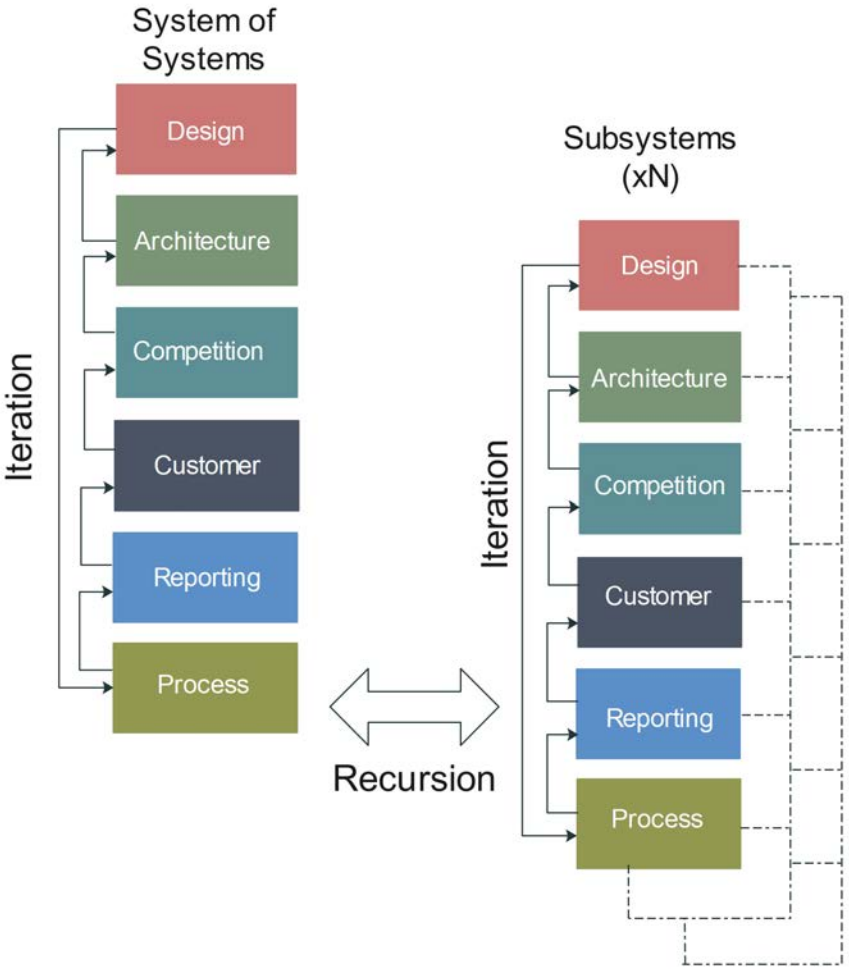


Figure 16: Prime Contractor's modified methodology for SoS.

4.1 Survey of the Final Modified Methodology

The previous sections described the incremental derivation of the final modified methodology for SE and SoS methodologies. The incremental derivations are summarized as follows:

- First incremental step modification of theoretical methodology was derived from the existing INCOSE foundation/framework and the existing generic life cycle (see Figure 12).

- Second incremental step modification of theoretical methodology was derived from mapping the key attributes developed from the ICIM workshop to the generic life cycle (see Figure 16).
- Third incremental step modification of theoretical methodology was derived from utilizing the ISM digraph (see Figures 14 and 15).
- Final modified methodology for a system of systems was derived by adding a system of systems approach (see Figure 16).

The final modified methodology for the Concept Stage was surveyed by practicing engineers to evaluate the following:

1. If current SE methodologies work for today's complex systems during the prime contractor's proposal generation in the concept stage.
2. If the final modified methodology for a system or a system of systems meets the prime contractor's need of solution generation for bid/no bid information for senior leadership proposal decision-making.

5 Survey of the Final Modified Methodology and Results

This section describes the survey's intent, the focus on participants with INCOSE background, the survey instrument description, the survey tool that was utilized, and the theory for performing Face Validity and the Lawshe Test.

5.1 Intention for Feedback

With the additional knowledge gained, whether the feedback is patterns of similarities or noted uniqueness, the feedback could be used to adjust the research strategy prior to initiating a case study to validate, or not validate, the final proposed SE methodology.

5.2 Focus Toward INCOSE Participants

The feedback needed for this research began in May 2020. A short video was produced to request the participation of the survey of practicing engineers. The video was a personable request to the new connections on LinkedIn as there was not an opportunity to meet the INCOSE members in person. A colleague of the researcher sent out the request, per Texas Tech University Human Research Protection Program (HRPP) guidelines, via LinkedIn and tagged the video allowing the new INCOSE connections to view the survey request and link to the survey. As INCOSE connections began to grow, the INCOSE North Texas Chapter Vice President of Chapter Development, sent out a personal email to INCOSE members creating an additional flow of completed surveys.

5.3 Instrumentation Description

The instrument used for this research was created by Zain Malik while he attended George Washington University in 2017 [38]. Zain Malik presented "An Application of Agile Principles to the Systems Engineering Lifecycle Process" for his dissertation. This research modified Malik's instrument to align with this research question and respective attributes.

The instrument questions were divided into a Quantitative section and a Qualitative section to evaluate the proposed systems engineering methodology. The Quantitative section has five criteria to evaluate as follows: Need, Attribute Overview, Methodology Overview, Comprehension, and Practicality. Each criterion is evaluated using a five-point Likert scale. The Qualitative section allowed the survey participants to have an open forum to present ideas for suggested Improvements, suggested Modifications, and the Overall Assessment of the proposed systems engineering methodology.

5.4 Transdisciplinary Assessment and Knowledge Integration

The *Transdisciplinary Assessment* methodology integrates social, technical, and cognitive aspects from various technical and non-technical knowledge domains [39] into an appropriate methodology [40]. To conduct scientifically valid research, it is crucial to involve societal players involved in the problem.

For this research, fifty-three participants completed the survey. The multi-dimensional represented disciplines and broad years of experience (the years of experience range from 2 years to 50 years, with the median age of 21 years of service) attributes to a transdisciplinary set of subject matter experts are described in Table 4.

Table 4: Survey participants

Profession	**Number of Participants for each discipline**
Chief Engineer/Systems Engineer	31
Architect	1
Software Engineer	6
Mechanical Engineer	1
Electrical Engineer	4
Program Management	3
Other (i.e., social and not listed above)	7
Total	53

The survey began with a brief description of the research and proceeded with a brief overview of existing systems engineering methodologies. The existing systems engineering methodologies that were shared in the survey included the Vee Model with a Traditional philosophy, the Set-Based Convergence Model with a Lean philosophy, and the Scrum Model with an Agile philosophy. The models each had brief descriptions respectively. The brief overview was shared, with the awareness that practicing engineers would already have knowledge of existing systems engineering methodologies. Finally, a description page consisting of the proposed systems engineering methodology and the attributes with their respective definitions was presented.

Test of Proportion: Approval proportion hypothesis tests were performed on the survey results to assess whether the results from the sampled population represent a statistically significant proportion of the entire population. The Test of Proportion was performed on each of the 20 quantitative survey questions as shown in Table 5. To enable quantitative analysis of the ordinal results from the Likert scale, ones, twos, and threes were considered non-supportive to the survey questions, while fours and fives were considered supportive to the survey questions.

The goal of this research was to establish 95% confidence that the surveyed engineers represent statistically significant support for the proposed SE methodology as described in each question. This research performed a right-tail hypothesis test to establish a confidence level for the results.

Survey Tool: As a recommendation from the Texas Tech University Human Research Protection Program, HRPP, the Qualtrics tool was used to build the instrument and conduct the survey. The Qualtrics tool allowed for description pages, multiple question types, multiple answer types, and multiple other options to customize the survey for flow and ease of reading.

Face Validity: After the survey was populated in the survey tool, the survey was reviewed by a System Engineer subject matter expert, to establish face validity. Face validity ensured the survey did in fact capture the content intended for this research.

Lawshe Test: This research also executed a mock survey with 7 system engineering, SMEs, to test the content validity of the survey using the Lawshe test [41,42]. The test gauged how essential a particular item/category was, therefore further validating the survey prior to research.

Table 5: Twenty survey questions

Questions	Statement of survey questions
1	Systems engineering has evolved in complexity from designing a single system to designing to designing a system of systems.
2	Systems engineering has evolved in complexity from designing a single system to designing to designing a system of systems.
3	The practice of systems engineering includes the interaction with multiple, other disciplines to succeed.
4	Having Process as defined in this survey for a systems engineering pursuit team increases the likelihood to win a proposal.
5	Having Reporting as defined in this survey for a systems engineering pursuit team increases the likelihood to win a proposal.
6	Having Customer as defined in this survey for a systems engineering pursuit team increases the likelihood to win a proposal.
7	Having Competition as defined in this survey for a systems engineering pursuit team increases the likelihood to win a proposal.
8	Having Architecture as defined in this survey for a systems engineering pursuit team increases the likelihood to win a proposal.
9	Having Design as defined in this survey for a systems engineering pursuit team increases the likelihood to win a proposal.
10	Having a systems engineering methodology that iterates through Process, Reporting, Customer, Competition, Architecture, and Design for a systems engineering pursuit team increases the likelihood to win a proposal.
11	Having a systems engineering methodology that iterates through Process, Reporting, Customer, Competition, Architecture, and Design for a systems engineering pursuit team may increase customer satisfaction.
12	The proposed systems engineering methodology may be more time efficient over existing system engineering methodologies.
13	The proposed systems engineering methodology may reduce cost over existing system engineering methodologies.
14	The proposed systems engineering methodology may increase efficiency over existing system engineering methodologies.
15	The proposed systems engineering methodology may increase the likelihood to win a contract over existing system engineering methodologies.
16	The proposed systems engineering methodology may increase customer satisfaction over existing system engineering methodologies.
17	The proposed systems engineering methodology is well laid out, clear, and easy to understand.
18	The proposed systems engineering methodology lays out what is necessary for systems engineering during the pursuit phase.
19	This proposed systems engineering methodology is applicable in the industry for systems engineering during the pursuit phase.
20	This proposed systems engineering methodology is necessary in industry for systems engineering during the pursuit phase.

5.5 Quantitative Analysis

The survey was comprised of five categories to score the proposed SE methodology for (1) Need - the proposed SE methodology addresses system of systems, (2) Attribute Overview – the proposed SE methodology attributes increase the likelihood of proposal win, (3) Methodology Overview - whether the proposed SE methodology showed advantages over existing SE methodologies, (4) Comprehension – whether the proposed SE methodology is clearly defined and understood, and (5) Practicality – is the proposed SE methodology applicable and necessary for industry.

5.5.1 Need Category

The first three questions in the "need category" in Table 5 were presented to the participants, and the results are listed in Table 6. Overwhelmingly, the Need section supports the importance of this research as systems are becoming increasingly more complex.

Table 6: Questions and survey results for need category: 1-3.

Category	Questions	Survey Results for questions
Need	Question 1	The research informed that 89% of practicing engineers somewhat agree or strongly agree that they are experiencing an increase in the complexity of systems.
	Question 2	The research also informed that 85% of practicing engineers somewhat agree or strongly agree that the systems engineering community could benefit from a system engineering methodology that can design for a system of systems.
	Question 3	The research informed that 94% of practicing engineers somewhat agree or strongly agree that systems engineering includes the interaction with multiple, other disciplines to succeed.

5.5.2 Attribute Overview

Eight questions in Table 5 (questions 4-11) were presented to the participants, and the results are listed in Table 7. The Attribute Overview sections show support for the attributes and their respective definitions as described in this research.

Table 7: Questions and survey results for Attribute Overview – question 4-11

Category	Questions	Survey Results for questions
Attributes	Question 4	The research informed that 85% of practicing engineers somewhat agree or strongly agree that having **Process** as defined in this research for a system engineering pursuit team increases the likelihood to win a proposal.
	Question 5	The research informed that 83% of practicing engineers somewhat agree or strongly agree that having **Reporting** as defined in this research for a system engineering pursuit team increases the likelihood to win a proposal.
	Question 6	The research informed that 76% of practicing engineers somewhat agree or strongly agree that having **Customer** as defined in this research for a system engineering pursuit team increases the likelihood to win a proposal.
	Question 7	The research informed that 83% of practicing engineers somewhat agree or strongly agree that having **Competition** as defined in this research for a system engineering pursuit team increases the likelihood to win a proposal.
	Question 8	The research informed that 87% of practicing engineers somewhat agree or strongly agree that having **Architecture** as defined in this research for a system engineering pursuit team increases the likelihood to win a proposal.

Table 7: Questions and survey results for Attribute Overview – question 4-11 (continued).

Category	Questions	Survey Results for questions
Attributes	Question 9	The research informed that 93% of practicing engineers somewhat agree or strongly agree that having **Design** as defined in this research for a system engineering pursuit team increases the likelihood to win a proposal.
	Question 10	The research informed that 74% of practicing engineers somewhat agree or strongly agree that having a systems engineering methodology that iterates through Process, Reporting, Customer, Competition, Architecture, and Design for a systems engineering pursuit team increases the likelihood to win a proposal.
	Question 11	The research informed that 85% of practicing engineers somewhat agree or stronglagree that having a systems engineering methodology that iterates through Process, Reporting, Customer, Competition, Architecture, and Design for a systems engineering pursuit team may increase customer satisfaction.

5.5.3 Methodology Overview

Five questions in Table 5 (questions 12-16) were presented to the participants, and the results are listed in Table 8.

The Methodology Overview section reveals some interesting feedback. The time and cost of supporting a system of systems methodology may be less time efficient and increase the cost of systems engineering. However, on the upside, 64% of the practicing engineers see increased efficiency of the proposed methodology over existing system engineering methodologies. 53% of practicing engineers responded that the proposed systems engineering methodology may increase the likelihood to win a contract over existing system engineering methodologies, and 63% of practicing engineers responded that the proposed systems engineering methodology may increase customer satisfaction over existing system engineering methodologies.

Table 8: Questions for Methodology Overview – question 12-16).

Category	Questions	Survey Results for questions
Methodology	Question 12	From the results in the Methodology Overview section of the survey, the research informed that 42% of practicing engineers somewhat agree or strongly agree that the proposed systems engineering methodology may be more **time efficient** over existing system engineering methodologies.
	Question 13	The research informed that 50% of practicing engineers somewhat agree or strongly agree that the systems engineering methodology may **reduce cost** over existing system engineering methodologies.
	Question 14	The research also informed that 64% of practicing engineers somewhat agree or strongly agree that the systems engineering methodology may **increase efficiency** over existing system engineering methodologies.
	Question 15	The research also informed that 53% of practicing engineers somewhat agree or strongly agree that the systems engineering methodology may increase the **likelihood to win a contract** over existing system engineering methodologies.
	Question 16	Lastly from the Methodology Overview section, the research informed that 63% of practicing engineers somewhat agree or strongly agree that systems engineering methodology may increase **customer satisfaction** over existing system engineering methodologies.

5.5.4 Comprehension

Two questions in Table 5 (questions 17-18) were presented to the participants, and the results are listed in Table 9. Overall, the Comprehension section is positive. The qualitative section may provide additional information from the participant's experiences during the pursuit phase.

5.5.5 Practicality

Two questions in Table 5 (questions 19-20) were presented to the participants, and the results are listed in Table 10. The Practicality section emphasizes that the proposed systems engineering methodology is applicable in the industry, yet only 40% of the practicing engineers suggest that the methodology is necessary in the industry.

Table 9: Questions for Comprehension – questions 17-18).

Category	Questions	Survey Results for questions
Comprehension	Question 17	From the results in the Comprehension section of the survey, the research informed that 72% of practicing engineers somewhat agree or strongly agree that the proposed systems engineering methodology is well laid out, clear, and easy to understand.
	Question 18	The research informed that 65% of practicing engineers somewhat agree or strongly agree that the systems engineering methodology lays out what is necessary for systems engineering during the pursuit phase.

Table 10: Questions for Practicality – questions 19-20.

Category	Questions	Survey Results for questions
Practicality	Question 19	From the results in the Practicality section of the survey, the research informed that 69% of practicing engineers somewhat agree or strongly agree that the proposed systems engineering methodology is **applicable in the industry** for systems engineering during the pursuit phase.
	Question 20	The research informed that 40% of practicing engineers somewhat agree or strongly agree that the systems engineering methodology is necessary for the industry for systems engineering during the pursuit phase.

5.6 Qualitative Analysis

The Qualitative section has three criteria to evaluate as follows: Improvement Factor, Possible Modification, and Overall Assessment. The Qualitative section allows the practicing engineers to have an open forum to present ideas for improvement, suggest modifications, and give an overall assessment of the proposed methodology.

The qualitative data was analyzed using *Content* analysis. Content analysis is the most common type of data analysis. The analysis is comprised of the categorization, tagging, and thematic analysis of qualitative data [43]. In qualitative research, coding is how you define the data you are analyzing [43]. Coding is a process of identifying a passage in the text or other data items, searching and identifying concepts, and finding relations between them. Coding is not just labeling. Coding is the linking of data back to the research problem statement. The process of coding is performed on what is called parent data. Parent data is then decomposed into what are called children in iterative steps. This research used three iterative steps.

The first iterative pass of Content analysis is called Open Coding. After the first iteration, a label or name of the code is assigned based on the overall idea or topic. The second iterative pass of Content analysis is called Axial Coding. After the second iteration, a refinement of labels or common themes is found to reduce the number of labels. This in return will reduce the number of ideas or topics. The last iterative pass of Content analysis is called Final Coding. The last iteration consists of a final attempt to group similar topics at the most reduced state possible without losing integrity or meaning. At the completion of the coding process, the qualitative data is tagged with a word or short phrase to link the data back to the research topic [44].

The qualitative survey results were reviewed and dispositioned to align to the quantitative questions that were scored from 3 to 4, which represents neither agree nor disagree to somewhat agree results. The alignment is defined in Table 11.

This research's survey was designed in a manner that the quantitative section questions provided the primary scoring of the proposed SE methodology. The qualitative section questions provided a means to address any noted deficiencies with written prose and guidance on how to improve the proposed SE methodology. In other words, the SMEs were provided a written forum guided by the relevant questions to develop and provide what the industry requires for SE in the concept stage.

The survey results clearly documented the responding SMEs were undecided on the proposed SE methodology as demonstrated in Table 11. The broad group of SMEs did not provide sufficient information in the qualitative categories of Methodology, Comprehension, and Practicality. After a careful review of the SMEs qualitative feedback, either the SMEs failed to address the Methodology, Comprehension, and Practicality categories, or the SMEs lacked the knowledge and experience to provide focused and experiential experience in SE methodology application of the proposed SE methodology.

Table 11: Quantitative Category/Question aligned to Qualitative provided input.

Quantitative Category	**Survey Question**	**Qualitative question/topic providing additional information**
Methodology	12 - The proposed systems engineering methodology may be more **time efficient** over existing system engineering methodologies.	Qualitative portion of the survey did not provide information for improvement.
Methodology	13 - The proposed systems engineering methodology may **reduce cost** over existing system engineering methodologies.	Qualitative portion of the survey did not provide information for improvement.

Table 11: Quantitative Category/Question aligned to Qualitative provided input (continued).

Quantitative Category	**Survey Question**	**Qualitative question/topic providing additional information**
Methodology	14 - The proposed systems engineering methodology may **increase efficiency** over existing system engineering methodologies.	Qualitative portion of the survey did not provide information for improvement.
Methodology	15 - The proposed systems engineering methodology may **increase the likelihood to win a contract**over existing system engineering methodologies.	Qualitative portion of the survey did not provide information for improvement.
Methodology	16 - The proposed systems engineering methodology may **increase customer satisfaction** over existing system engineering methodologies.	Improve/Customer Focus: Maintain close communication with customer as needs may change.
Comprehension	17 - The proposed systems engineering methodology is **well laid out, clear, and easy to understand.**	Improve/Careful definition of terms: Nomenclature and definitions could be clearer.
Comprehension	18 - The proposed systems engineering methodology **lays out what is necessary for systems engineering** during the pursuit phase.	Qualitative portion of the survey did not provide information for improvement.
Practicality	19 - This proposed systems engineering methodology is **applicable in industry** for systems engineering during the pursuit phase.	Improve/General Comment: Is there a score metric in the overall method to assess effectivity.
Practicality	20 - This proposed systems engineering methodology is **necessary in industry** for systems engineering during the pursuit phase.	Improve/General Comment: Is there a score metric in the overall method to assess effectivity.

The lack of information in the qualitative results from the responding SMEs, resulted in this research gathering additional a new SMEs group, specifically with 30 plus years of proposal experience.

The new focus group of SMEs addressed quantitative questions that were scored from 3 to 4, which represents neither agree nor disagree to somewhat agree results. The first author of this paper focused on the new SME group selection to those with extensive SoS proposal and execution experience for complex systems. The participants are recognized experts in at least two of the following sectors: commercial, defense, and U.S. Government. The Focused SME group is described in Table 12.

Table 12: New focused SME group

Expert	Sector Experience	Proposal Experience	SE Experience
SME #1	Commercial, Defense, U.S. Government	33 years	40 years
SME #2	Commercial, Defense, U.S. Government	35 years	42 years
SME #3	Commercial, Defense, U.S. Government	38 years	45 years
SME #4	Commercial, Defense, U.S. Government	28 years	35 years
SME #5	Defense, U.S. Government	36 years	43 years
SME #6	Defense, U.S. Government	27 years	34 years

The focused SME group's inputs were integrated into the surveyed proposed SE methodology creating the final proposed SE methodology as illustrated in Figure 17.

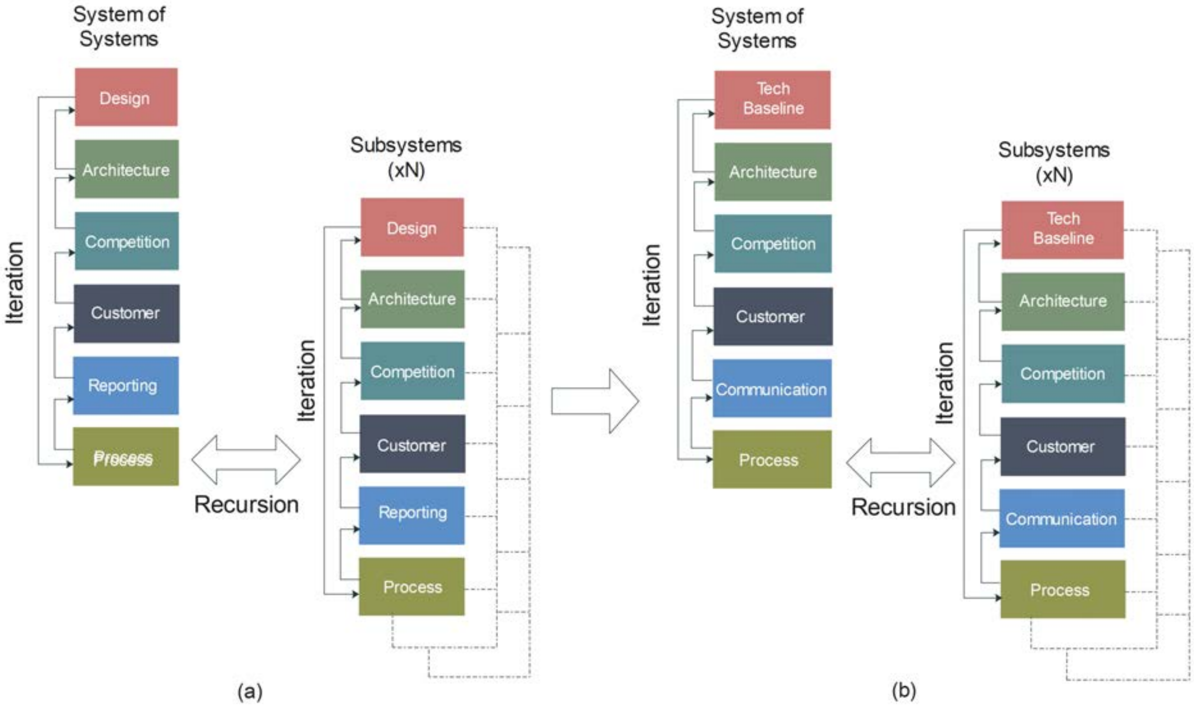


Figure 17: Surveyed proposed SE methodology versus final proposed SE methodology.

This focused set of SMEs was solicited by email to assist in the final recommendations of this research. Each participant committed two hours of time reviewing and providing inputs to refine the proposed SE methodology. Each SME was provided a copy of the survey and survey results, including both quantitative and qualitative results. The ask was to review and provide guidance to address the categories of Methodology, Comprehension, and Practicality as described in Table 13. Each SME was allotted two weeks prior to a scheduled Zoom call as a group to discuss the recommendations brought forward to this research.

The cumulation of inputs from the focused SME group was compiled and defined in Table 13.

Table 13: Information from the focused SME group.

Quantitative Category	**Survey Question**	**Qualitative question/topic providing additional information**	**Focused SME group**
Methodology	12 - The proposed systems engineering methodology may be more **time efficient** over existing system engineering methodologies.	Qualitative portion of the survey did not provide information for improvement.	A technical baseline is tailored to meet the customer's key mission technical and sustainment requirements.
Methodology	13 - The proposed systems engineering methodology may **reduce cost** over existing system engineering methodologies.	Qualitative portion of the survey did not provide information for improvement.	The cost is reduced based on Competition. A price to win drives the technical baseline implementation.
Methodology	14 - The proposed systems engineering methodology may **increase efficiency** over existing system engineering methodologies.	Qualitative portion of the survey did not provide information for improvement.	Process definition and scope are enhanced.
Methodology	15 - The proposed systems engineering methodology may **increase the likelihood to win a contract**over existing system engineering methodologies.	Qualitative portion of the survey did not provide information for improvement.	Process and Technical Baseline are tailored to meet the customer's scoring matrix.
Methodology	16 - The proposed systems engineering methodology may **increase customer satisfaction** over existing system engineering methodologies.	Improve/Customer Focus: Maintain close communication with customer as needs may change.	The early architecture development with the customer prior to official request for proposal release permits requirement refinement based on prime contractor's technical baseline.
Comprehension	17 - The proposed systems engineering methodology is **well laid out, clear, and easy to understand.**	Improve/Careful definition of terms: Nomenclature and definitions could be clearer.	The attribute definitions were enhanced and two were focused specific to proposal activities (i.e., communication and technical baseline)
Comprehension	18 - The proposed systems engineering methodology **lays out what is necessary for systems engineering** during the pursuit phase.	Qualitative portion of the survey did not provide information for improvement.	Process was expanded to include necessary activities for SE during the pursuit phase.
Practicality	19 - This proposed systems engineering methodology is **applicable in industry** for systems engineering during the pursuit phase.	Improve/General Comment: Is there a score metric in the overall method to assess effectivity.	The focused SME group confirmed applicability in industry in the pursuit phase.
Practicality	20 - This proposed systems engineering methodology is **necessary in industry** for systems engineering during the pursuit phase.	Improve/General Comment: Is there a score metric in the overall method to assess effectivity.	The focused SME group confirmed necessity in industry and the importance of a technical baseline maturity score to assess effectivity in the pursuit phase.

Equally important, the attribute definitions were expanded and enhanced to provide clarity specific to the proposal phase as defined in Table 14.

Table 14: Final proposed SE methodology attribute definitions.

Attributes	**Attribute definations**
Process	Process defines a set of interrelated or interacting activities that transforms inputs into outputs. The process includes four elements: controls (applicable laws and regulations, standards, and program management controls), inputs (data and, material) enablers (policies, procedures, and standards, organizational infrastructure, project infrastructure, management systems), and outputs (products and services).
Communication	Communication provides to interested parties the official status, results, and outcomes of the specific process and activities.
Customer	Customer refers to customer's key mission and business drivers/technical requirements/sustainment requirements and concepts of operations to successfully complete the deployed mission operational capability.
Competition	Competition refers to competitive evaluations, the competitor's likely strategy and technical/business solution and the offer meeting the source selection criteria. The key factors evaluated include price to win, terms and conditions, U.S. government export laws, and company's core capabilities. These key factors are included in the evaluation when companies compare their own offering to the offering of the competitor and weigh the pros and cons of each to the customer's scoring matrix.
Architecture	Architecture defines the customer functions, the architecture views and allocates functions through architectural elements to ensure the completeness and integrity of the architectural models meeting the customers mission, concept of operation, and all requirements. The architecture studies determine requirement priorities, acceptable performance, cost, schedule, risk, and mission assurance items.
Technical Baseline	Technical Baseline refers to the transition of the architecture model into a realizable products and services defining the system of systems solution. The technical baseline is tailored to the customer's proposal package which best meets the customer's scoring matrix.

6 Conclusion

Transdisciplinary collaboration has a large potential to speed up the rate at which research can contribute to the understanding of the problem, accelerate the pace of new discoveries, and expand human knowledge. Transdisciplinarity provides a good framework and adds to the current approaches of system engineering. That is, transdisciplinary *collective intelligence,* which is a new mode of information gathering, knowledge creation, and decision-making that draws on expertise from a wider range of organizations, and collaborative partnerships, hence, selectively and collectively initiating successful *collective impact* [45].

This research focused on expanding the Concept Stage of an existing SE methodology to assess the technical maturity during the proposal phase in support of executive leadership decision-making during contract negotiations to better position the company for success and profit. During this research, it was concluded that none of the existing SE methodologies were adequate to provide SE guidance during the proposal phase. Subsequently, a proposed SE methodology was developed and presented in this paper.

The proposed SE methodology was developed using proven scientific techniques and methods demonstrated and documented in this paper. To begin with, the problem set was best addressed using transdisciplinary methods to address societal issues, theoretical engineering, and transformation of theory into products. The Nominal Group Technique, Interpretative Structural Modeling, and a formal survey per Texas Tech University Human Research Protection Program (HRPP) guidelines scored using a 1-5 Likert scale were utilized in adapting the INCOSE foundation/framework and the generic lifecycle to develop the final proposed SE methodology.

Contributions: This paper was written from LynnDee Ford's dissertation. A. Etas. is the advisor of LynnDee Ford's Conceptualization.

Funding: This research work was supported by Raytheon Technologies (RTX).

Conflicts of Interest: The authors declare that there is no conflict of interest regarding the publication of this paper.

References

1. Flores, M. (2018). *Set-Based Concurrent Engineering (SBCE): Why should you be interested?* Lean Analytics Association. http://lean-analytics.org/set-based-concurrent-engineering-sbce-why-should-you-be-interested/
2. Schwaber, K. (2004). *Agile Project Management with Scrum* (1st ed.). Microsoft Press.
3. Sols Rodriguez-Candela, A. (2014). *Systems Engineering Theory and Practice* (1st ed.). Universidad Pontificia Comillas.
4. U.S. Department of Defense. (2022, July 5). Fact Sheet on U.S. Security Assistance to Ukraine. https://www.defense.gov/News/Releases/Release/Article/3083102/fact-sheet-on-us-security-assistance-to-ukraine/
5. Williams, J. (2022, May 4). US defense industry strained by Ukraine weapons deliveries. The Hill. https://thehill.com/policy/defense/3476193-us-defense-industry-strained-by-ukraine-weapons-deliveries/
6. De Luce, D., & Dilanian, K. (2022, March 31). Can the U.S. and NATO provide Ukraine with enough weapons? NBC News. https://www.nbcnews.com/politics/national-security/can-us-nato-provide-ukraine-enough-weapons-rcna22066digité. (n.d.). What is Kanban?
7. Everstine, B. W. (2020, November 10). State Department Approves F-35, MQ-9 Sale to UAE. Air Force Magazine. https://www.airforcemag.com/state-department-approves-f-35-mq-9-sale-to-uae/
8. US General Accounting Office. (2001). Joint Strike Fighter Acquisition; Report to the Chairman, Subcommittee on National Security. USGAO.
9. Gould, J. (2022, April 29). US National Guard's aging battle taxis find new use in Ukraine fight. Defense News. https://www.defensenews.com/pentagon/2022/04/29/national-guards-aging-battle-taxis-find-new-use-in-ukraine-fight/

10. Buede, D. (2000). *The Engineering Design of Systems: Models and Methods.* John J. Wiley & Sons
11. NASA. (2017). *NASA Systems Engineering Handbook* ((SP-2016-6105), Rev 2). https://ntrs.nasa.gov/citations/20170001761
12. INCOSE. (2015). *INCOSE Systems Engineering Handbook: A Guide for System Life Cycle Processes and Activities.* 4th Edition (4th Edition). Wiley.
13. Boehm, & Turner, R. (2003). *Balancing Agility and Discipline: A Guide for the Perplexed.* Addison-Wesley Longman Publishing Co., Inc.
14. Carson, R. (2013). Can Systems Engineering be Agile? Development Lifecycles for Systems, Hardware, and Software. *INCOSE International Symposium,* 23, 16–28. https://doi.org/10.1002/j.2334-5837.2013.tb03001.x
15. Ertas, A., Gulbulak, U. (2021). *Managing System Complexity through Integrated Transdisciplinary Design Tools.* Atlas Publishing, ISBN: 978-0-9998733-1-1; doi:10.22545/2021b/B1
16. Dorien J. DeTombe, (2001). Compra, a Method for Handling Complex Societal Problems. *European Journal of Operational Research*, 128, 266–281.
17. Ertas A., (2018). *Transdisciplinary Engineering Design Process.* Wiley & Sons Inc., New York, 2018, ISBN: 9781119474777.
18. Cronin, K. (2008). Transdisciplinary research and sustainability. *Environmental Science and Research (ESR), ltd.*
19. Engardio , P., & Einhorn, B., (2005, March 21). Outsourcing Innovation. Business Week.
20. Moorman, C., (1995). Organizational market information processes: cultural antecedents and new product outcomes. *Journal of marketing research,* 318-335.
21. National Academy of Engineering. NAE Grand Challenges for Engineering. Retrieved September 7, 2012, from http://www.
engineeringchallenges.org/
22. Derry, J. S., and Fischer, G. (2006). Transdisciplinary Graduate Education. Retrieved from: Report, http://l3d.cs.colorado.edu/ gerhard/papers/ transdisciplinary-sharon.pdf.
23. Ertas, A., Maxwell, T., Rainey, V. P., & Tanik, M. M. (2003). Transformation of higher education: the transdisciplinary approach in engineering. *IEEE Transactions on Education,* 46(2), 289-295.
24. Abdoullaev, A., (2021). Transdisciplinary Science and Technology: The Matter of Life and Death. European Al Alliance. https://www.bbntimes.com/technology/transdisciplinary-science-and-technology-the-matter-of-life-and-death, Accessed November 19, 2021.
25. Bergmann, M., (2017). Methods for integration in transdisciplinary research. Integration and Implementation Insights. https://i2insights.org/2017/05/09/transdisciplinary-integration-methods/, Accessed November 13, 2021.
26. Madni, M. A., (2018). Transdisciplinary Systems Engineering. *Springer*, 2018, ISBN 978-3-319-62183-8
27. Mokiy, V. and Lukyanova, T. (2022). Prospects of Integrating Transdisciplinarity and Systems Thinking in the Historical Framework of Various Socio-Cultural Contexts. *Transdisciplinary Journal of Engineering & Science,* Vol. 13, pp. 143-158.
28. Klein, J. T., (2008). Integration in der inter- und transdisziplinären Forschung, M. Bergmann, E. Schramm (Eds.), Transdisziplinäre Forschung. Integrative Forschungsprozesse verstehen und bewerten, Campus Verlag, Frankfurt/New York (2008), pp. 93-116.
29. Pohl, C., Klein, T. J., Mitchell H. C., Fam, D., (2021). Conceptualising transdisciplinary integration as a multidimensional interactive process. *Environmental Science & Policy,* Volume 118, April 2021, Pages 18-26.
30. Nicolescu, B. (2010). Methodology of Transdisciplinarity–Levels of Reality, Logic of the Included Middle and Complexity. *Transdisciplinary Journal of Engineering & Science,* Vol 1, pp.17-32.
31. Star S. L., and James R. (1989). GriesemerInstitutional Ecology, 'Translations' and Boundary Objects: Amateurs and Professionals in Berkeley's Museum of Vertebrate Zoology, 1907-39. *Social Studies of Science,* Vol. 19, pp. 387-420.

32. Warfield J. N., and Cardenas, A. R. (1994). *A Handbook of Interactive Management,* Iowa State University Press/AMES.
33. Delbecq A. L. and VandeVen A. H, (1971). A Group Process Model for Problem Identification and Program Planning. *Journal Of Applied Behavioral Science* 7, 466 -91.
34. Warfield, J. (1974). *Structuring Complex Systems.* Battelle Monograph, 4. https://cir.nii.ac.jp/crid/1571980074728224640
35. Harary, F., Norman, R. V., and Cartwright, D. (1965). *Structural Models: An Introduction to the Theory of Directed Graphs,* Willey, New York.
36. Duperrin, J. C., and Godet, M. (1973). Methode De Hierar Chization des Elements D'um System, *Rapport Economique de CEA,* pp.45–51.
37. Mandal, A., and Deshmukh, S.G. (1994). Vendor Selection Using Interpretive Structural Modelling (ISM). *International Journal of Operations & Production Management,* 14(6).
38. Malik, Z. (2017). *An Application of Agile Principles to the Systems Engineering Lifecycle Process*, Open Access [Ph.D., George Washington University]. https://scholarspace.library.gwu.edu/etd/bg257f160
39. Blomberg, K-L, Eriksson, J., Svensson, J. (2005). Mapping of relations and dependencies using DSM/DMM-analysis. *Internationel la Handelshogskolan*, Hogskolan I Jonkoping, 2005.
40. Hinkel, J. (2008). *Transdisciplinary knowledge integration: Cases from integrated assessment and vulnerability assessment*, Ph.D. thesis, Wageningen University, Wageningen, The Netherlands, 2008. ISBN 978-90-8504-825-1.
41. Lawshe, C. H. (1975). A Quantitative Approach to Content Validity. Personnel Psychology, 28(4), 563–575. https://doi.org/10.1111/j.1744-6570.1975.tb01393.x Lean Manufacturing Tools. (n.d.). Kanban. Lean Manufacturing Tools. Retrieved October 30, 2018, from https://leanmanufacturingtools.org/kanban/
42. Wilson, F. R., Pan, W., & Schumsky, D. A. (2012). Recalculation of the Critical Values for Lawshe's Content Validity Ratio. Measurement and Evaluation in Counseling and Development, 45(3), 197–210. https://doi.org/10.1177/0748175612440286
43. Gibbs, G. (2007). Analyzing Qualitative Data. SAGE Publications, Ltd. DOI: https://doi.org/10.4135/9781849208574
44. Saldana, J. (2013). The Coding Manual for Qualitative Researchers (2nd ed.). Sage Publications.
45. Ertas, A., Frias, K. M., Tate, D., & Back, S. M. (2015). Shifting Engineering Education from Disciplinary to Transdisciplinary Practice. *International Journal of Engineering Education,* 31(1), 94-105.

About the Authors

LynnDee Ford is the associate director and systems engineering discipline lead at Raytheon Intelligence & Space, part of Raytheon Technologies. Over a 27-year career, she has demonstrated strategic visionary leadership, orchestrating and empowering teams and leveraging transdisciplinary engineering to solve high-consequence problems. In her current role, Ford is responsible for ensuring systems engineering excellence across RI&S, focusing on execution to produce the most capable technologies at an affordable cost and a faster time to market for the world's most advanced defense and information systems. Ford has held numerous challenging technical leadership roles in systems engineering across diverse businesses, namely Secure Sensor Systems, Electronic Warfare Systems and Intelligence, and Surveillance and Reconnaissance (ISR) Systems. She led the special mission aircraft command, control, communications, computers (C4) for ISR architecture and mission system software, and system of systems (SoS) for international pursuits. Her experiences span all phases of the product lifecycle, from early research and development and pursuits through production and sustainment. Ford is a PhD candidate in Design, Process, and Systems Engineering from Texas Tech University. Ford earned a Master's degree in Electrical and Computer Engineering and a dual Bachelor's degree in Chemistry and Biology from Purdue University.

Dr. A. Ertas, Professor of Mechanical Engineering and director of the Academy for Transdisciplinary Studies at Texas Tech University, received his master's and Ph.D. from Texas A&M University. He had 12 years of industrial experience prior to pursuing graduate studies. Dr. A. Ertas has been the driving force behind the conception and development of the transdisciplinary model for education and research. His pioneering efforts in transdisciplinary research and education have been recognized internationally by several awards. He was a Senior Research Fellow of the ICC Institute at the University of Texas Austin (1996-2019), a Fellow of ASME, a Fellow of Society for Design and Process Science (SDPS), Founding Fellow of Luminary Research Institute in Taiwan, an honorary member of International Center for Transdisciplinary Research (CIRET), France, and a member of ASEE. Dr. Ertas has earned both national and international reputations in engineering design. Dr. Ertas is the author of a number of books, among them: Ertas, A. and Jones, J. C., *The Engineering Design Process,* John Wiley & Sons, Inc., first edition 1993 and second edition 1996; Ertas, A., *Prevention through Design (PtD): Transdisciplinary Process,* funded by the National Institute for Occupational Safety and Health, 2010; Ertas, A., *Engineering Mechanics and Design Applications, Transdisciplinary Engineering Fundamentals*, CRC Press, Taylor & Francis Group, 2011; A. Ertas, A., *Transdisciplinarity Engineering Design Process,* John Wiley & Sons, 2018. He has edited many research books specific to transdisciplinary engineering design, among them: Ertas, A., (editor), *Transdisciplinarity: Bridging Natural Science, Social Science, Humanities & Engineering*, ATLAS Publications, 2011; B. Nicolescu, B. and Ertas A., (editors), *Transdisciplinary Theory and Practice*, ATLAS Publications, 2013; Nicolescu, B., Ertas, A., (Editors), *Transdisciplinary Education, Philosophy, & Applications,* ATLAS Publications, 2014; Ertas, A., Nicolescu, B., S. Gehlert, S., (Editors), *Convergence: Transdisciplinary Knowledge & Approaches to Education and Public Health*, ATLAS Publishing, 2016; Nicolescu, B., Yeh, R. T., Ertas, A., (Editors), *Being Transdisciplinary.* ATLAS Publishing, 2019; Ertas, A., (Editor), *Additive Manufacturing Research & Applications*, MDPI Publishing, Switzerland. He has also edited/co-edited more than 35 conference proceedings. Dr. Ertas' contributions to teaching and research have been recognized by numerous honors and awards. He has published over 200 scientific papers and book chapters that cover many engineering technical fields. He has been PI or Co-PI on over 40 funded research projects. Under his supervision, more than 190 MS and Ph.D. graduate students have received degrees.