DISSERTATION

INTEGRATION OF SYSTEMS ENGINEERING AND PROJECT MANAGEMENT USING A MANAGEMENT FLIGHT SIMULATOR

Submitted by

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ABSTRACT

INTEGRATION OF SYSTEMS ENGINEERING AND PROJECT MANAGEMENT USING A MANAGEMENT FLIGHT SIMULATOR

Cost overruns and schedule delays are pervasive in complex projects despite the use of systems engineering and traditional project management models and tools. These disciplines can often work in isolation leading to inconsistencies in product information, tracking of design changes and challenges in decision-making. While literature proposes philosophical approaches to integrating these disciplines, there does not appear to be a practical approach offered.

The current study proposes a practical approach by way of a management flight simulator that integrates systems engineering and management models for data-driven risk-informed decision-making. This simulator provides immediate feedback on whether a change is going to help or disrupt design integrity through the monitoring of system attribute trends and cues. It also provides the impact on lifecycle management curves using a system dynamics sub-model.

From this feedback, several system, policy and process levers are available within the simulator for what-if scenarios with the goal to improve product, organizational and project performance. The value in the emergent properties of the simulator as a decision support system is viewed as greater than from the sum of its sub-models.

In developing the simulator, integration requirements, systems thinking, systems science and systems engineering practices are leveraged to develop an integration strategy. For bringing multiple disciplines together to address design changes risks, a response strategy is proposed that includes aspects of set-based goal-based design and agile management practices.

ACKNOWLEDGMENTS

I would like to express my appreciation and gratitude to my advisor, Dr. Kamran Eftekhari Shahroudi for his guidance and mentorship through this journey of continued learning, discovery and growth.

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I would also like to thank survey participants at the International Council on Systems Engineering (INCOSE) International Workshop (IW2020) and the Project Management - Systems Engineering Working Group of INCOSE which is aligned with the objectives of this dissertation.

Last, but not least, I would like to acknowledge the sacrifice made by my wife Loretta while I pursued this final degree.

DEDICATION

For my daughter Kathleen and son Thomas who inspired and reminded me that you can’t put a price on education and you’re never too old to learn.

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Chapter 1 – Introduction

1.1 Introduction

The International Council on Systems Engineering (INCOSE) Vision 2025 provides considerations for how systems engineering (SE) will need to evolve. This includes SE as a key integrating role to support collaboration across a broad range of disciplines and capable models and tools that allow for a better understanding of complex systems and decisions under uncertainty [1]. In a Project Management Institute (PMI) report on project managers of the future, developing digital-age skills was highlighted as a requirement to manage the impact of increasingly disruptive technologies. These skills include collaborative leadership, data science and the ability to make data-driven decisions [2]. In a NASA review of past project challenges, it was noted that the technical and programmatic sides of projects were not well-coupled, hampering effective project decision-making and increasing developmental risks [3].

The lack of integration between SE and Project Management (PM) can lead to inconsistent and incomplete information exchange, and in many cases, product and project failure. It has been reported that 85 percent of technology and product costs are committed prior to detailed design when little is known about the impact of design changes [4]. The lack of knowledge and design flexibility early in the design can postpone design change decisions when it becomes more expensive and difficult to implement these changes. To compound this problem, increased product and project complexity can often lead to an increase in information and create challenges in decision-making.

There has been limited research into the integration of SE and PM. The results from one study showed that the relationship between integration, unproductive tension and organizational performance was unclear but that the use of integration tools could be beneficial in bringing these two disciplines together. At the same time, identifying the action mechanisms for enabling greater levels of integration was also found to be unclear [5]. In the same study, lack of planning, authorities not clearly defined and conflicting practices were noted as the top three sources leading to PM and SE unproductive tension, where unproductive tension is defined as any issues between PM and SE that might negatively affect performance. Unproductive tension can include lack of communication, not having a shared vision of outcomes and not valuing the different perspectives and roles of others.

In relation to the current study, planning can include early knowledge, the reduction of risks, increasing system ease-of-change for a robust design, and increasing communication and collaboration through use of a common language and platform for decision-making.

While some guiding principles and philosophical requirements for integration have been provided, the challenge remains in understanding the underlying interrelationships, hidden influences and how to put theory into practice. Moreover, it is not apparent that there has been research into a single standard, practical approach, common language or platform for this integration. With the many disparate and discipline-specific processes, models and tools, there can be confusion on what to integrate for product and project success. One approach to alleviate this confusion is to apply systems thinking, systems science and systems engineering practices for the effective integration of SE and PM methodologies and tools. Moreover, SE may be viewed as a common view and application that may be used by several different disciplines [6].

The focus of the current study is to understand the ‘big picture’ for developing an integrated PM-SE model for the effective design and management of complex physical systems. It includes consideration to the techno-socio-economic and cultural factors in complex product and project management. Using a practical integrated model, based on a real ‘non-toy’ advanced marine integrated power system (IPS) case study, can bring SE and PM disciplines together where they can game design change scenarios, gain early knowledge and ultimately reduce project costs and delays. The central themes for integration, as depicted in Figure 1.1, were identified through a literature review, author experience, surveys and interviews with industry experts.

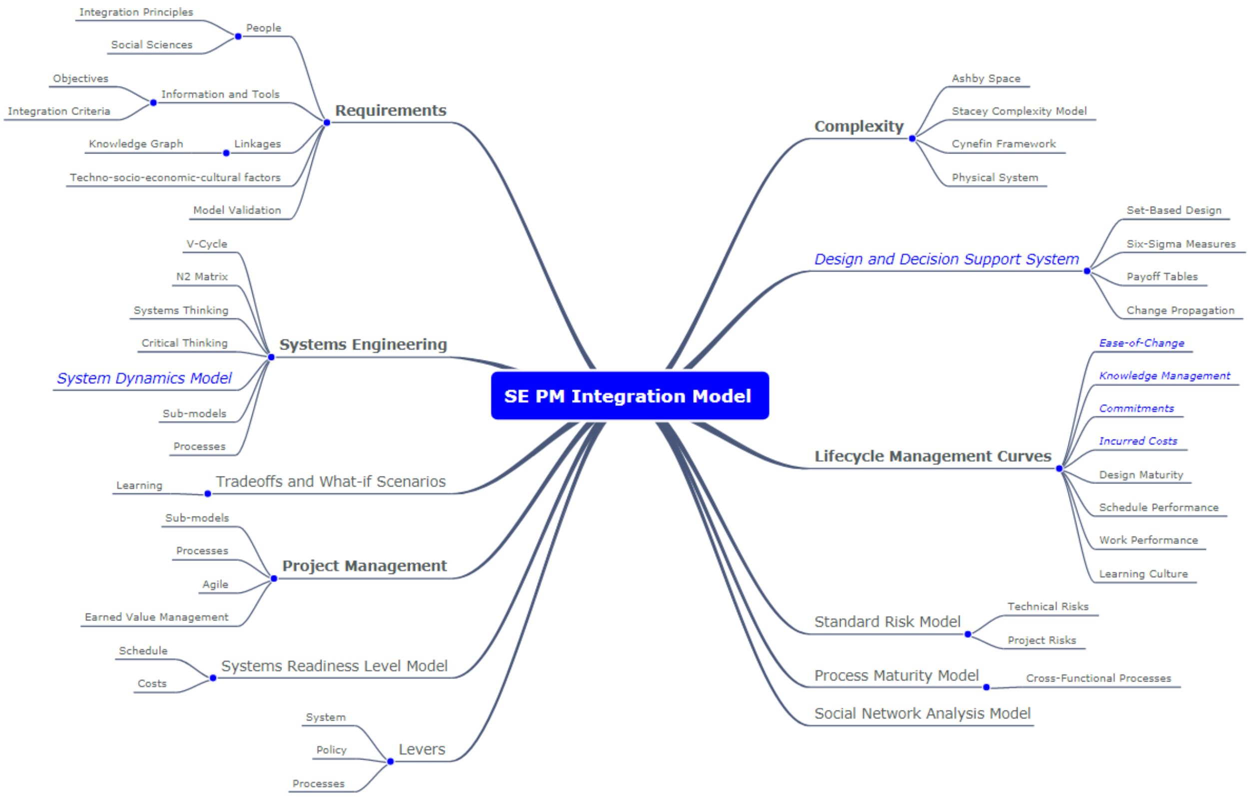


Figure 1.1. Central Themes for The Integration of SE and PM Disciplines and Models

For integrated model development, a systems thinking approach is taken that includes consideration to the SE V-cycle, requirements and attributes, techno-socio-economic and cultural factors, cross-functional processes, the complex project environment, and the different perspectives of SE and PM and the models that they use. Use of this integrated model can provide for situational awareness, learning, early knowledge for decision-making, and critical thinking. For the effective design and management of complex physical systems, a set-based goal-based design approach and aspects of agile PM are adopted.

The simulator presented in the current study provides a structured approach for multiple disciplines to address and manage product and project complexity through cross-functional processes within an interactive dynamic model environment consisting of system, process and policy levers.

As part of the simulator, the decision support system allows for trade-off and what-if analysis where six-sigma measured attributes are managed. The system dynamics sub-model provides visualization and control of design life cycle management curves as impacted by system state. System, policy and process interactive levers can be adjusted to improve the behavior of these curves. With adjustment to just a few key levers, knowledge can be gained early in design and system ease-of-change increased, leading to reduced design change costs and schedule delays.

1.2 Background

Systems engineering integrates all disciplines into a team effort and provides a structured product development process from concept design into production [7]. The typical V-cycle represents processes across the product lifecycle. This cycle can also include the models and tools used in design and in helping to bring SE and PM together for product and project success. Product success can include maintaining design integrity, design intent and quality throughout the design cycle despite changes that may occur along the way.

The need for analytical decision management tools is supported by project and product failures in the past where it has been difficult to decide what to change in product design development when everything seems to have an influence [8]. Moreover, the adoption of model-based systems to support decision-making has been sporadic where they have been applied in a piecemeal approach.

There can be several reasons for this including the lack of confidence or knowledge in the return of investment that these systems might bring. To overcome these barriers, the current study provides a practical tool to enhanced decision-making where the return in investment can be realized through technical system and program improved performance.

Bridging solutions provide for coupling of information between SE and PM through the notion of aggregate common indicators and sharing of this information through dashboards [9]. In the current study, these bridging solutions include combining well known discipline-specific models while recognizing common design variables, optimization of objectives and adherence to constraints. This includes balancing attribute performance and technological choice to provide optimal solutions in meeting design and project requirements.

One area for consideration in developing these tools is the exploration of the effects of uncertainty and quantification methods for the impact of different variables during design [10]. In the current study, the uncertainty of design changes and new technology are quantified through a decision support system (DSS) and standard risk model (SRM). Their impact is predicted through the management of design attributes, ease of changeability in components and lifecycle management curves.

As depicted in Figure 1.2, several models have been integrated in the current study to form a management flight simulator for enhanced decision making, design change management and knowledge management early in the design cycle. These models are integrated in a unique way where the emergent properties of the overall simulator provide more value than from the sum of its parts.

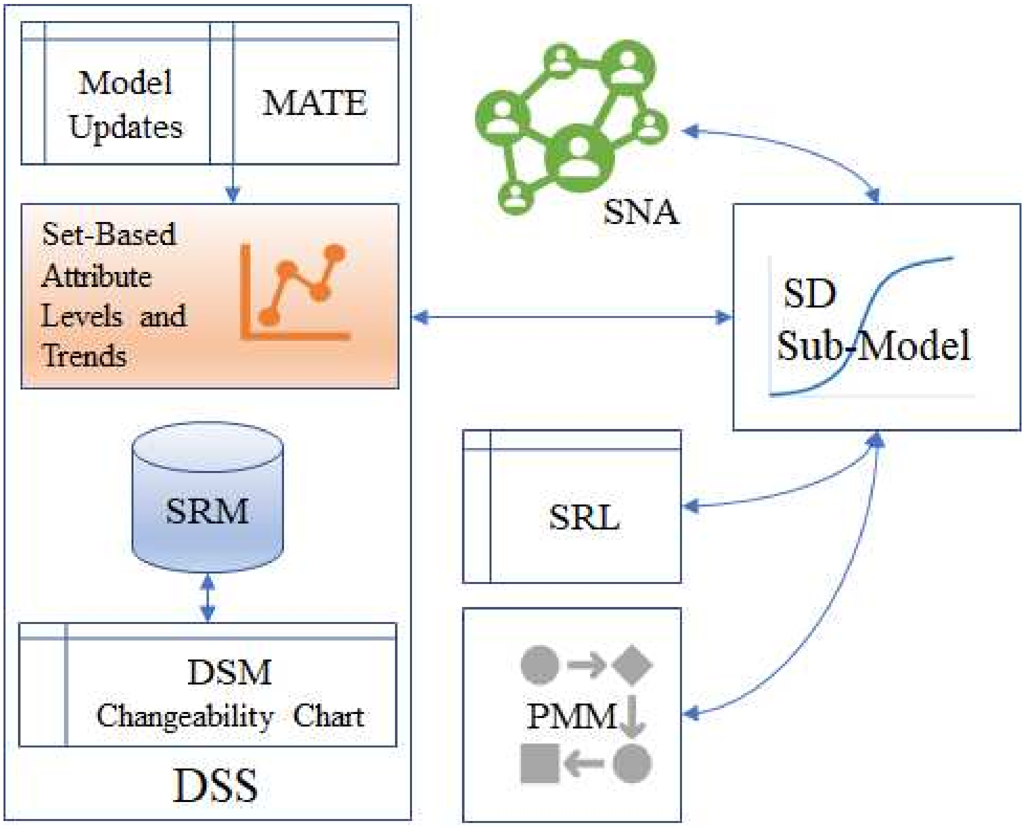


Figure 1.2. Management Flight Simulator Models

The systems engineering models considered in development of the simulator in the current study include a DSS, management of system attributes and payoffs, Multi-Attribute Tradespace Exploration (MATE), Design Structure Matrices (DSM), System Readiness Level (SRL); the program management models include the SRM which is linked to the DSM, Social Network Analysis (SNA), a Process Maturity Model (PMM), and design lifecycle management curves as represented within a System Dynamics (SD) model. Six sigma methodology and process control measures are included for visualization of patterns and trends in system attributes, as affected by design changes. Along with non-dimensional design attribute levels, six sigma measures and visual indicators provide for a common language among the different disciplines.

1.3 Case Study

The simulator in the current study is based on a future advanced IPS. The underlying physical laws for IPS system components are used to translate requirements into design performance and survivability attributes. The IPS consists of two diesel generator sets, two gas turbines, an advanced power management system, and a high-energy storage system (HESS).

1.4 Hypothesis

A practical SE-PM integrated analytical decision model by way of a management flight simulator can help maintain design integrity, design intent, promote a collaborative environment, enable better decision-making, and help assure product and program success.

As depicted in Figure 1.3, through the careful linking of models and methodologies, the Knowledge curve may be advanced in design and Ease-of-Change curve moved up, thereby reducing costs and schedule delays. This will better accommodate design changes, procurement options and technology insertion throughout the design cycle.

The Ease-of-Change curve starts at a contribution level of 100 percent and decays over the design cycle with the goal to remain slightly above zero percent. This goal is aligned with that of a robust design that continues into production and in-service. Maintaining a level above zero percent can help maintain both design intent and design integrity.

The simulator can be used to help understand state of the current system and management curves and may be used to predict new states. These four curves are considered typical lifecycle management curves [11]. This cycle includes the design stage gates of preliminary design review (PDR) and critical design review (CDR).

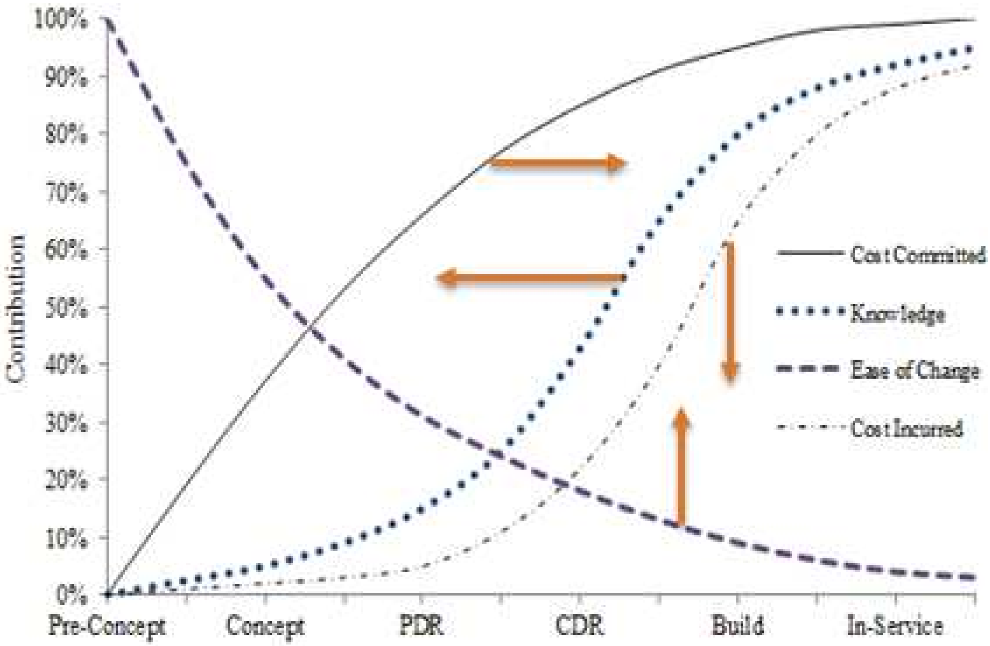


Figure 1.3. Influencing Design Lifecycle Management Curves. Adapted from [11]

1.5 Research Goals

In developing the management flight simulator for PM-SE integration, with a set-based design and agile management approach for using it, there are several research goals.

- An integration strategy for developing a PM-SE integration framework and model
- With use of the model, a decision support and response strategy for adapting to complexity and design changes
- Functional prototype based on a real 'non-toy' complex system
- Verification and validation of approach and integrated model
- Demonstrate benefits and return-on-investment from using the model

1.6 Research Questions

In order to achieve these goals, research questions can help form the methodology taken in the current study. These questions surround how an integrated model and the approach in using it can bring PM and SE disciplines together for product and project success.

- What are the requirements, supporting theories, key processes and elements for a SE-PM integrated framework?
- How can early knowledge, design analysis and risk reduction be achieved?
- How can the model improve collaboration, communication and decision-making?
- How can the model help in adapting to complexity and design changes?
- What is a good 'non-toy' complex problem (case-study) for testing the model?
- How can the model and approach in using it be verified and validated?
- How can stability of the model be validated?
- Why have previous attempts failed at implementing integrated models?
- What can be the benefits and return on investment from using the model?

1.7 Motivation for Research

Several warship design-build programs have incurred significant cost overruns and schedule slippage, with causes linked to underestimating risks, complexity and challenges with advancing new technology [12] [13]. With increased complexity comes increased information with the need for increased effort in the integration of systems, processes, models and SE and PM disciplines.

Several studies reveal that only 16 percent of organizations are fully integrated and that over 60 percent of complex projects fail in terms of cost overruns and delays. It has been also stated that organizational and project dynamics have not been understood until it is too late [5]. The field of systems dynamics can help in understanding the social and project dynamics within an organization. In the current study, use of a SD model can help to describe and understand these dynamic interrelationships.

According to the U.S. Government Accountability Office (GAO), half of defense acquisition programs experience cost overruns with the causes attributed to budget pressure, schedule pressure and changing requirements [14]. Design change management is viewed as a key process in the current study. Set-based attribute and component changeability measures are used within the simulator for enhancing design change management.

With product and project failures, the lack of a practical analytical decision support model to bring PM-SE disciplines together and the challenges in design change management of complex systems, the motivation of the current study is to advance the field of PM-SE integration, decision management and to present a management flight simulator for product and project success.

With increased globalization, more decentralized teams and government initiatives in data analytics and visualization, there is an opportunity to develop and exploit the simulator in the current study.

1.8 Methodology

The research hypothesis, goals, questions and motivation provide the provenance and vector for development of the management flight simulator and how it might be used for PM-SE integration, product and project success. In developing the framework for the simulator, several supporting theories and laws are discussed and leveraged in the current study.

Key supporting theories include Decision Theory, Game Theory and the Theory of Knowledge or epistemology. Related laws include Revan's Law of Action Learning, Ashby's Law of Requisite Variety and Jaque's Law of Cognitive Capacity.

The methodology in the current study follows the scientific process steps of research, hypothesis, iterative experimentation of candidate models for integration, analysis of results and validation of the hypothesis and simulator. This research includes a reductionist, systems engineering and systems thinking approach where individual candidate parts for the simulator are decomposed, analyzed and reassembled in a new and different way that provides more value than from the sum of its parts.

An integration strategy by way of pillars is developed and introduced. The governance and response strategy for using the simulator is also presented. This strategy includes the transition from data and measures, to information and patterns for decision-making and finally to a simulator that provides knowledge and new insights.

With a functioning prototype, the simulator and the approach in using it are verified and validated through a literature review, interviews and surveys with industry.

1.9 Chapter Breakdown

The methodology is reflected in the chapter breakdown in the current study. These chapters address the central themes and requirements for the integration of SE and PM disciplines and development of the simulator.

Chapter 1 provides the introduction, background, hypothesis and motivation for the current study.

Chapter 2 begins with the MATE model and how it might be modified to exploit a new value space including a hierarchy of system performance, survivability and mission capability attributes. The IPS case study is investigated and applied to the modified MATE model, which is leveraged as a reference model in the simulator and brought forward into the design cycle. The value of commercial plant models for updating and validating design attributes is investigated. Homer Pro® software is used to validate component sizing, design variants and their attributes within the MATE model. The Analytical Hierarchy Process (AHP), Multi-

Attribute Utility (MAU) and Quality Functional Deployment (QFD) methods are discussed in this chapter.

Chapter 3 builds on design attribute management and introduces a preliminary DSS framework that is focused on technical measures. This framework includes exploratory linkages between models where they make sense. This includes a unique and novel linkage between the SRM, DSM, system change propagation trees, and a component changeability dynamic chart. For attribute management, six sigma process variability metrics are applied in a different way to measure system attribute levels and trends. The SRL model is adapted to the simulator as it affects program schedule and costs. For decision-making and tradeoff solutions, payoff tables include costs, schedule and the performance of several design attributes. Bayes' decision theory is discussed in this chapter as it relates to the expanded payoff tables proposed in the current study. Prospect Theory and shifting-the-burden concepts are also discussed in this chapter where the value of the DSS is highlighted in addressing challenges in the decision-making process. Typical design changes that may occur for the IPS are investigated through a literature review and interviews with industry.

Chapter 4 addresses the social, cultural and human factors involved in decision-making and how these factors might be addressed using the simulator. Game Theory, Theory of Mind, Theory of Knowledge, Learning Theory, Revan's Law of Action Learning, and Social Network Analysis (SNA) are investigated in this chapter.

Chapter 5 discusses the design change process and information flow in the context of integrating models and teams. This chapter introduces the concept of linking transformational variables across platforms for information flow. MacLeamy Design Process curves are introduced as they relate to early knowledge, design analysis and a robust design. This chapter presents a strategy and governance structure to respond to design changes and new technology insertion. This structure includes the monitoring and management of design attributes in adapting to changes and new technology. Set-based design is introduced as an approach to manage these attributes. The related Theory of Constraints (TOC) and Theory of Inventive Problem Solving (TRIZ) are discussed. This chapter includes results from a survey with industry on the adequacy of existing design change processes and information flow.

Chapter 6 builds on decision-making and information flow by reviewing cross-functional processes that are relevant to development of the simulator. This includes an investigation into potential policy and process improvement levers. The process maturity model (PMM) is leveraged and brought into the simulator model. An integrated approach is followed in coupling the strategy and risk management processes for resolving change problems. In terms of information flow, the communication, integration and supply-VFI management processes are reviewed.

Chapter 7 investigates an integration strategy for a framework of integrated PM and SE models and processes. This includes taking a systems thinking, systems science and SE approach to this integration. Aspects of Control Theory are discussed in helping to understand the PM-SE integration phenomenon and how the management flight simulator can help. The linkages between simulator sub-models are presented by way of a digital thread or knowledge graph of transformational variables. The simulator is discussed in its ability to adapt to complexity. Supporting laws include Ashby's Law of Requisite Variety and Jaque's Law of Cognitive Capacity.

Chapter 8 presents causal loop diagrams (CLD) of the processes, entities and influencing factors consider in development of the simulator. This provides a foundation for the development of key management curves within the simulator. The SD model and its sub-models are presented along with the policy and process levers.

Chapter 9 provides simulator results from the application of three different design change scenarios. The simulator is verified in meeting integration requirements and validated in terms of its structure and behavior. This includes validation of the hypothesis in the current study.

Additional validation results are presented from a demonstration of the simulator and an accompanying survey at the INCOSE IW2020 model-based systems engineering (MBSE) workshop. Benefits and the return on investment from using the simulator are presented.

Chapter 10 provides a perspective on model-based systems engineering (MBSE) and how the management flight simulator might be connected to both MBSE software systems as well as with the larger enterprise system. As part of both a systems engineering and MBSE approach, integration requirements are mapped to management flight simulator high-level entities.

Chapter 11 provides conclusions, limitations of the current work and discusses potential future work.

Chapter 12 provides reflections on the current study including any excluded integration requirements, management curve behavior and potential application of the simulator in industry.

1.10 Publications

Over the course of the current research, the following papers were published:

Jonkers R., and Shahroudi K.E., "A Design Change, Knowledge And Project Management Flight Simulator for Product and Project Success", *IEEE Systems Journal*, July 21, 2020.
https://ieeexplore.ieee.org/document/9145681

Jonkers R., and Shahroudi K.E., "Systems Thinking, Complexity and an Integrated SE-PM Model", Paper, *INCOSE IS 2020 Conference*, publication in process, July 21, 2020.
https://www.incose.org/symp2020/symposium/event-schedule

Jonkers R., and Shahroudi K.E., “Reducing the Costs of Engineering Design Changes Through Adoption of a Decision Support and Knowledge Management System Early in the Design”, Paper, *IEEE International Systems Conference (SysCon),* April 9, 2019.
https://ieeexplore.ieee.org/document/8836740

Jonkers R., and Shahroudi K.E., “Integration of Multi-Discipline Attributes For Decision Making in Design of a Future Marine Integrated Power System”, Paper, *IEEE International Conference on Systems, Man and Cybernetics (SMC)*, October 6, 2017.
https://ieeexplore.ieee.org/document/8122788

Jonkers R., and Shahroudi K.E., “Bridging the Gap Across Program Management, Systems Engineering and Plant Modeling”, Paper, *IEEE International Systems Conference (SysCon)*, April 21, 2017.
https://ieeexplore.ieee.org/document/7934781

Chapter 2 – A New Value Space in MATE and an IPS Design Case Study

2.1 Introduction

The tools and techniques proposed in the current research are investigated through a case study based on a notional marine IPS design. Selecting an appropriate IPS architecture that is complex and relevant is important in supporting validation of the models and simulator presented in the current study. The central theme of maintaining an optimal design throughout the design cycle starts with selection of an optimal baseline design.

The concepts and results in this chapter are based on a literature review, modification and application of the MATE model. The main result is a modified MATE model and process that provides for a new and more comprehensive value space, one that can be used by both PM and SE disciplines to assess design changes and improve system design throughout the design life cycle. The standard MATE model was expanded upon to include a distinct survivability attribute, as well as, mission capability, environmental, safety, and the program risk attributes of Relative Schedule Slippage (RSS), Technology Readiness Level (TRL) and System Readiness Level (SRL). Survivability is viewed as an important and distinct attribute for military systems, as investigated in other work [15].

The modified MATE model is considered a living reference model that may be used and updated throughout the product design life cycle. Adoption of this model requires thorough upfront work to a reasonable level of fidelity that can be refined and updated later in the design life cycle.

Interest in IPS has increased in recent years as an approach to improve plant efficiency, reliability and to meet future electrical loads. While marine propulsion electrical loads have accounted for most of the power required, the power associated with future weapon systems are expected to outweigh propulsion requirements.

Based on extensive research, it is not apparent that there is a standard IPS architecture for current modern naval ships. The drivers for a diverse range of IPS architectures may be found within the different disciplines of plant modeling, systems engineering, and program management.

Advances in technology have made the IPS a realistic option but with it comes a complex, information intensive system that is best managed using a multi-discipline management approach.

2.2 Motivation

Ship design can be an ad hoc process where the design is assessed by experience, rules-of-thumb, and preference. Furthermore, objective attributes are not properly synthesized or presented to support decision-making [16].

The motivation for modifying and expanding the MATE value space is to help align multiple disciplines on a platform of common capability-based outcome measures, with enhanced information and visualization of attribute levels and variances throughout the product design lifecycle.

Project management methods have been investigated as to their applicability within systems engineering, leading to different perspectives of separate or shared project-product domains [17]. Leveraging methods from other disciplines to provide a more holistic view to product development and lifecycle management have been investigated in the past but it is not readily apparent that there has been extensive research into a common language and platform.

2.3 Objectives and Related Research Questions

In the current chapter, what a suitable system case study might look like is investigated through several IPS architectures. The objective is to select an architecture that is complex enough to validate proposed models for integration. Determining the framework for these models starts with investigating the pre-design conceptual MATE model.

The exercise of going through the steps in selecting an optimal baseline design provides an appreciation of the SE models and tools used as well as how key variables and attributes are selected that may in turn be monitored and managed during the design cycle.

In developing the simulator in the current study, evaluative models are combined in a unique way to provide a new and holistic value space for PM and SE disciplines. Investigating the MATE model is a logical first step as part of the design cycle in working toward a new value space.

2.4 Background

In this chapter, the Model-Based Systems Engineering (MBSE) diagrams and IPS attributes of interest are investigated for developing the modified MATE model. Establishing these attributes provides a basis to develop the simulator in the current study and validate its ability to maintain design integrity and design intent in the face of design changes and technology insertion.

Typically, the MATE model is discarded after concept design with selection of an optimal baseline design. However, the MATE model, its design variants and associated attribute values can be of value later in the design cycle when changes to components are made.

2.4.1 *Describing System Architectures*

The IPS architecture in this case study is described using the System Modeling Language

(SysML) profile of the Unified Modeling Language (UML). Diagrams are exported from a model built in the IBM Rational Rhapsody Architect for System Engineers™ tool. As depicted in Figure 2.1, this tool provides for various stakeholder views and diagrams that are suitable to both systems engineers and program management early in the design. Internal and behavior diagrams provide additional detail that is more suitable to the systems engineer and key stakeholders during detailed design. The value of MBSE in the current study is seen in its simplicity and ability to describe the system to multiple stakeholders.

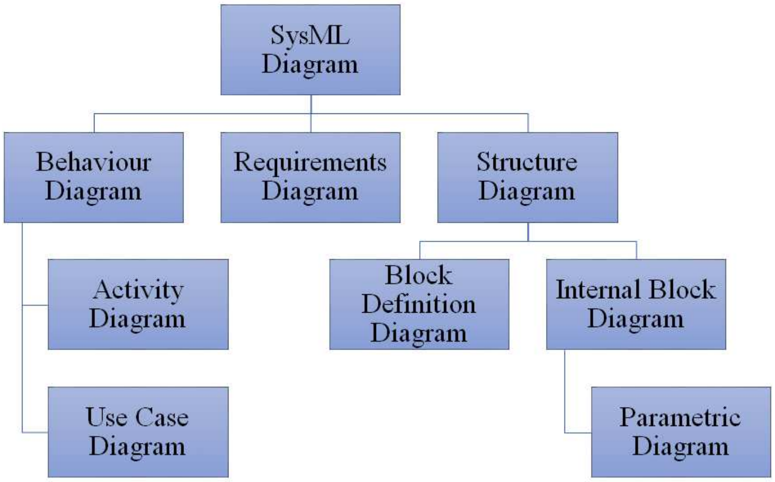


Figure 2.1. SysML Model-Based Systems Engineering Diagrams. Adapted from [18]

MBSE system architecting is useful for developing, describing and understanding the architecture and requirements of the system. Both functional and non-functional requirements are linked to system components and flowed down to related sub-system components. For instance, some requirements such as weight may be apportioned to sub-components while other performance type system requirements are derivatives of the sub-systems.

MBSE is a best practice increasingly used by defense departments and NASA to better understand operational needs and requirements [18].

However, the MBSE architect tool for the current study has limited capabilities in analytics and the linking of several models; emphasis will be placed on other methods to link models to achieve the necessary analytics for decision-making.

Both MBSE architecting and the path taken toward a management flight simulator in the current study may be viewed as complimentary. Development of attribute management within the simulator involves decomposing the case study requirements listed in Appendix A and translating them into key variables and attributes using quality functional decomposition (QFD). In this way, requirements are inherently linked to attributes where a deficient attribute level can indicate risk with a related requirement not being satisfied. Both the approach taken in the current study and MBSE architecting are depicted in Figure 2.2.

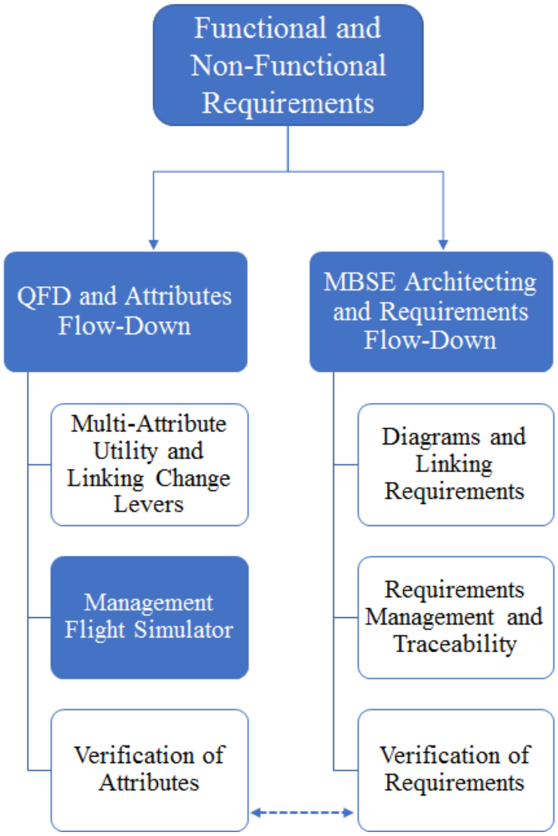


Figure 2.2. Flow-Down of Requirements in The Current Study Versus MBSE

2.4.2 *Multi-Attribute TradeSpace Exploration*

MATE may be defined as quantitatively exploring the relationships within a multivariable design space to identify feasible alternatives that satisfy system objectives and attributes, typically in support of designing, selecting, or optimizing a system. MATE is a conceptual design methodology that applies decision theory to model and simulation-based design [18].

For complex systems such as an IPS, system objectives and requirements can often conflict where difficult tradeoff decisions are required. The preference requirements are often traded off to find the preferred alternatives that still satisfy the mandatory requirements. Within the design variables and attributes, ranges from acceptable to desired are assigned.

Stakeholder salience defines the degree to which the stakeholders give priority to competing criteria variables in their decision-making process. In a tradeoff study, stakeholder salience affects the weighting of objectives and attributes. In this study, the Analytical Hierarchy Process (AHP) approach is adopted for assigning weights to attributes.

The overall approach for MATE follows a design-value loop perspective for decision making using evaluative and value models, as depicted in Figure 2.3.

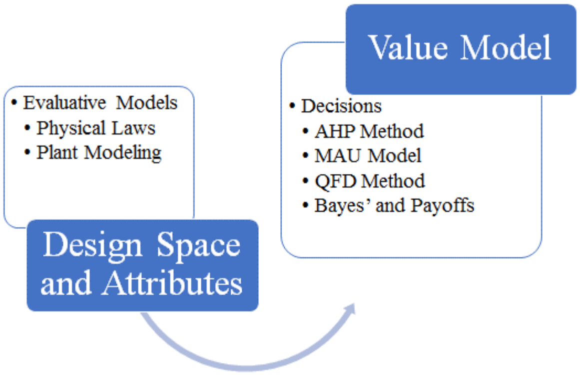


Figure 2.3. Design Value Loop Perspective. Adapted from [18]

The design space consists of feasible alternative solutions to the design problem, consisting of different architectures and designs, as depicted in Figure 2.4.

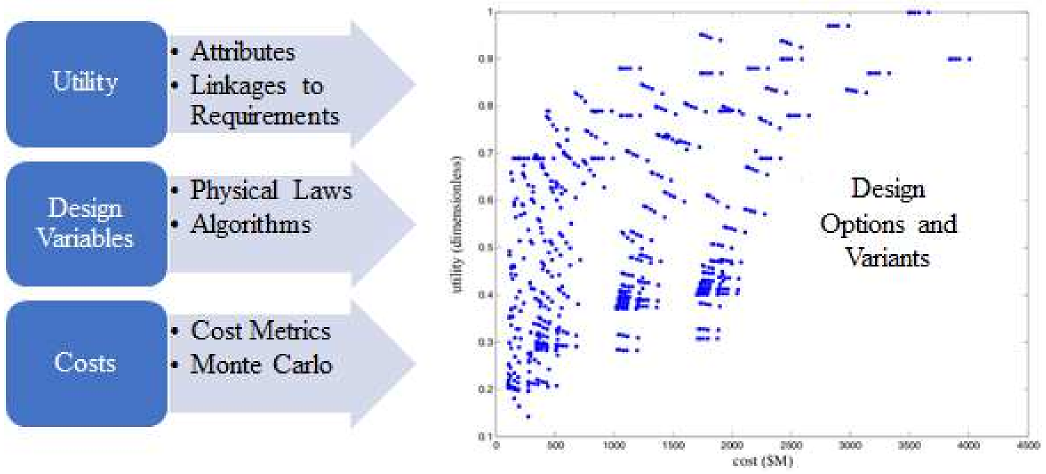


Figure 2.4. Design Value Tradespace. Adapted from [18]

Cost models evaluate potential designs in terms of the resources such as costs for the design and product lifecycle. On the other hand, performance models evaluate potential designs in terms of capabilities or performance that they provide to achieve goals and objectives. These are usually related to the behavior of the design, such as speed, range and responsiveness of a system. Value models assign scores to potential designs in terms of benefits or utility.

In general, mapping attribute levels to degree of satisfaction has been called a value function [18]. The utility of a value function considers the degree of satisfaction for an attribute level and is typically rated from acceptable (0) to desirable (1) in its benefits, as depicted in Figure 2.5.

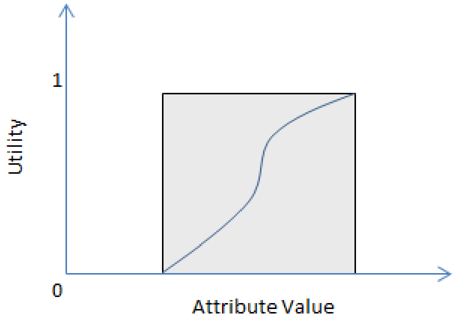


Figure 2.5. Single Utility Attribute Function [18]

Multi-attribute approaches are used when there is more than one attribute that determines value. Various multi-attribute methods of quantifying and comparing attribute values are available; the current study adopts the Quality Functional Decomposition QFD-like method, Multi-Attribute Utility (MAU) method, and the Analytical Hierarchy Process (AHP).

In the QFD-like method, the contributions of design variables are scored against relevant attributes using a scale with four values: 0 (none), 1 (weak), 3 (moderate), and 9 (strong). Design variables and attributes are then rationalized for the design problem. The attribute weightings can be determined through user preferences using AHP and pair-wise comparison.

This QFD process includes prioritizing the essential and preferred requirements, variables and attributes for the design. With a succinct set of attributes, complexity is simplified for further decision-making using other tools and models.

2.4.3 *Factorial Experiments and Response Surface Methodology*

Design of Experiments (DOE) is the simultaneous study of several process variables and is known to be more efficient than conducting trials or experiments testing one variable at a time. It also considers the interaction of independent variables as they affect the output variable. Factorial experiments are used in situations where there are several ambiguous factors affecting a process [19]. Such experiments are traditionally used for process improvement in the chemical industry where input variables are optimized to provide maximum yield.

This method is investigated in the current study for the visualization and optimization of design and capability attributes using three-dimensional Response Surface Methodology (RSM).

2.5 Modified MATE and Additional Attributes of Interest

In the current study, additional value elements are proposed that are not only applicable to naval ship systems but to systems in general. Based on previous work [15], the attribute of survivability is viewed as distinct and separate from the performance attribute and forms part of the value space. Also, platform missions and operational capabilities are viewed as high-level attributes and shared stakeholder outcomes that form part of the overall Multi-Attribute Utility (MAU) for the system.

As safety and environmental attributes form part of many engineering system requirements, these attributes are proposed within the MATE model. As well, the concept of linking multi-discipline attributes is extended for plant modeling and program management attributes, as depicted in Figure 2.6.

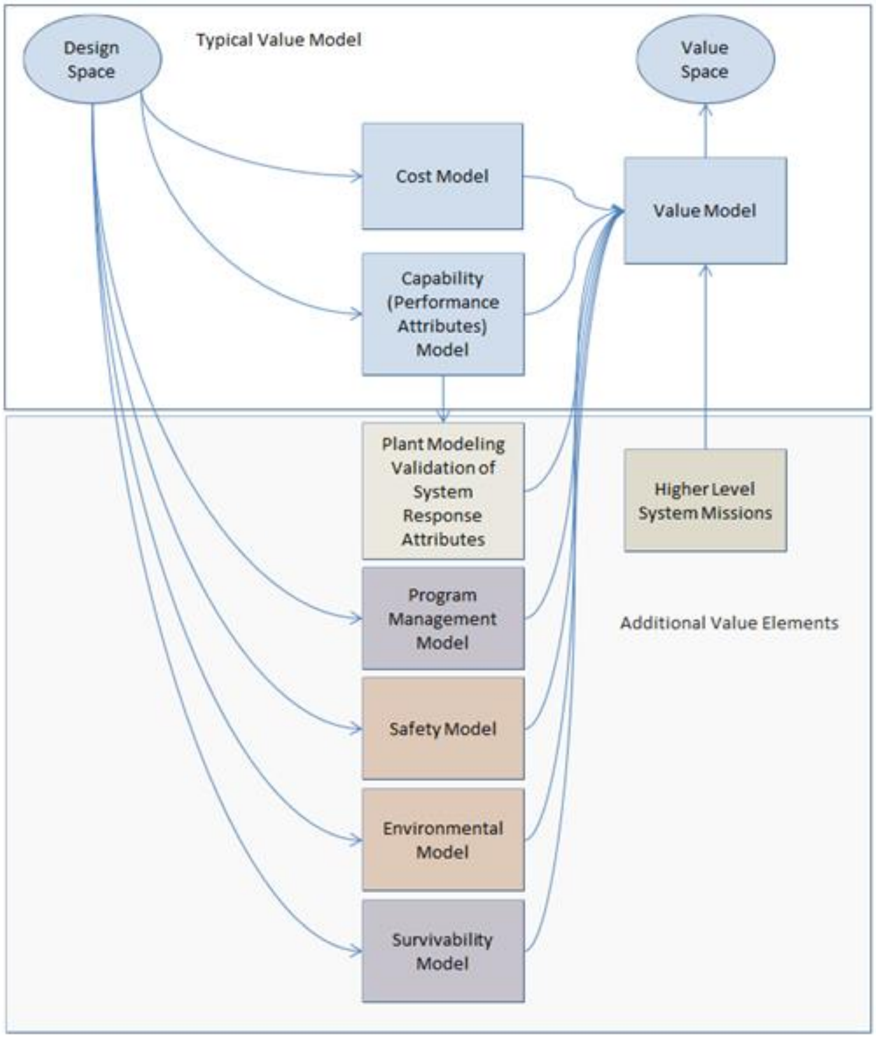


Figure 2.6. Modified Value Model

Evaluative models take design variables as input and predict performance and cost, as depicted in Figure 2.7. The Pareto Front represents the set of non-dominated designs across objectives (typically cost and value metrics) and are considered the best solutions in the tradespace.

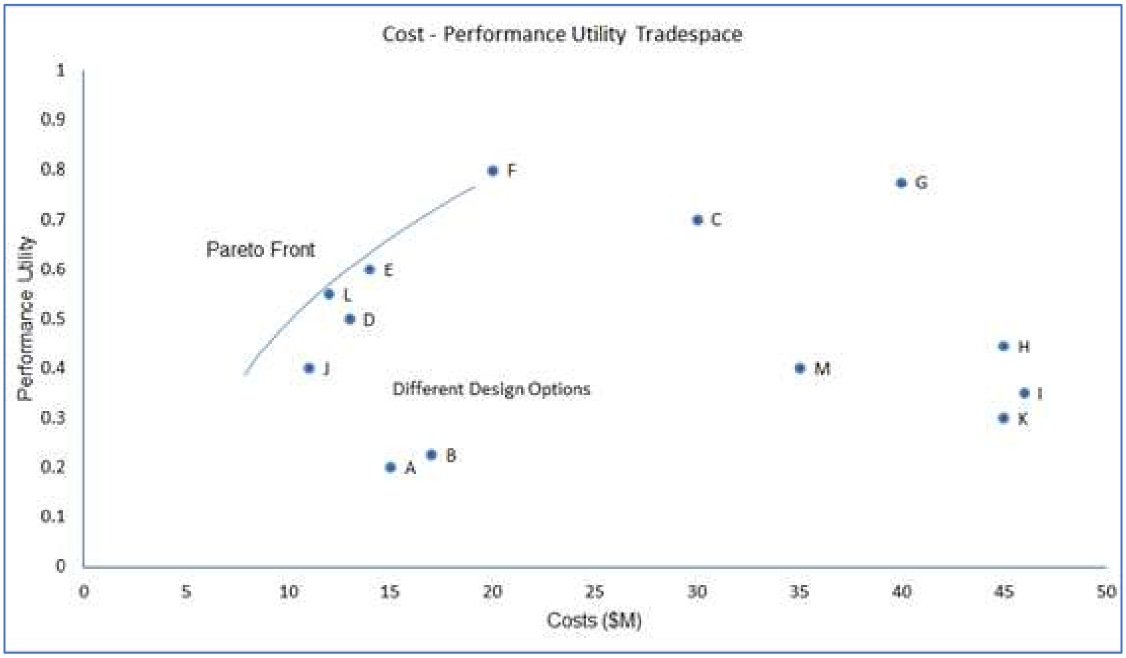


Figure 2.7. Performance Utility and Costs Tradespace

There are several approaches to navigating the tradespace for optimal designs while respecting the balance of utility and costs. These approaches include analyzing design options on and near the pareto front as well as considering iso-bars for bands of cost and utility within the tradespace [18].

When considering systems that are susceptible and vulnerable to damage or disturbances in the environment, the distinct capability of survivability is of value in developing the tradespace. In achieving survivability through design, the standards for naval ships and their systems range from commercial to more stringent classification society Naval Vessel Rules (NVR). This generally corresponds to increased costs where adoption of NVR entails additional compartmentalization, fire zones, damage control systems, increased separation of systems and equipment, increased redundancy, shock hardening, and signature reduction. This in turn leads to increased complexity, costs, and additional survivability design variables that are explored in the current study.

The aspect of increased safety to personnel and equipment for naval ships, as well as increased environmental stewardship leads to consideration of two additional attributes. These attributes consist of a system safety attribute and the Energy Efficiency Design Index (EEDI).

For naval ships, under the North Atlantic Treaty Organization (NATO), the Naval Ship Code (NSC) is based on International Maritime Organization (IMO) conventions and resolutions [20]. The NSC is a goal-based approach that provides a framework for the design, construction and maintenance of naval ships. The philosophy behind the NSC is based on the management of safety risks.

The environmental attribute, EEDI, is applicable to new ship commercial design and while naval ships are currently exempt from this regulatory measure, it is of interest to this case study as opportunities exist to incorporate new technologies including energy storage system technology.

The EEDI is an index that indicates the energy efficiency of a ship in terms of gCO_2 (generated) / *tonne-mile* (cargo carried), as represented by Equation 2-1. The intention of imposing EEDI limits is to drive ship technologies to more energy efficient ones over time [21].

$$EEDI = \frac{Engine\ Power * SFC * C_F}{DWT * Speed} \left(\frac{gCO_2}{tonne-mile}\right) \tag{2.1}$$

where SFC is the specific fuel consumption, C_F is a carbon factor for the fuel consumed, and DWT is the dead weight or lightship of the vessel.

The basic concept behind this measure is a baseline reference EEDI as a function of ship size, the attained EEDI, a reduction factor for EEDI as mandated for future years, and implementation of EEDI in phases. Ship designers are free to choose the technologies to satisfy the EEDI requirements in a specific ship design.

The lower the EEDI; the more efficient the ship is from an environmental perspective. As EEDI is proportional to power required, the preference would be to reduce the power required through investigating alternative designs. With the objectives to reduce fuel consumption, lower CO_2, and reduce exhaust infrared signature, alternative designs include prime movers with Waste Heat Recovery (WHR) options. For large power demands greater than 25 MW, the steam turbine and generator WHR system is preferred where fuel savings of six percent and CO_2 reductions of eight percent can be achieved [22].

The components of the EEDI formula relate to system components, design concepts and variables, and may be used in the MATE construct for evaluating design alternatives. In terms of a future IPS design, the requirement for high energy storage systems for advanced weapon loads provides the opportunity to achieve improved energy efficiency in power generation.

Future weapon needs include high energy pulse weapons such as rail guns and lasers, these provide an opportunity to incorporate HESS into IPS designs. Moreover, rail gun non-explosive ammunition provides for safe stowage and a reduced environmental footprint in disposal.

In seeking system environmental performance and affordability, options for system components and architectures are considered in developing the design variables as part of the MATE process in the current study. For instance, Distributed Electrical Zones (ZED), prime movers with WHR, and HESS options form part of the overall IPS design vector.

The mission profiles for a ship require different levels of capability that may be captured as high-level MATE attributes, where the sub-attributes aggregate up into these capability measures.

2.6 IPS Assumptions

The future IPS will require advanced technology to ensure naval ships remain effective; the following assumptions are made in moving toward this goal:

i. propulsion and high energy weapons will require HESS with the IPS;
ii. the power required for these weapons will be pulse-type loads of short duration, exceeding the available power from generator sets; and
iii. there is a need to integrate future IPS performance, energy efficiency, survivability and program risks into the total ship design.

2.7 IPS Requirements

IPS provides advantages over traditional separate electrical and propulsion systems in terms of space utilization, fuel savings, and a common energy architecture. IPS lends itself to power management systems (PMS) for efficiency, prolonged survivability, and in the case of a pulsed high-power weapon system, an enhanced Anti-Surface Warfare (ASuW) capability.

The PMS has advantages in sustaining vital power loads, shifting power distribution between generators, reducing propulsion loads when needed, switching feeders, and in the current case study managing HESS. HESS options can include electro-mechanical flywheels, ultracapacitors, and batteries. The emerging technology of ultracapacitors is providing a viable option for high energy storage and surge capability.

The naval ship is different in its operations compared to commercial ships, in that, a naval ship IPS is subjected to continuous and various discrete events that test the system’s ability to satisfactorily respond. Continuous events include fluctuations in load demands, transient loads from wave-propeller action, and harmonics. Discrete events include unannounced tripping of breakers and generators or battle damage to equipment that can cause blackouts. Other discrete events include large load demand swings as is the case with weapon pulse load demands.

Naval ships must meet the requirements of speed, endurance, ancillary and auxiliary services, weapon loads, and allow a margin for future expansion. Consideration to new mission weapon power loads in design can contribute to an affordability gap due to increased vessel size, increased power generation, and costs.

IPS architectures and designs are varied across modern naval platforms due to competing stakeholder requirements and attributes. The current study provides a framework to capture the requirements and attributes considered important by the various stakeholders.

The high-level functional non-functional requirements for the notional IPS are listed in Appendix A. Several of these requirements are governed by naval and ship classification standards. The author has validated these requirements for the purposes of developing a functional management flight simulator in the current study. These requirements may be validated through review by naval electrical subject matter experts and industry liaison.

2.8 IPS Architectures

Based on a literature review, three different IPS configurations exist, namely conventional, ZED, and a conceptual future hybrid IPS with energy storage. The future IPS with HESS will be the focus of the current study.

2.8.1 *Conventional IPS Architecture*

The conventional IPS consists of several generator sets supplying a linked series of switchboards that provide both propulsion and ship service power. This conventional IPS architecture has been implemented on U.K defense vessels Albion Class Landing Platform Deck

(LPD) and Type 45 destroyers [23] [24]. Service loads are typically supplied by a set of longitudinal cables throughout the ship. Figure 2.8 provides a simplified conventional IPS architecture.

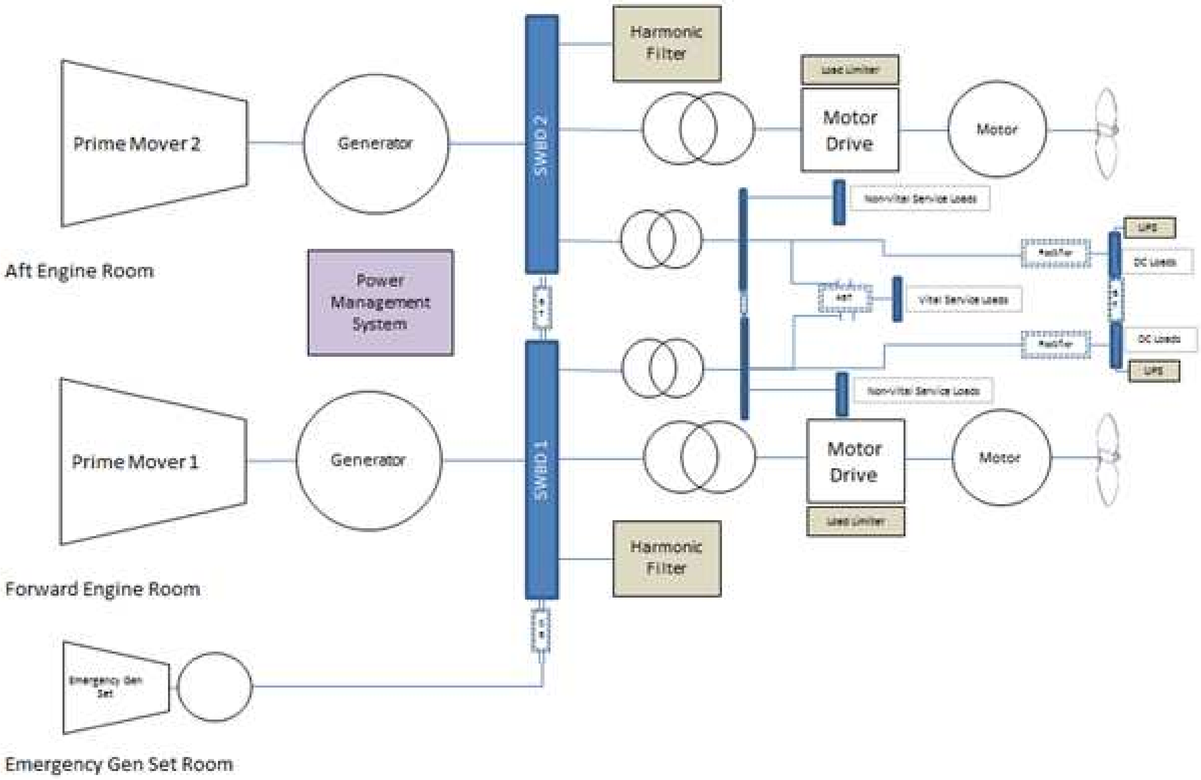


Figure 2.8. Conventional IPS Architecture

2.8.2 *Zonal Electrical Distribution IPS Architecture*

The ZED IPS also consists of several generator sets supplying a linked series of switchboards that provide both propulsion and ship service power. The difference with this architecture is that it utilizes a zonal approach with a direct current (DC) and/or alternating current (AC) distribution system that distributes power to various loads within ship zones [25] [26]. This approach prevents faults from impacting multiple zones by isolating the affected zone. Vital loads are supplied with redundant sources within the same zone and are arranged for automatic bus transfer between the sources. The ZED IPS is a relatively new field under consideration by the U.S Navy, Figure 2.9 provides a simplified ZED IPS arrangement.

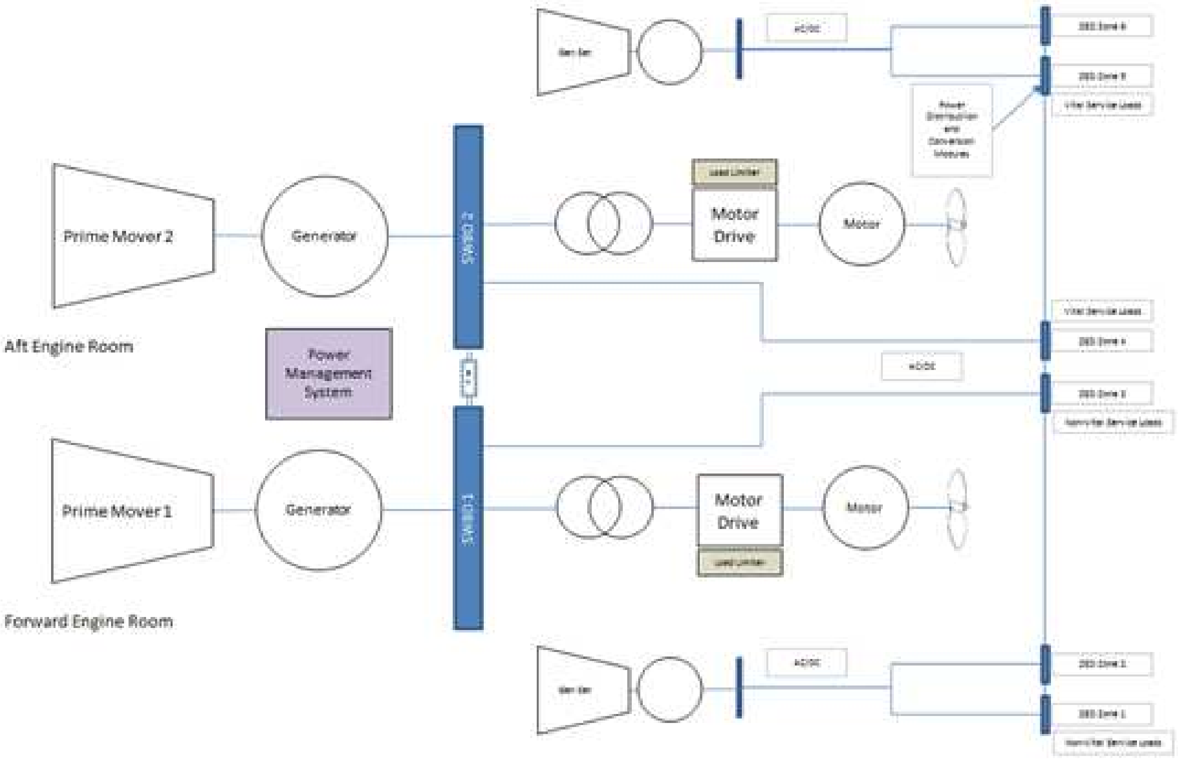


Figure 2.9. Zonal Electrical Distribution IPS Architecture

2.8.3 *Future Advanced IPS Architecture With High Energy Storage System*

One of the key benefits of IPS architectures is their ability to share generated power among a variety of loads while allowing prime movers to operate near peak efficiency.

The reduced number of engines, increased integration, flexibility in layout, advances in electronics and control technology make IPS an attractive option for future marine power systems. However, the introduction of a high-energy weapon system will require a different electrical plant option, one that may include an advanced HESS.

The notional future IPS with HESS architecture is depicted in Figure 2.10. Of note, the ZED option can be incorporated into this architecture and considered as a design principle for enhancing survivability.

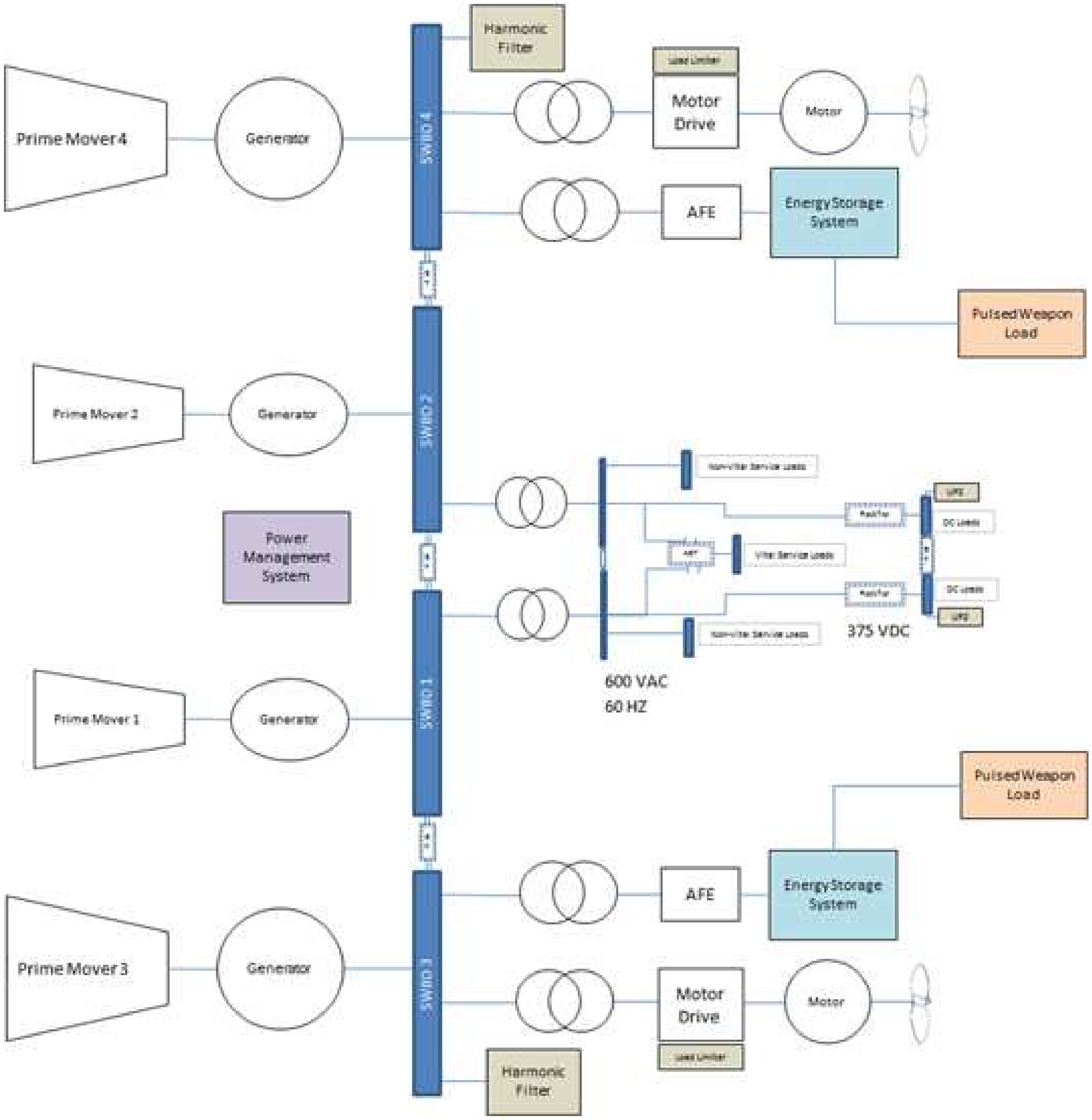


Figure 2.10. Future Advanced IPS Architecture With Energy Storage System

2.9 Future IPS MBSE Architecture Description

MBSE provides for a simple description of the IPS-HESS architecture that can be understood by the various stakeholders. The high-level structural Block Definition Diagram (BDD) of the notional IPS-HESS is depicted in Figure 2.11. The BDD can be decomposed into more detailed diagrams with standard fields for defining attributes, operations, functions, and system data.

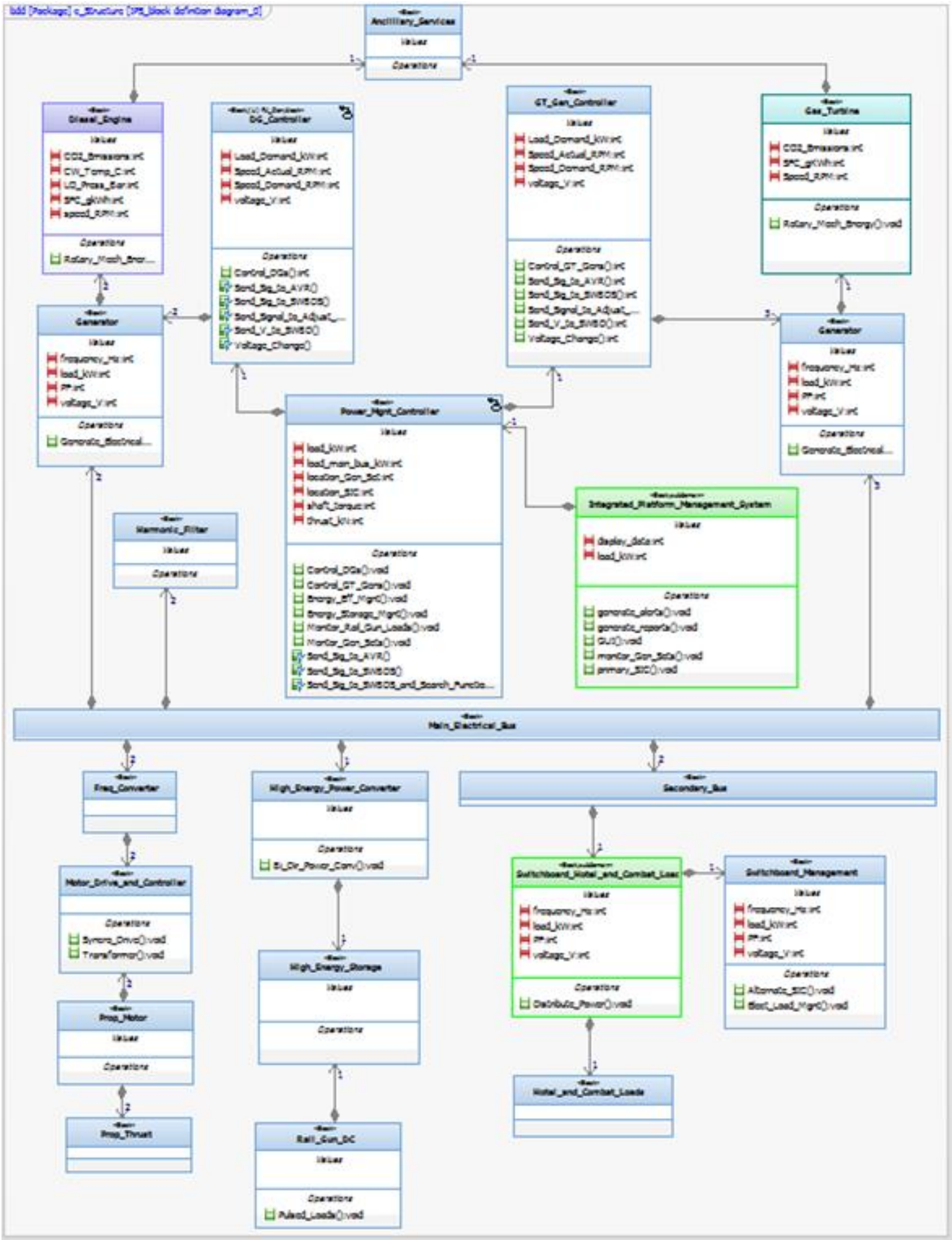


Figure 2.11. Future Advanced IPS Architecture Block Definition Diagram

2.10 IPS Use Cases and Scenarios

As noted in ABS Rules for Naval Vessels [27], the military IPS must support more operational scenarios compared to commercial vessel systems and must be designed with more flexibility to allow for many types of loading scenarios, including both fault and disturbance scenarios. The use cases for the IPS are of interest in developing system attributes such as survivability and in meeting associated IPS functional requirements .

2.10.1 *Normal IPS Operation Optimization*

Normal IPS operation consists of a closed electrical grid, fed from an optimum number of generator sets including a high-energy storage system. The ship is expected to be at normal peacetime cruising, 15 knots (24 MW), with hotel loads up to 5 MW and potential weapon loads from 1 to 7 MW [28]. With progressive loading of the generator sets, the objectives of reduced specific fuel consumption and emissions are of interest.

For transient loads under normal operation, the parameters of voltage, frequency, Total Harmonic Distortion (THD), response time, and settling time can be monitored and analyzed.

2.10.2 *Combat Battle I Operation With Transient Loads*

In high threat areas, the typical naval ship electrical plant configuration consists of open main grid bus ties between main switchboards, each supplied by dedicated generator sets.

In this battle state, transient loads are expected from changing ship speed (0-30 knots), conventional weapon loads (1-10 MW), and pulse loads from a high-energy laser weapon or rail gun (160-320 MJ) [29]. Providing power to advanced high energy weapons may require reducing the ship's speed dependent on available spare generating capacity.

2.10.3 *Load Dependent Starting and Sequencing of Generator Sets*

With traditional marine power systems, a load of 80 percent on the running generator set will trigger the starting of a designated alternate generator set. Should a fault interruption lead to a blackout condition, time is required to bring up and synchronize online an alternate generator set. Most naval ships have Uninterruptible Power Supplies (UPS) that can sustain essential control and lighting loads; however, loss of propulsion can occur for IPS plants where there is only one operating generator set online [30]. The risk of a power failure in this case can be mitigated through use of a HESS.

2.10.4 *Fault Consequence*

Fault consequence for IPS supports the attribute of Quality of Service (QOS) and the ability for the IPS to sustain load demands under threats and disturbances to the system.

2.10.4.1 *Loss of Only Online Generator*

The loss of the only online generator set for a conventional IPS arrangement means a loss of propulsion where there is a requirement to restore power within 30-45 seconds [27]. Ship control and monitoring systems are maintained using Uninterruptable Power Supplies (UPS).

The future IPS arrangement with HESS would provide enough power to maintain minimal hotel and propulsion loads until an alternate generator set in brought online. This applies to the scenario where a generator set fault leads to a trip condition and subsequent blackout condition.

2.10.4.2 *Tripping of a Bus Tie Breaker.*

Dependent on the IPS configuration, tripping of one bus tie breaker in a ring-main arrangement may not pose a problem. In other configurations, the remote chance of several bus tie breakers tripping could lead to a blackout condition.

2.10.4.3 *Blackout Power Failure*

Traditional marine electrical power systems are distinct from propulsion power where a power failure does not directly impact propulsion. In most cases, warships operate multiple generator sets at one time to provide redundancy in the case of loss of a generator. This is required for close quarter operations, transiting harbor, and in battle conditions. Common practice for traditional power systems in safe transiting is to put an alternate generator set in standby, ready to be brought online as required.

For conventional IPS arrangements, a loss of power can mean a loss in propulsion until an alternate generator set can be brought online.

2.10.5 *Energy Storage Charge-Discharge Simulation*

For the cases where energy storage is required, the rate of discharge and charging of the system must be optimal to supply the necessary power for various time periods. Where there is the loss of the only online generator set, 30-45 seconds of power is required to maintain minimal hotel and propulsion load requirements. For battle conditions, the frequency of pulse loads will provide parameters for maximum energy storage charge and discharge rates.

These use cases can be described in MBSE system behavior diagrams and simulated in plant modeling software more suited to validating system response-type attributes.

2.11 Plant Modeling Standard for IPS Component Sizing and Use Cases

There are several electrical plant modeling applications used by academia and industry that can be used to simulate and analyze IPS plants under various use case scenarios. These models may also be used throughout the design to update performance parameters as the design changes and matures.

2.11.1 *MATLAB®/Simulink*

Models of IPS with pulsed loads have been developed in a MATLAB®/Simulink environment in other work. This includes modeling of Model Based Predictive Control (MPC) and its interactions with the IPS plant [31]. Super-Capacitor energy storage has been simulated in a MATLAB®/Simulink environment using components from the ABB library [32]. Energy efficiency, operational costs, and optimized control of generator sets for an IPS system can be investigated using components from the Simulink/SimPowerSystem environment [33]. The Marine Systems Simulator (MSS) library for MATLAB®/Simulink has been used to study complex systems for both ship positioning and the power system [34].

The Centre for Electromechanics (CEM) at the University of Texas supported development of a future IPS architecture in the MATLAB®/Simulink environment. In this case, MATLAB®/Simulink was chosen based on availability, familiarity and experience at the CEM. When compared to other software, MATLAB®/Simulink was found to be similar with respect to execution time, ease of modeling, and portability [35].

2.11.2 *Virtual Test Bed (VTB) Pro® Simulation Software*

VTB Pro® has been used to test IPS harmonic measures for different architectures in order to select the best location for harmonic filters [36]. Based on a literature review, it is not apparent that commercial software such as VTB Pro® is widely used.

2.11.3 *Homer Pro® Hybrid Electrical Plan Optimization*

Homer Pro® software provides for design, sizing and optimization of hybrid electrical plants. It has similarities to the MATE process but with built-in libraries of standard components. While this software is based on land electrical installations, it has promise as a tool to augment MATE for marine IPS design. It is used in the sizing and validation of IPS components and their parameters for use within the simulator in the current study.

2.12 IPS Modeling Standard and Challenges

Based on a literature review of IPS models, the prevalent standard for plant modelers is MATLAB®/Simulink; however, as with other models it has its limitations.

There are challenges in modeling electrical plants including numerical stability, efficiency in building models, consistent modeling practices, compliance requirements, and achieving reasonable model accuracy [37].

In building models, collecting and compiling the data for dynamic models becomes complicated in trying to make everything work together. User-defined models (UDM) with little documentation makes this task even more complicated. Nevertheless, UDM are often required to make overall models work, although these UDM typically take longer to develop and manage compared to standard commercial models [37].

Progress has been made in advancing standards for generator modeling, but work is required in standard practices for dynamic modeling of the larger electrical system [31].

Numerical instability of dynamic models for marine electrical plants and its components has been cited by several authors [29] [30] [35], leading to work arounds and continued use of UDM.

The current study adopts Homer Pro® software as a suitable IPS low-fidelity model that can expose key variables and attributes of interest early in the design process. These variables and attributes are used in testing the management flight simulator in the current study.

2.13 Model Fidelity and Model Credibility

As the complexity of a system grows and detail is added, model fidelity may increase but at the expense of computational speed. It was proposed in other work that modular design and low fidelity models be used to help identify where high-fidelity models are required for a system [34].

While several models are considered in the current study, it should be noted that models can produce predictions that are in error with realty, adding risk to the program. This can be described using a four-box model, as depicted in Figure 2.12, for perceived model quality and actual model quality where the ideal model is in quadrant II [38]. As the design matures, it is expected that the system model will progress toward quadrant II.

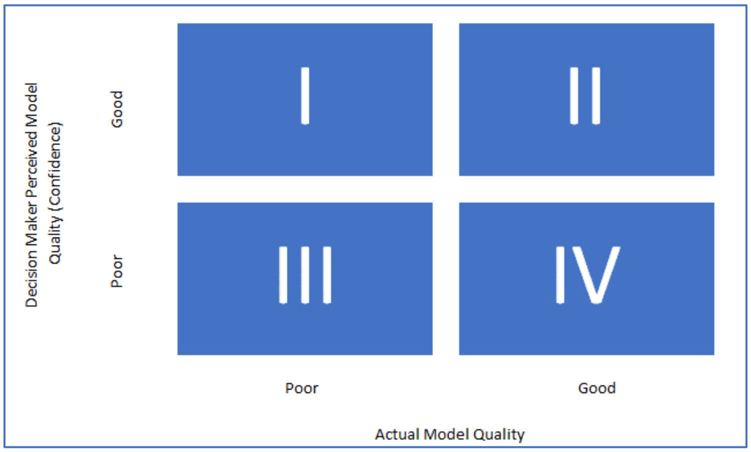


Figure 2.12. Model Quality [38]

In the current study, low fidelity models include the modified MATE model, known systems engineering models, and use of optimization software (Homer Pro®). Nevertheless, these models can work together to provide insight and a gauge for the impact of changes to the system.

Using several models to gain insight into design is useful for cross-validation of model results. In the current chapter, robustness of the selected IPS architecture is validated through a sensitivity analysis where assigned attribute weightings may be slightly modified. Other sensitivity studies include analyzing the volatility of estimated costs for a system design.

2.14 IPS Cost and Sizing Data

The challenge with assigning cost and sizing data to system components within MATE is with its accuracy and ability to source such data. In this case study, data was obtained from several sources including wide use of the internet; Appendix B provides relevant data to this study. In applying life cycle data, the time value of money is considered using Net Present

Value (NPV) cash flows as compared to the initial investment of equipment. This is of importance when considering energy efficient components for the various IPS design alternatives. For instance, the pay back of larger WHR systems can be five years with continued savings in the order of $25M over 20 years [39].

Previous studies showed that the TRL of a system impacts the cost estimate and that based on past projects and system TRL, a Cost Correction Factor (CCF) can be applied to improve future project estimates [40]. The current study applies a similar CCF for IPS design options and components, the CCF is represented by:

$$CCF \ = \propto \cdot \, e^{-\lambda \cdot TRL} \tag{2.2}$$

where α and λ are constants based on similar past projects at equivalent stages during the design process. As depicted in Figure 2.13, the current study adopts the conservative values of α=10 and λ=0.25 for the purposes of demonstrating the application of a CCF within the modified MATE model.

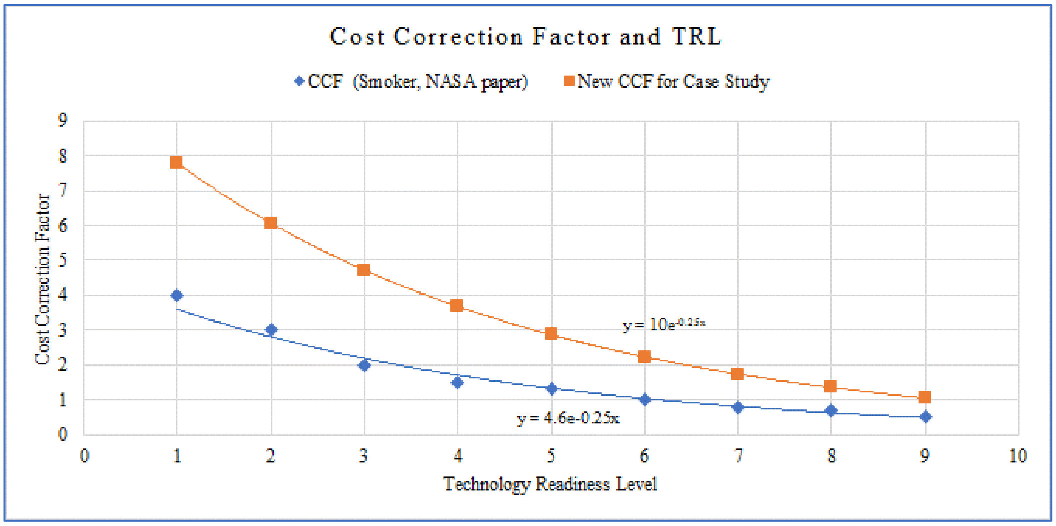


Figure 2.13. TRL and the Cost Correction Factor. Adapted from [40]

In terms of using SRL instead of TRL, a similar CCF is developed where α and λ are adjusted to account for the normalized SRL values. In this case, α=3.0 and λ=3.5, where these variables may be adjusted to reflect past similar project cost performance.

$$CCF \ = \propto \cdot \, e^{-\lambda \cdot SRL} \tag{2.3}$$

As depicted in Figure 2.14, an SRL value of 0.1 can translate into a CCF of 2.5. The CCF is used in the development of the management flight simulator as it can affect design change costs incurred.

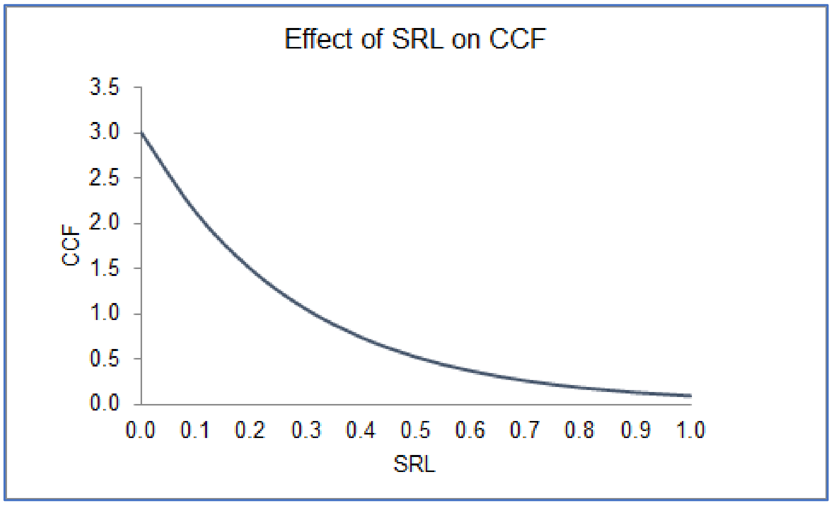


Figure 2.14. Effect of SRL on the CCF

Sources of cost uncertainty include those associated with high-level requirements and costs. The high-level requirements listed in the case study stem from the author’s experience and from a literature review. As these requirements are linked to MATE attributes, any changes to them presents the risk of different pareto front design alternatives. Sources of cost uncertainty can be found in equipment data, poor Cost Estimating Relationships (CERs), and in flawed parametric equations.

Distinct cost probability distributions do not pose a problem for determining clear design alternatives through the MATE process; however overlapping distributions present uncertainty in choosing one alternative over another. Cost estimates may have an uncertainty range from minus 30 percent to plus 50 percent during early design development, denoted as Class 4 [41]. Other standard cost-class ranges can be applied throughout the design process.

Monte Carlo methods can be used to solve problems having a probabilistic interpretation and allows for prediction of outcomes within certain confidence levels [42].

The current study proposes applying the Monte Carlo method to baseline MATE cost estimates as means to account for uncertainty and to support a MATE sensitivity analysis based on cost uncertainty across the different alternative designs. The Monte Carlo method applied in the current study is based on a beta distribution that consists of a minimum, likely (baseline), and maximum cost values.

2.15 IPS MATE Model

The IPS requirements, associated attributes, use case scenarios and trade space exploration for the IPS and its components provide a foundation for decision-making in design, systems engineering and in program management. In the current study, the modified MATE model serves as a reference model later in design when changes and their impact are assessed.

Two value models are considered in this case study, one for the design variables of various IPS architectures and corresponding multi-attribute utility values; the other for naval ship survivability as a separate and distinct attribute.

Within the context of the modified MATE model, ship platform attributes or capabilities can be described by high-level "ilities" including operability, interoperability, mobility, survivability, habitability and supportability [20]. This study also includes safety and environmental attributes that are viewed as important in the design of most engineering systems.

For the current study, the applicable IPS "ilities" are mobility, operability, and survivability. Operability consists of several aspects such as the operating environment, system functionality, ship complement, training, human factors, and security. In the current study, system functionality and associated operability type sub-attributes are the focus for the IPS.

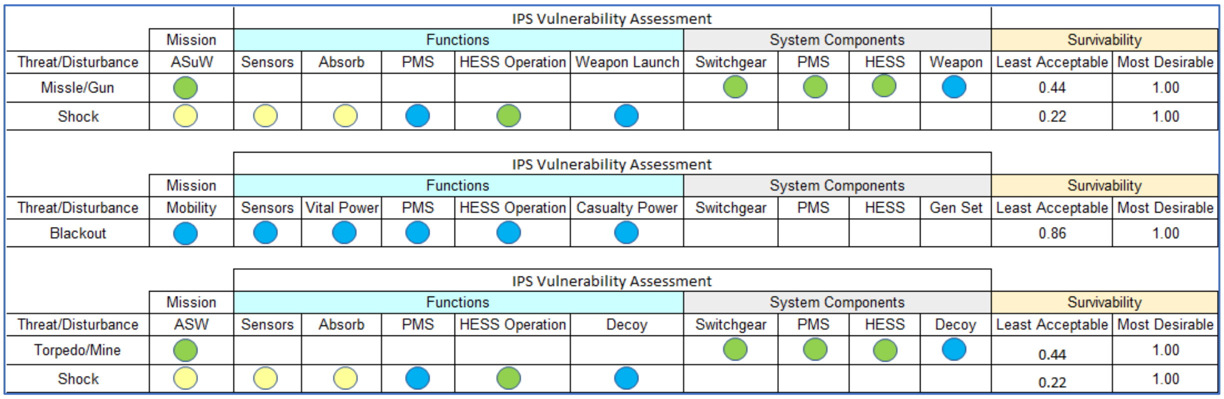
Mobility includes the aspects of ship endurance, speed, maneuvering, and sea worthiness. Warships differ from merchant ships in that they require the ability to maintain maximum speed whereas merchant ships can be optimized for a defined voyage speed [20].

Survivability for warships is described in terms of susceptibility, vulnerability and recoverability. Susceptibility is the ability of the ship to avoid detection, vulnerability is the ability of the ship and its systems to resist damage, and recoverability is the ability of the ship to recover following damage [20].

Levels of vulnerability can be described in terms of basic, moderate and naval [20]. The basic level consists of redundancy of critical systems only, the moderate level consists of redundancy of systems associated with the float and move aspects of the ship, and the naval level consists of redundancy of all systems associated with operational capabilities [20]. Military platforms tend to lean toward those with redundancy built into the design.

Expanding on work that provides a framework to quantify survivability of systems, this study focuses on the Vulnerability Risk Assessment (VRA) and Vulnerability Risk Matrix (VRM) as a starting point to identify and assess potential threats and disturbances to the ship and its systems [43].

The probabilistic assessment of the survivability attribute for a ship has been recommended in other work [15]. This approach provides for a simplistic approach for assessing the threat spectrum against a system [43]. This study looks at threat susceptibility of a system in terms of its functions and components, considering the threat or disturbance event imposed upon the system. Figure 2.15 provides an assessment for different IPS missions as they relate to the modified MATE model. The circles indicate the level of vulnerability risk, red being the highest level; blue the lowest. The survivability analysis starts with describing system functions and components and then how each threat or disturbance impacts them.



		IPS Vulnerability Assessment										
	Mission	Functions					System Components				Survivability	
Threat/Disturbance	ASuW	Sensors	Absorb	PMS	HESS Operation	Weapon Launch	Switchgear	PMS	HESS	Weapon	Least Acceptable	Most Desirable
Missle/Gun	🟢						🟢	🟢	🟢	🔵	0.44	1.00
Shock	🟡	🟡	🟡	🔵	🟢	🔵					0.22	1.00

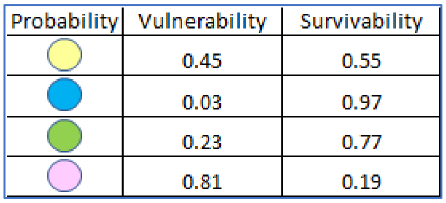
		IPS Vulnerability Assessment										
	Mission	Functions					System Components				Survivability	
Threat/Disturbance	Mobility	Sensors	Vital Power	PMS	HESS Operation	Casualty Power	Switchgear	PMS	HESS	Gen Set	Least Acceptable	Most Desirable
Blackout	🔵	🔵	🔵	🔵	🔵	🔵					0.86	1.00

		IPS Vulnerability Assessment										
	Mission	Functions					System Components				Survivability	
Threat/Disturbance	ASW	Sensors	Absorb	PMS	HESS Operation	Decoy	Switchgear	PMS	HESS	Decoy	Least Acceptable	Most Desirable
Torpedo/Mine	🟢						🟢	🟢	🟢	🔵	0.44	1.00
Shock	🟡	🟡	🟡	🔵	🟢	🔵					0.22	1.00

Figure 2.15. IPS Function and Component Survivability Analysis Results

The VRM probability list of values depicted in Table 2.1 provides a guide for assigned values in the IPS function and component survivability analysis. This guide is based on VRM matrix reference values.

Table 2.1. VRM Guide to Probability Values



Probability	Vulnerability	Survivability
🟡	0.45	0.55
🔵	0.03	0.97
🟢	0.23	0.77
🟣	0.81	0.19

The probability of survival from each threat/disturbance for a mission can be determined.

$$P_{Survivability} = 1 - P_{Vulnerability} \tag{2.4}$$

where probabilities P can be multiplied together to provide an overall system probability of survival for a given mission. These form baseline least acceptable values where any changes to components later in the design will require further analysis. Capturing survivability attribute values for different design variants within a MATE model can reduce this analysis effort.

The threats/disturbances and corresponding probability values are displayed in the VRM in Figure 2.16. The VRM provides mission capability vulnerability values as a guide for conducting the component vulnerability and survivability analysis.

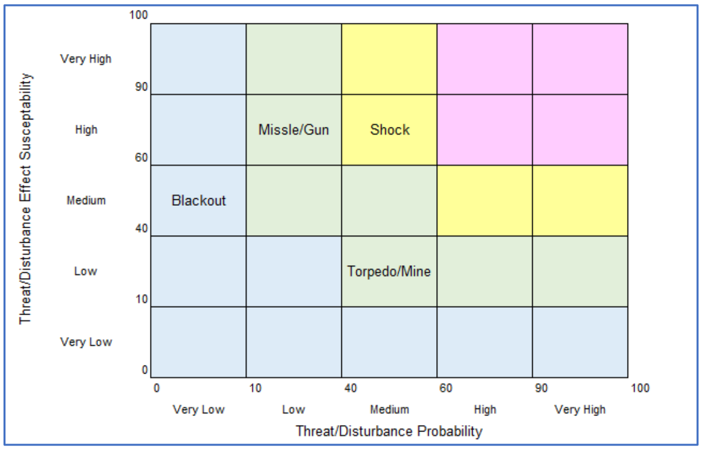


Figure 2.16. Vulnerability Risk Matrix for The IPS With HESS

Warship weapon related capabilities can include Anti-Air Warfare (AAW), Anti-Surface Warfare (ASuW), Anti-Submarine Warfare (ASW) and Mine Counter Measures (MCM). As the IPS design is integral to the Rail Gun high energy power requirements and aspects of susceptibility, the related weapon capabilities of ASuW and ASW are included as high-level attributes in the current study.

In terms of the safety attribute, adherence to the Naval Ship Code, Naval Vessel Rules (NVR), and applicable system standards provides a measure of safety assurance [20] [27].

Reliability is a sub-attribute to Safety that may be assessed through a Failure Mode, Effects and Criticality Analysis (FMECA) of the key IPS components, of which are dependent on the design alternatives. FMEA is listed as a functional requirement in the current study in accordance with classification rules. The VRA and VRM survivability analysis may be used as input into the FMECA, where high risk failures of the IPS are identified such as a black out due to tripping of a single generator or main breaker. The design principles of incorporating machinery rafts and ZED form part of the IPS design variables and may be viewed as ways to prevent IPS failures. For simplicity, the choice between raft and ZED is used to determine reliability values in the current study.

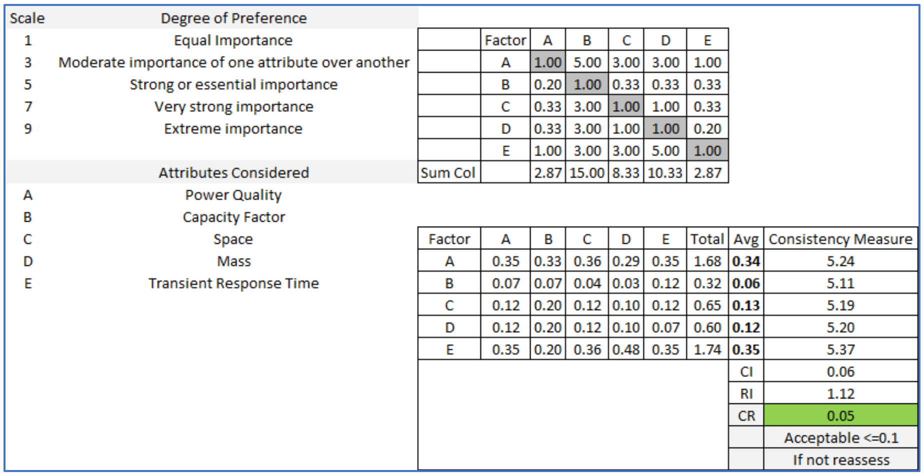
2.16 The Analytical Hierarchy Process for Attribute Weightings

AHP provides a method to determine the weights of the performance, survivability and capability attributes in the current study. AHP was developed in the 1970's as a method to weigh weapons tradeoffs, resource and asset allocation, and other competing factors [44]. In validating attribute weights, an acceptable Consistency Ratio (CR) was achieved, indicating successful pair-wise comparison as depicted in Table 2.2.

The AHP method is used to assign weightings to the hierarchy of attributes considered in the current study. These weightings are taken into consideration when aggregating subservient attribute values into their respective higher-level mission capability attribute values.

The assignment of weightings to a limited number of other mission type attributes was estimated from electrical load profiles for peacetime and wartime cruising for the Arleigh-Burke DDG 51 destroyer [28]. The EEDI environmental attribute was nominally assigned a weight of 0.10 under the higher-level performance attribute.

Table 2.2. AHP and IPS Operability Attribute Weightings



Scale	Degree of Preference
1	Equal Importance
3	Moderate importance of one attribute over another
5	Strong or essential importance
7	Very strong importance
9	Extreme importance

	Attributes Considered
A	Power Quality
B	Capacity Factor
C	Space
D	Mass
E	Transient Response Time

	Factor	A	B	C	D	E
	A	1.00	5.00	3.00	3.00	1.00
	B	0.20	1.00	0.33	0.33	0.33
	C	0.33	3.00	1.00	1.00	0.33
	D	0.33	3.00	1.00	1.00	0.20
	E	1.00	3.00	3.00	5.00	1.00
Sum Col		2.87	15.00	8.33	10.33	2.87

Factor	A	B	C	D	E	Total	Avg	Consistency Measure
A	0.35	0.33	0.36	0.29	0.35	1.68	**0.34**	5.24
B	0.07	0.07	0.04	0.03	0.12	0.32	**0.06**	5.11
C	0.12	0.20	0.12	0.10	0.12	0.65	**0.13**	5.19
D	0.12	0.20	0.12	0.10	0.07	0.60	**0.12**	5.20
E	0.35	0.20	0.36	0.48	0.35	1.74	**0.35**	5.37
							CI	0.06
							RI	1.12
							CR	0.05
								Acceptable <=0.1
								If not reassess

The sensitivity to design alternatives from different weightings assigned to attributes was tested and analyzed through a second MATE model.

The multi-attribute utility functions (U) developed in the current work represents the weighted sum of several attributes.

$$U = \sum_{i=1}^{n} ki\ ui \tag{2.5}$$

where ki is a scalar weight for the performance utility i.

2.17 IPS Design Variables and Attributes for Analysis

The design vector is a list of variables that define the system architecture where the variables are limited to those having the greatest effect on the attributes. The Quality Functional Deployment (QFD) process followed in the current study resulted in a limited number of design variables considered for the IPS MATE. This reduction in the number of design variables leads to a reduction in computational resources required to calculate the various design alternatives. In the real world, the assignment of QFD scores requires validation by subject matter experts (SME) in IPS architectures and the respective high-level requirements. The design variables and their respective ranges that lend themselves to the attributes of interest in this study are described in the following sections.

2.17.1 *Total Installed Power 36-78 MW*

The total installed power was based on the electrical load profile for the DDG 51 destroyer [28]. The intermediary variables include the Gas Turbine (GT) generator and Diesel Generator (DG) set power, as detailed in Appendix B. The total power contributes to the attributes of Maximum Speed, Range, Electrical Capacity Factor, Space, Mass, Rail Gun Performance, EEDI, and Costs.

2.17.2 *Diesel Generator (DG) Sets Conventional or with a Waste Heat Recovery (WHR) System*

The size and number of DGs set is kept constant in this study, each at 3 MW. The DG type contributes to the attributes of Range, Space, Mass, EEDI, and Costs. As one of the overall key objectives is to reduce fuel consumption, lower CO2 emissions, and reduce Infrared Signature (IR), prime movers designed with WHR were considered in the case study. For large power demands in excess of 25 MW, the steam turbine and generator WHR system is preferred [39].

2.17.3 *GT Generator Sets 15-36 MW Each Pair Conventional or with WHR*

The number of GT sets in the case study is kept at two for redundancy and power generation. The GT type and size contribute to the attributes of Range, Space, Mass, EEDI, and Costs.

2.17.4 *Power Management Controller Type*

The type of controller contributes to the attributes of Range, Power Quality, Transient Load Response Time, EEDI, Costs, Naval Ship Code (NSC) and Naval Vessel Rules adherence. For the purposes of the current study, Model Predictive Control (MPC) is assumed to be more efficient than Proportional-Integral-Derivative (PID) control in providing optimum loading of generator sets for given load profiles.

2.17.5 *High Energy Storage System Type*

The type of HESS selected contributes to the attributes of Space, Mass, Costs, and regardless of type, to the attributes of EEDI and probability of survivability. The costs associated with HESS type is based on a flywheel parametric and ultra-capacitor spreadsheet template. The HESS provides for an opportunity to satisfy several requirements including ride-through capability, rail gun high power demand, increased IPS efficiency through fewer prime movers operating online at peak SFC, and the benefit of reduced emissions.

2.17.6 *HESS Power Capacity*

The HESS power capacity contributes to Space, Mass, Rail Gun Performance, Reliability through added redundancy, and Costs. 160 MJ is assumed for a 64 MJ Rail Gun shot at 40 percent efficiency. One shot at an impulse load across 4 seconds is assumed with minimal recharge time. This also assumes that the ship may have to reduce speed to allow for spare capacity to charge the HESS between shots.

2.17.7 *Compartmentalization Conventional or Zonal Electrical Distribution*

The compartmentalization variable represents a survivability design principle and contributes to the attributes of electrical disruption by way of a Blackout, direct threats by way of Torpedo/Mine hits, Missile/Gun hits, and to Reliability.

2.17.8 *Shock Hardening Isolators or a Machinery Raft*

The shock mounting arrangement variable represents a survivability design principle and contributes to the attributes of Mass, Blackout, Shock, Reliability, and Costs.

2.18 Performance Attributes

Several IPS attributes are considered in this case study and may be derived from both unique IPS high-level requirements and those that are common to many engineering systems, regardless of platform. These attributes fall into a hierarchy of attribute domains that include mission-type capability outcomes that may be viewed as goal-based and common to multiple disciplines. The range values for these attributes are provided and made non-dimensional for use within the MATE and subsequent simulator models. This provides for a common language among multiple stakeholders.

2.18.1 *Mission Capabilities*

The capability domains of Mobility, Operability, Anti-Surface Warfare (ASuW), Anti-Submarine Warfare (ASW), and Survivability are defined in military doctrine. For this case study, a limited number of relevant attributes are assigned to these domains. The values calculated for common attributes can be aggregated up into the higher-level ship attributes and corresponding mission-capability domains.

2.18.1.1 *Mobility*

The attributes under Mobility consist of Maximum Speed and Range. The Maximum Speed considered in this study is from 25 to 30 knots. The load profile for the DDG 51 reveals that anything in excess of 25 knots is only required for 0.1 percent of the time for both peacetime and wartime cruising. Preliminary calculations of Range for different configurations led to a minimum of 2631 nm and a maximum of 3491 nm, the range for the current case study was assigned from 2500 nm to 4000 nm. The fuel capacity for Range calculation was assumed constant at 800 cubic metres and at an economical ship cruising speed of 15 knots. Reductions in fuel consumption are assumed at 6 percent GTs, 2 percent DGs with WHR, and 10 percent each for HESS and MPC configurations. Calculations for Range for different IPS architectures were performed within Microsoft Excel®, with an excerpt provided in Appendix B.

2.18.1.2 *Operability*

Under the capability of Operability, five sub-attributes were assigned for this case study.

2.18.1.2.1 *Power Quality*

Power Quality is viewed as an important attribute that is traced back to the high-level IPS requirements. For the purposes of this case study, a minimum Total Harmonic Distortion (THD) of 2 percent is desired while a maximum of 5 percent THD is acceptable.

2.18.1.2.2 *Capacity Factor*

The Capacity Factor measures the utilization or percent of specific loads that contribute to either the peacetime cruising of wartime cruising profile. The wartime cruising profile for the DDG 51 is used as a reference in this case study and leads to a range from 17 to 50 percent for the Capacity Factor. While this range appears to be on the low side compared to a commercial ship Capacity Factor, it is reasonable for a warship design that includes additional redundancy and allowance for achieving maximum speed.

2.18.1.2.3 *Space*

Preliminary calculations for the various design alternatives revealed that a Space range from 250 to 1030 cubic metres is appropriate for the purposes of performing the MATE process. The main contributors to higher volumetric values may be seen in WHR options and additional HESS capacity.

2.18.1.2.4 *Mass*

For the design alternatives considered in this study, a Mass range from 130,000 kg to 360,000 kg was assigned. This attribute affects Maximum Speed and Range.

2.18.1.2.5 *Transient Response Time*

The Transient Response Time attribute was assigned either a “slow” or “fast” value based on PMS Controller type.

2.18.2 *Rail Gun*

In the current study, the range of HESS power capacity is from 160 MJ to 320 MJ, primarily for use in rail gun operation. This corresponds to a rail gun operational range from 12 to 24 rounds/min respectively.

2.18.3 *EEDI*

The EEDI attribute was assigned a range from 40 to 59 g CO_2/tonne-nm. Reduction in CO_2 for GTs with WHR is assumed to be 6 percent, DGs with WHR 2 percent, HESS 7 percent, and MPC 5 percent. The lower the EEDI, the more efficient the ship is from an environmental perspective. As EEDI is proportional to power required, the preference is to reduce the size and number of prime movers. This leads to considering a lower maximum speed required for the ship at 25 knots vice 30, where the higher speed is seldom required.

2.19 Program Risks

2.19.1 *Technology and System Readiness Level*

Technology Readiness Level (TRL) is a metric widely used by NASA and defense [45]. It was introduced in the 1980's and is organized along 9 levels of technology development. The TRLs are described in Table 2.3.

TRLs provide a measure for system maturity at a point in time during product development where most technologies should progress to TRL 9 by the end of design. If progress is not made toward this level, more viable solutions may need to be explored.

Table 2.3. Summary of Different Technology Readiness Levels [45]

TRL	Description
TRL 1	Basic principles observed and reported
TRL 2	Technology concept and or application formulated
TRL 3	Analytical, experimental critical function and/or characteristic proof-of-concept
TRL 4	Component validation in laboratory environment
TRL 5	Component validation in relevant environment
TRL 6	System/subsystem model or prototype demonstration in a relevant environment
TRL 7	System prototype demonstration in a Naval environment
TRL 8	Actual system completed, tested and demonstrated
TRL 9	Actual system proven through successful mission operations

When TRL is abstracted as a metric at the systems level, it may not be useful for making design decisions without considering the integration aspect [46]. The SRL metric incorporates both the TRL metric and an Integration Readiness Level (IRL) metric. This case study adopts the SRL metric as a more comprehensive systems engineering and program risk metric, the IRLs are described in Table 2.4.

Table 2.4 Summary of Different Integration Readiness Levels [46]

IRL	Description
IRL 1	An Interface between technologies has been identified with sufficient detail to allow characterization of the relationship
IRL 2	There is some level of specificity to characterize the Interaction (i.e. ability to influence) between technologies through their Interface
IRL 3	There is Compatibility (i.e. common language) between technologies to orderly and efficiently integrate and interact
IRL 4	There is sufficient detail in the Quality Assurance of the Integration between technologies.
IRL 5	There is sufficient Control between technologies necessary to establish, manage and terminate the integration
IRL 6	The integrating technologies can Accept, Translate and Structure Information for its intended application
IRL 7	The Integration of technologies has been Verified and Validated with sufficient detail to be actionable
IRL 8	Actual Integration completed and Mission Qualified through test and demonstration, in the system environment
IRL 9	Integration is Mission Proven through successful mission operations

To estimate SRL at a stage in product development, TRL and IRL matrices are developed, normalized, and the SRL is calculated through the product of the *TRL* and *IRL* matrices.

$$[SRL]_{nx1} = [IRL]_{nxn} X \; [TRL]_{nx1} \tag{2.6}$$

2.19.2 *Schedule Slippage*

Low Technology Readiness Level (TRL) has been linked as a key driver to schedule slippage [45]. TRL schedule risk curves may help program managers in assigning appropriate schedule margins to a program. In this study, a similar curve is adopted with schedule slippage decreasing with an increase in TRL. Relative Schedule Slippage (RSS) is defined as the percentage schedule growth given the initial schedule estimate, it is represented by:

$$RSS \ = \propto \cdot \ e^{-\lambda \cdot TRL} \tag{2.7}$$

where α and λ are constants based on similar past projects at equivalent stages during the design process, this case study adopts α=8 and λ=0.5, as depicted in Figure 2.17.

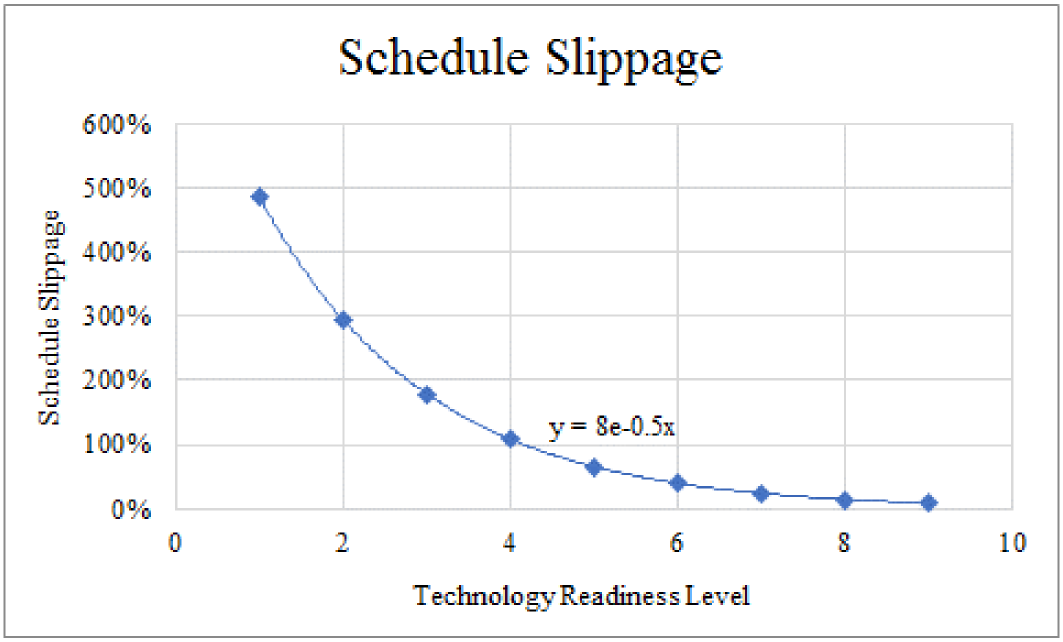


Figure 2.17. TRL and Schedule Slippage. Adapted from [45]

In terms of using SRL instead of TRL, a similar RSS is developed where α and λ are adjusted to account for the normalized SRL values. In this case, α=5.0 and λ=4.0, where these variables may be adjusted to reflect past similar project schedule performance.

$$RSS \ = \propto \cdot \ e^{-\lambda \cdot SRL} \tag{2.8}$$

The effect of SRL on RSS is depicted in Figure 2.18. In the current study, SRL is used as a factor that affects the task completion rate and design maturity within the SD model.

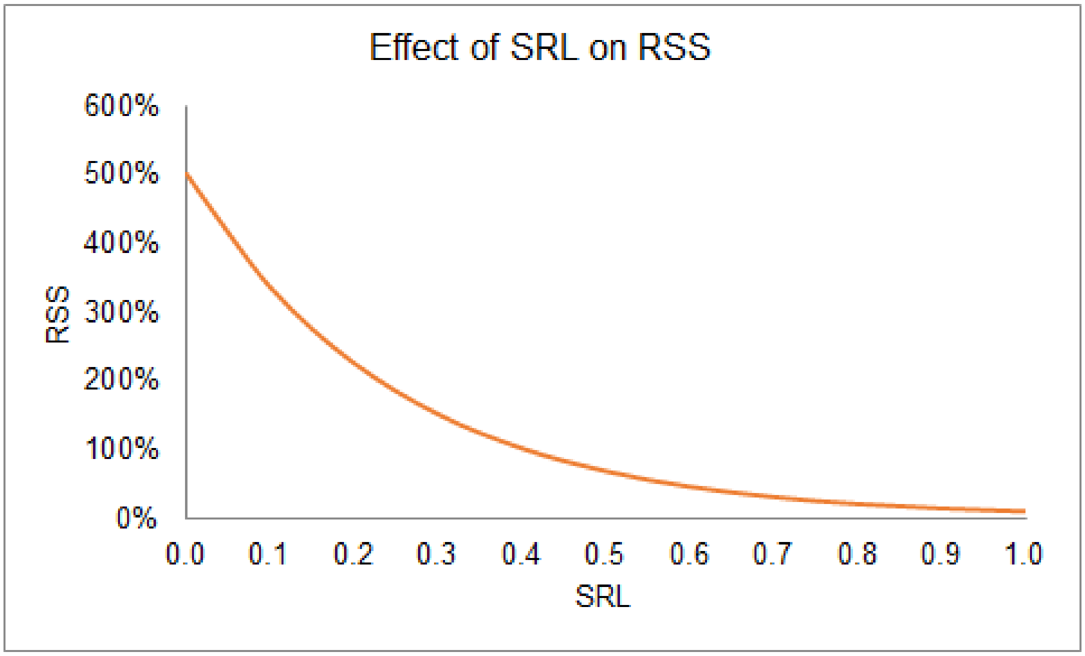


Figure 2.18. SRL and Schedule Slippage

2.20 Survivability Attributes

Using the VRM, the probability baseline was estimated for key IPS components and their functions. The survivability design principles of compartmentalization and shock hardening were used as design variables that contribute to improving the survivability attribute baseline values. The baseline probability of survivability for a Blackout was estimated at 0.86, Shock at 0.22, Missile/Gun and Torpedo/Mine both at 0.44. The high limit range for survivability attributes was set at 1.0.

2.20.1 *Blackout*

The Blackout attribute score was increased through successive combinations of improved IPS Compartmentalization type and Shock Hardening type, where adoption of ZED and a Raft system increased the Blackout score to a maximum of 0.98.

2.20.2 *Shock*

The Shock attribute score was improved upon through application of the Raft system to a maximum score of 0.75. The Missile/Gun and Torpedo/Mine attribute scores were both improved up through adoption of ZED compartmentalization to a maximum score of 0.75.

2.20.3 *Safety*

Safety is built into systems and requires attributes that can be measures of assurance during product development. The adherence of a system to NSC and NVR standards provide a measure for a Safety sub-attribute. The range for this attribute is from 0.25 to 1, where improvement is recognized through the NSC and NVR design principles of zonal electrical distribution (ZED) and advanced load management controllers such as MPC.

2.20.4 *Reliability-Quality of Service*

The Reliability-Quality of Service (QOS) attribute is considered a key input into the Survivability attribute. For simplicity, this study takes the approach of assessing IPS function and component susceptibility in determining the reliability value. QOS is based on the concept of power interruption tolerance and managing loads cost effectively without sacrificing performance [47].

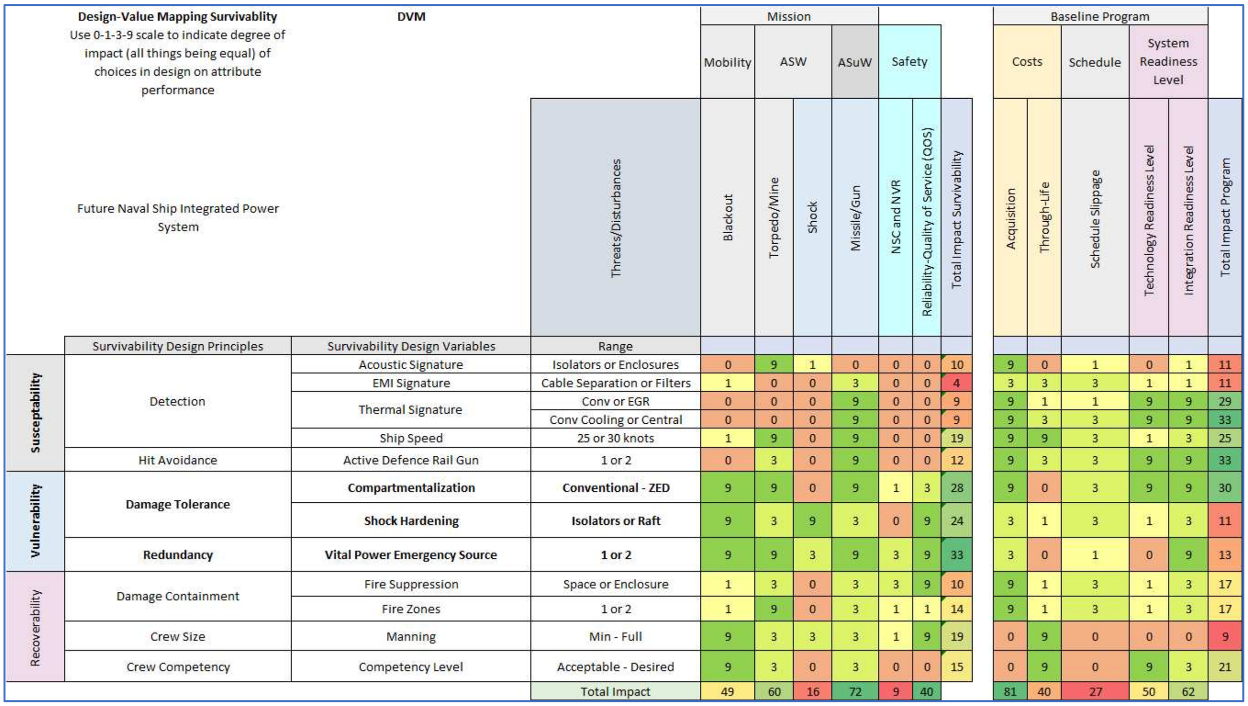
2.21 Results

The design variables for both the system performance matrix and the survivability matrix can result in a tradespace consisting of thousands of designs that can be computationally expensive. Therefore, it is of value to further reduce the number of variables and attributes to a manageable set that represents the key interests of stakeholders. This can be achieved through assessing the impact of design variables on their associated attributes, Figures 2.19 and 2.20

depict the QFD method applied to the IPS case study where design variables in bold depict those that are used for the modified MATE model.

Design-Value Mapping	DVM		Mission															
			Mobility		Operability					ASuW	Environmental		Baseline Program					
Use 0-1-3-9 scale to indicate degree of impact (all things being equal) of choices in design on attribute performance		Units	nmi/h	nmi	THD %	%	m^3	tonne	s	Rounds/min	dimensionless		Costs		Schedule	System Readiness Level		
Future Naval Ship Integrated Power System		Attributes	Maximum Speed	Range	Power Quality	Capacity Factor	Space	Weight	Transient Load Response Time	Rail Gun Performance	Energy-Efficiency Design Index	Total Impact Performance	Acquisition	Through-Life	Schedule	Technology Readiness Level	Integration Readiness Level	Total Impact Program
Design Variables	Units	Range																
Total Installed Gen Power	MW	36 or 78	9	9	0	3	9	9	9	9	3	60	9	9	0	0	9	27
DG	dimensionless	Conv - WHR	3	9	1	9	3	3	0	0	9	37	9	9	9	9	9	45
GT	dimensionless	Conv - WHR	3	9	1	9	3	3	0	0	9	37						
PMS Controller	dimensionless	PID - MPC	0	9	1	9	0	0	9	9	9	46	9	9	9	9	9	45
Prop Motor Type	dimensionless	Synchro or Induction	3	0	3	3	1	1	1	0	3	15	9	3	3	1	1	17
Power Converter Type	dimensionless	Freq or PFM	0	0	9	3	3	3	3	0	3	24	3	1	1	1	3	9
THD Filter Type	dimensionless	passive - dynamic	0	0	9	0	0	0	0	0	0	9	1	3	3	1	3	11
HESS Type	dimensionless	flywheel - ultracapacitor	0	3	3	3	3	9	3	9	1	34	9	9	3	9	9	39
HESS Power Capacity	MJ	160 or 320	1	3	1	1	9	9	3	9	9	45	9	9	0	0	9	27
		Total Impact	19	42	28	40	31	37	28	36	46		58	52	28	30	52	

Figure 2.19. IPS QFD Analysis of Performance, Program Risks and Cost Attributes



	Design-Value Mapping Survivablity Use 0-1-3-9 scale to indicate degree of impact (all things being equal) of choices in design on attribute performance	DVM		Mission							Baseline Program					
				Mobility	ASW		ASuW	Safety			Costs		Schedule	System Readiness Level		
	Future Naval Ship Integrated Power System		Threats/Disturbances	Blackout	Torpedo/Mine	Shock	Missile/Gun	NSC and NVR	Reliability-Quality of Service (QOS)	Total Impact Survivability	Acquisition	Through-Life	Schedule Slippage	Technology Readiness Level	Integration Readiness Level	Total Impact Program
	Survivability Design Principles	Survivability Design Variables	Range													
Susceptability	Detection	Acoustic Signature	Isolators or Enclosures	0	9	1	0	0	0	10	9	0	1	0	1	11
		EMI Signature	Cable Separation or Filters	1	0	0	3	0	0	4	3	3	3	1	1	11
		Thermal Signature	Conv or EGR	0	0	0	9	0	0	9	9	1	1	9	9	29
			Conv Cooling or Central	0	0	0	9	0	0	9	9	3	3	9	9	33
		Ship Speed	25 or 30 knots	1	9	0	9	0	0	19	9	9	3	1	3	25
	Hit Avoidance	Active Defence Rail Gun	1 or 2	0	3	0	9	0	0	12	9	3	3	9	9	33
Vulnerability	**Damage Tolerance**	**Compartmentalization**	**Conventional - ZED**	9	9	0	9	1	3	28	9	0	3	9	9	30
		Shock Hardening	**Isolators or Raft**	9	3	9	3	0	9	24	3	1	3	1	3	11
	Redundancy	**Vital Power Emergency Source**	**1 or 2**	9	9	3	9	3	9	33	3	0	1	0	9	13
Recoverability	Damage Containment	Fire Suppression	Space or Enclosure	1	3	0	3	3	9	10	9	1	3	1	3	17
		Fire Zones	1 or 2	1	9	0	3	1	1	14	9	1	3	1	3	17
	Crew Size	Manning	Min - Full	9	3	3	3	1	9	19	0	9	0	0	0	9
	Crew Competency	Competency Level	Acceptable - Desired	9	3	0	3	0	0	15	0	9	0	9	3	21
			Total Impact	49	60	16	72	9	40		81	40	27	50	62	

Figure 2.20. IPS QFD Analysis of Survivability, Program Risks, and Cost Attributes

In helping to initially size IPS components for the current study, ship electrical load profiles were established. Table 2.5 provides notional electrical load profiles for the IPS with loads consisting of propulsion, hotel and weapon system loads; the utilization of these loads is listed in Table 2.6 [28]. The high energy weapon load of 160 MJ to 320 MJ is in addition to these loads. For the purpose of this case study, the mission capabilities of mobility, ASuW and ASW are mapped to peacetime and wartime cruising scenarios in these tables.

Table 2.5. Assumed IPS Load Profile [28]

Speed	Shore Power	Anchored	Mobility	ASuW and ASW
		kW	Peacetime Cruising kW	Wartime Cruising kW
0	-	4474	8203	9694
5	-	0	8321	9813
10	-	0	9118	10609
15	-	0	11465	12957
20	-	0	15892	17384
25	-	0	26185	27677
30	-	0	60635	62127

Table 2.6. Utilization of Loads [28]

Speed	Shore Power (percent)	Anchored (percent)	Mobility	ASuW and ASW
			Peacetime Cruising (percent)	Wartime Cruising (percent)
0	53.0%	1.6%	0.0%	0.0%
5	0.0%	0.0%	6.8%	5.2%
10	0.0%	0.0%	4.7%	3.6%
15	0.0%	0.0%	6.4%	4.9%
20	0.0%	0.0%	6.0%	4.6%
25	0.0%	0.0%	1.5%	1.2%
Max	0.0%	0.0%	0.1%	0.1%
Total	53.0%	1.6%	25.7%	19.7%

With installed power options of 36 and 78 MW, the architectures of interest include baseline 2 Diesel Generator (DG) sets of 3 MW each, options for 2 Gas Turbines (GT) each at 15 MW or 36 MW, and HESS at 160 MJ or 320 MJ.

A sensitivity analysis on the MATE model is important in assessing the robustness of designs of interest. This is conducted by changing the weighting of the attributes and verifying any changes in design alternatives on the pareto front.

In accordance with these notional future IPS architectures and the adopted DDG 51 load profile, optimization software (Homer Pro®) was utilized to verify IPS parameters.

This software is limited in providing other attribute data such as cost of components, as required for the MATE process. Several assumptions and scaled estimates for costs and sizing were made in order to achieve a functional MATE model that can be used to demonstrate attributes of importance.

2.21.1 *Modified MATE and Selected IPS Architectures*

The modified MATE tables and translation of variables into non-dimensional attributes are developed with Microsoft Excel® software, attribute headings are depicted in Figure 2.21.

											Performance									Survivability						Program		
											Mission								Enviro	Mission				Safety		Costs	Schedule	Risks
											Mobility	Operability						ASuW		Mobility	ASW		ASuW					
	Units	MW	dimensionless	dimensionless	dimensionless	dimensionless	MJ	dimensionless	dimensionless	Units	nmi/h	nmi	THD %	%	m^3	kg	dimensionless	Rounds/min	g CO_2/t nm	dimensionless	dimensionless	dimensionless	dimensionless	dimensionless	dimensionless	$US	%	dimensionless
Design ID	Design Variables	Total Installed Power	DG	GT	PMS Controller	HESS Type	HESS Power Capacity	Compartmentalization	Shock Hardening	Attributes	Maximum Speed	Range	Power Quality	Capacity Factor	Space	Mass	Transient Load Response Time*	Rail Gun Performance	Energy-Efficiency Design Index	Blackout	Torpedo/Mine	Shock	Missile/Gun	NSC and NVR	Reliability	Acquisition	Schedule Slippage	System Readiness Level
1		36	Conv	Conv	PID	flywheel	160	Conv	ISO		25	2983	5	38.6	324	134190	slow	12	54.2	0.86	0.44	0.22	0.44	0.25	0.50	$68,199,322	24%	0.47
2		36	Conv	Conv	PID	flywheel	160	Conv	Raft		25	2983	5	38.6	324	138190	slow	12	54.2	0.94	0.44	0.75	0.44	0.25	0.50	$71,674,801	24%	0.47
255		78	WHR	WHR	MPC	ultracapacitor	320	ZED	ISO		30	3079	2	17.8	958	348383	fast	24	41.0	0.96	0.75	0.22	0.75	1.00	0.70	$381,075,718	108%	0.27
256		78	WHR	WHR	MPC	ultracapacitor	320	ZED	Raft		30	3079	2	17.8	958	352383	fast	24	41.0	0.98	0.75	0.75	0.75	1.00	1.00	$388,433,307	108%	0.27

Figure 2.21. MATE Table Attribute Headings

The MATE table consists of 256 design variants with different combinations of IPS components and parameter values. The baseline MATE tradespaces for the IPS are depicted in Figures 2.22 and 2.23. With the IPS tradespace explored, only a few optimum architectures are considered.

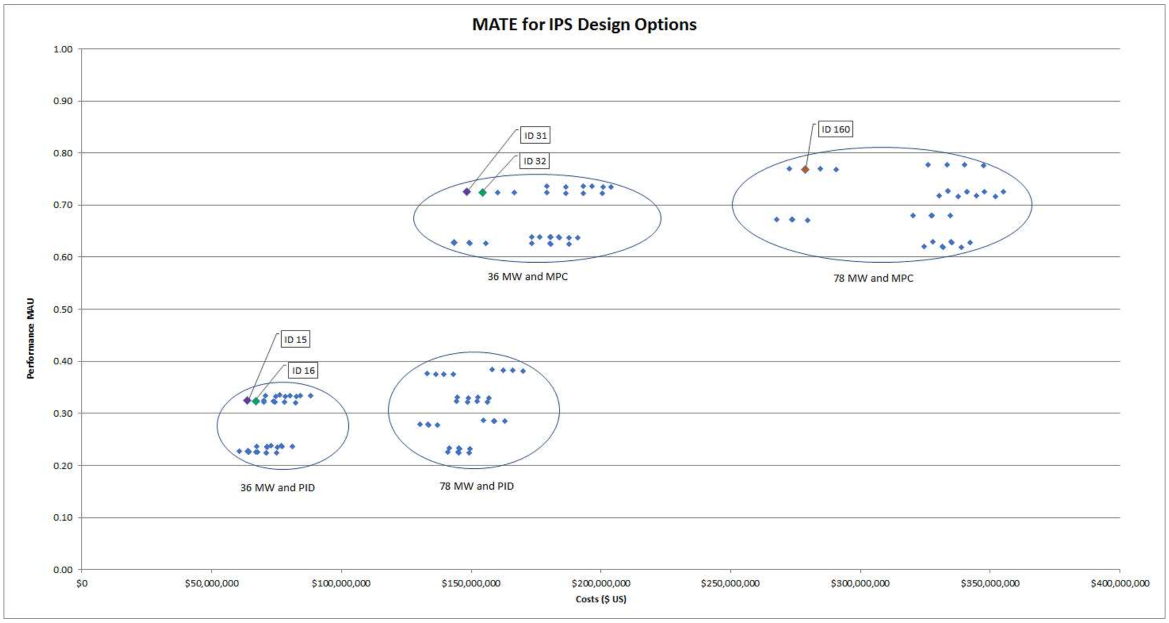


Figure 2.22. Baseline MATE IPS Design Alternatives for Performance and Costs

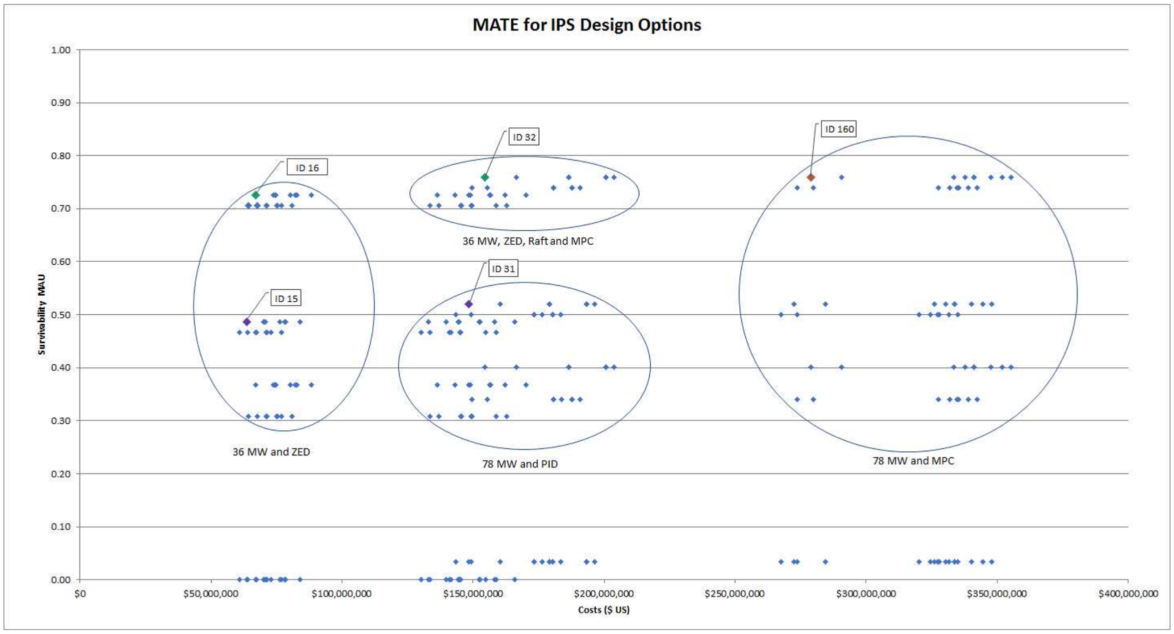


Figure 2.23. Baseline MATE IPS Design Alternatives for Survivability and Costs

The attributes of performance, survivability and costs are plotted together in order to visualize a different perspective with a three-dimensional pareto front, as depicted in Figure 2.24.

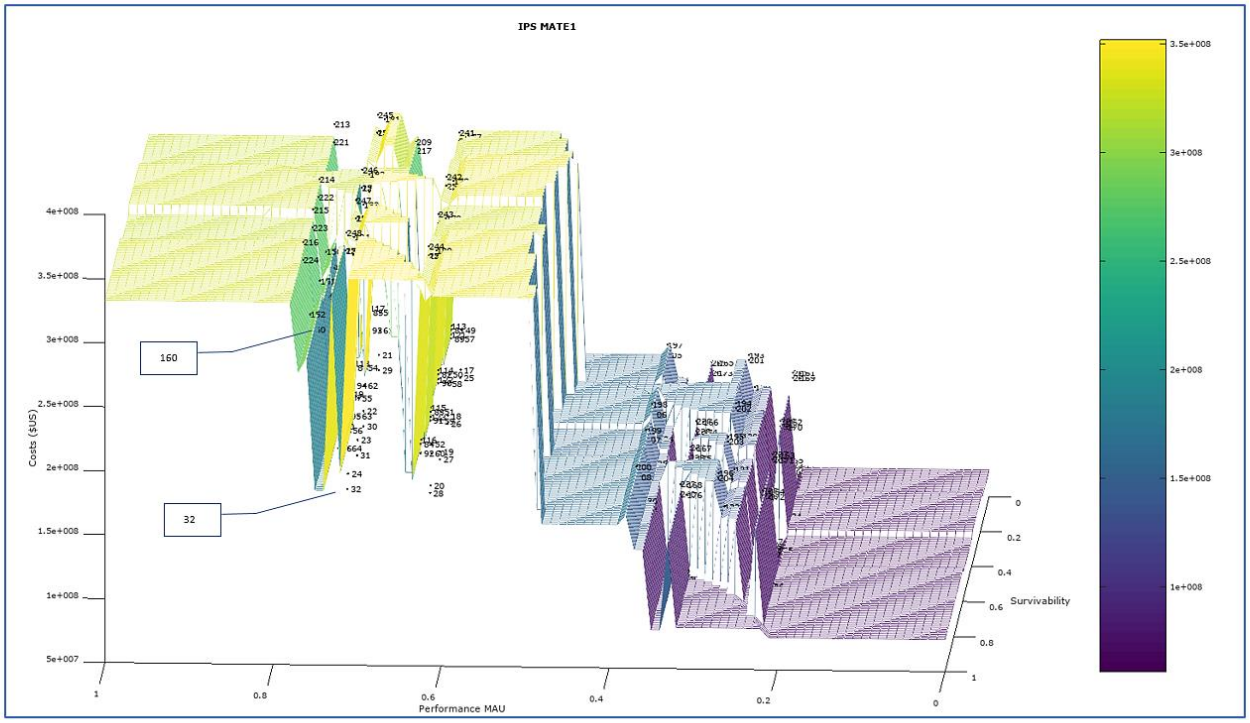


Figure 2.24. Baseline MATE IPS Design Alternatives for Performance, Survivability and Costs

2.21.2 *IPS Design Attribute Sensitivity Analysis*

There can be sensitivity with baseline design alternatives to remain on the pareto front given uncertainty with cost and estimates of attribute weights. In this case study, the weightings of the attributes under the Performance utility were changed in order to investigate the robustness of the baseline pareto design alternatives. In particular, the Mobility attribute was increased by 0.2 while the Operability attribute was decreased by 0.2. As depicted in Figure 2.25, the result of this sensitivity analysis was that the baseline design alternatives remained on the pareto front.

The optimum designs across the performance and survivability versus cost tradespaces were found to be design IDs 32 and 160. Both designs are based on conventional diesel generators and gas turbines, MPC, 320 MW Ultra-Capacitors, ZED, and Raft configurations.

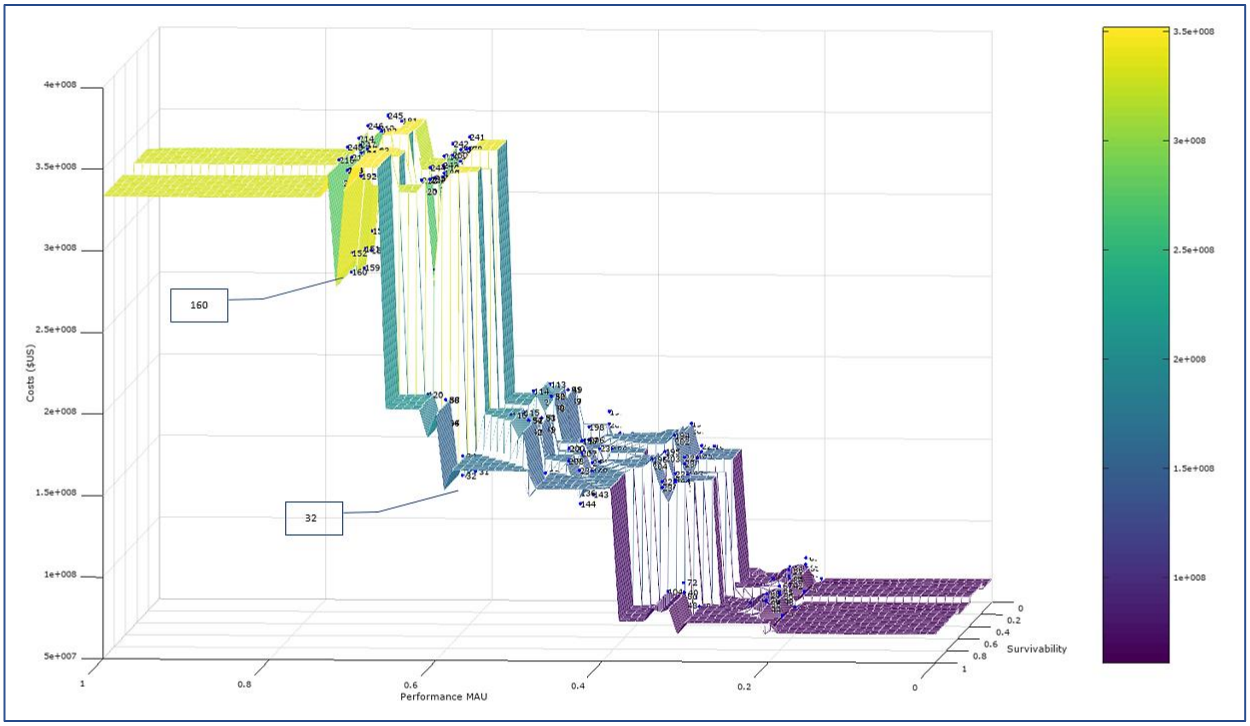


Figure 2.25. Attribute Weighting Sensitivity Analysis and MATE-Capability Design Alternatives Performance, Survivability and Costs

2.21.3 *IPS Design Cost Sensitivity Analysis*

A second sensitivity analysis was conducted with respect to cost volatility across the different design alternatives using the Monte Carlo method. This is based on a beta distribution for each design with a minimum cost of minus 30 percent and a maximum of plus 150 percent. As depicted in Figure 2.26, the result of this analysis indicated that optimum design IDs 32 and 160 remained on the pareto front.

Design ID 32 corresponds to 36 MW total power, conventional DGs and GTs, MPC controller, 320 MJ HESS, ZED configuration, and Raft mounting. Design ID 160 corresponds to the same components as ID 32 but with a total generating capacity of 78 MW.

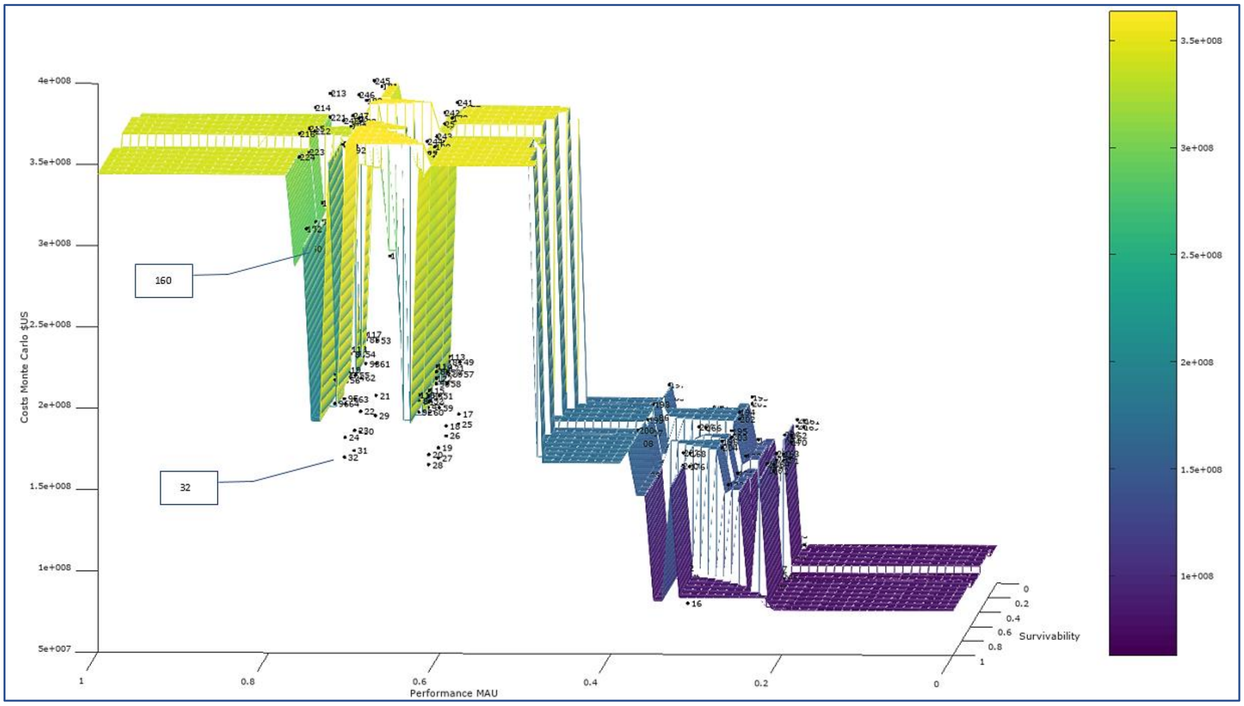


Figure 2.26. Cost Sensitivity Analysis and MATE-Capability Design Alternatives

2.21.4 *Homer Pro® Electrical Plant Optimization Software and IPS Designs*

In order to further validate the sizing of IPS components for these two designs, Homer Pro® Microgrid software was utilized. The wartime cruising load profile was used as input into this software with the high-end load estimated as peak load. The DG and GT sets and Ultra-Capacitor were simulated while MPC and the attributes of Power Quality, Transient Time Response, and QOS were not, but could be validated in software such as MATLAB®. The fidelity of Homer Pro® software was not adequate to analyze high energy weapon pulse loads; again MATLAB® may serve this purpose.

The design alternative ID 32 with two 3 MW DG sets and two 15 MW GT generator sets was analyzed with Homer Pro® software using a Cycle Charging controller. This controller has a charging strategy where whenever a generator is required, it operates near or at full power. When available, surplus energy is used to charge energy storage.

The 320 MJ Ultracapacitor was also included in the architecture consisting of 118 banks of 200 cells in series, providing 600V. The nominal cell voltage used was 3V with a maximum charge/discharge of 2200 amps, the rated capacitance of the ultracapacitor is 3000 Farads.

The overall configuration generally follows design ID 32 with an electrical load profile based on DDG 51 at 25 knots under wartime cruising, as depicted in Figure 2.27. The percentage utility of loads for DDG 51 destroyer were scaled for a 24-hour period for input into Homer Pro® software.

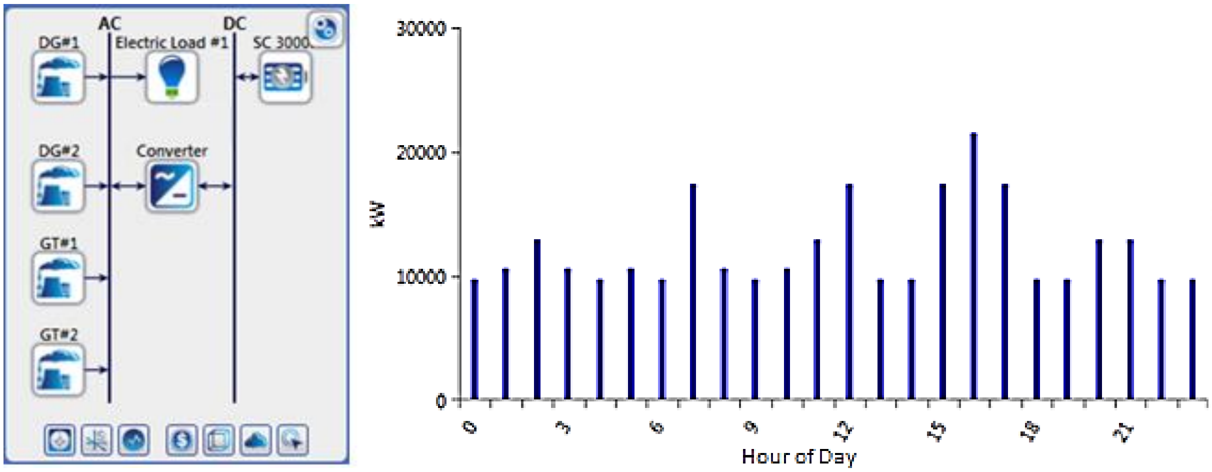


Figure 2.27. IPS Configuration and Assumed Load Profile in Homer Pro® Software

With simulation across the year for this load profile and plant configuration, the peak operating load was estimated at 36.1 MW with an average load of 12.3 MW and an average fuel consumption of 3.2 m^3/hr. The load profile across a few days with 10 percent randomness is depicted in Figure 2.28.

With the Cycle Charging controller, the on-off operation of generator sets at near peak efficiency is apparent in Figure 2.29, with some supplemented power from the ultracapacitor.

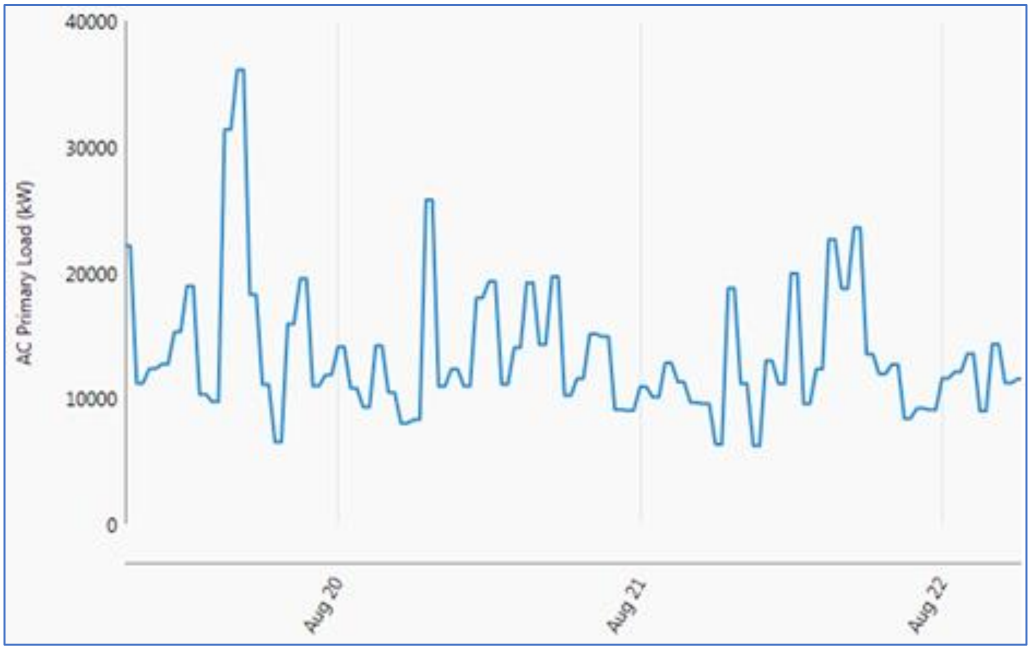


Figure 2.28. IPS 36 MW Capacity Load Profile

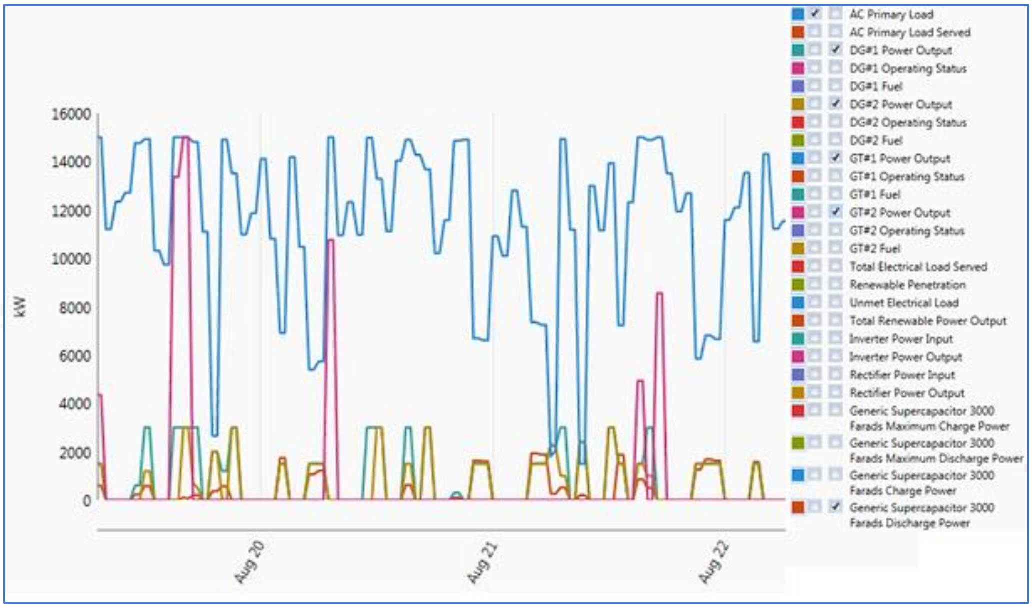


Figure 2.29. IPS 36 MW Plant Response to Load Profile With Cycle Charging

The same simulation was conducted for the design alternative with two 3 MW DG sets and two 36 MW GT generator and a cycle charging controller. The overall configuration generally follows design ID 160 with a load profile in accordance with the DDG 51 at 30 knots under wartime cruising, as depicted in Figure 2.30.

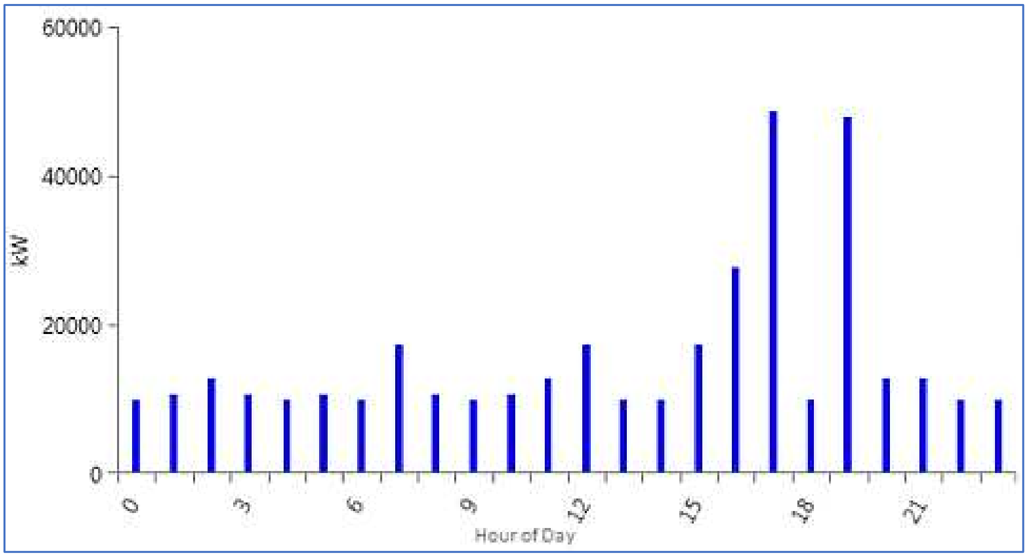


Figure 2.30. IPS 78 MW Capacity Load Profile

With simulation across the year for this load profile and configuration, the peak operating load was estimated at 78.1 MW with an average load of 15.4 MW and an average fuel consumption of 4.3 m^3/hr. The load profile across a few days with 10 percent randomness is depicted in Figure 2.31.

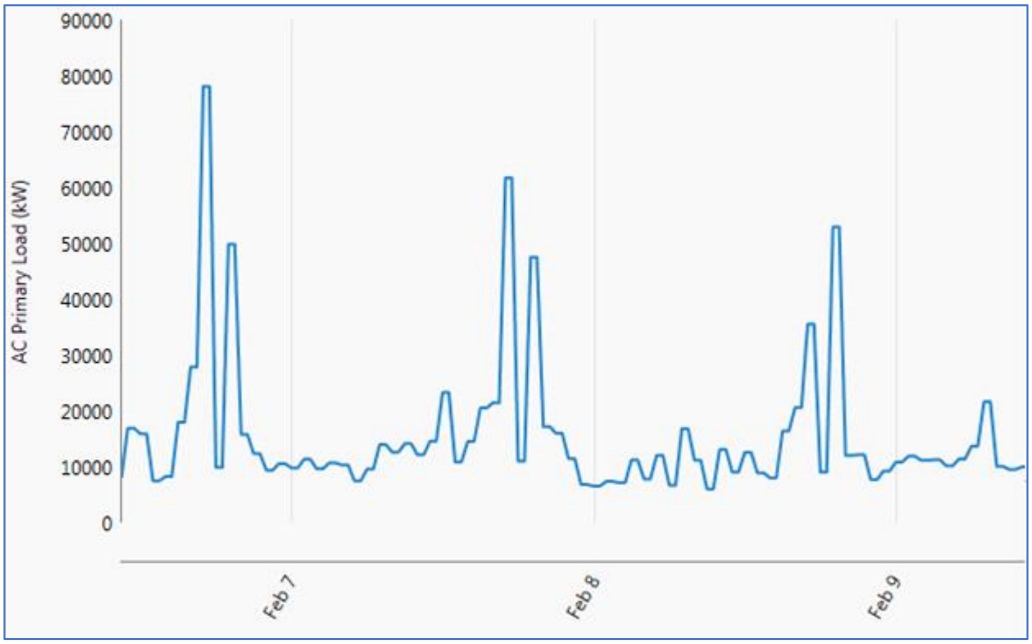


Figure 2.31. IPS 78 MW Capacity Load Profile Within Homer Pro® Software

With the Cycle Charging controller, the on-off operation of generator sets at near peak efficiency is apparent in Figure 2.32 with some supplemented power from the ultracapacitor.

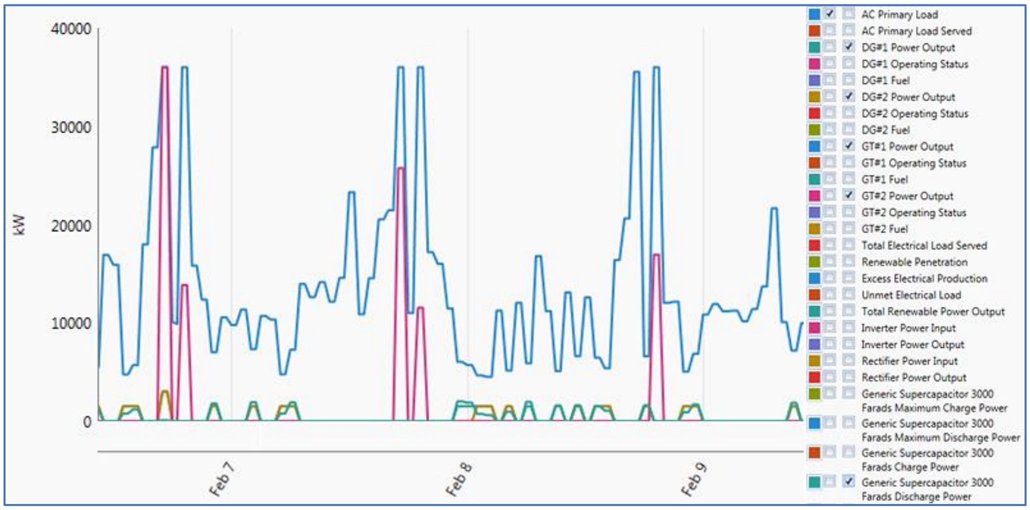


Figure 2.32. IPS 78 MW Plant Response to Load Profile with Cycle Charging

The effect from changing the controller from Cycle Charging to Load Following was investigated through use of Homer Pro® software for the 78 MW plant configuration. Load following controls generators to produce only enough power to meet load demand. As depicted in Figure 2.33, the number of on-off cycles for generators is reduced compared to the case with cycle charging. The HESS supplements power as required.

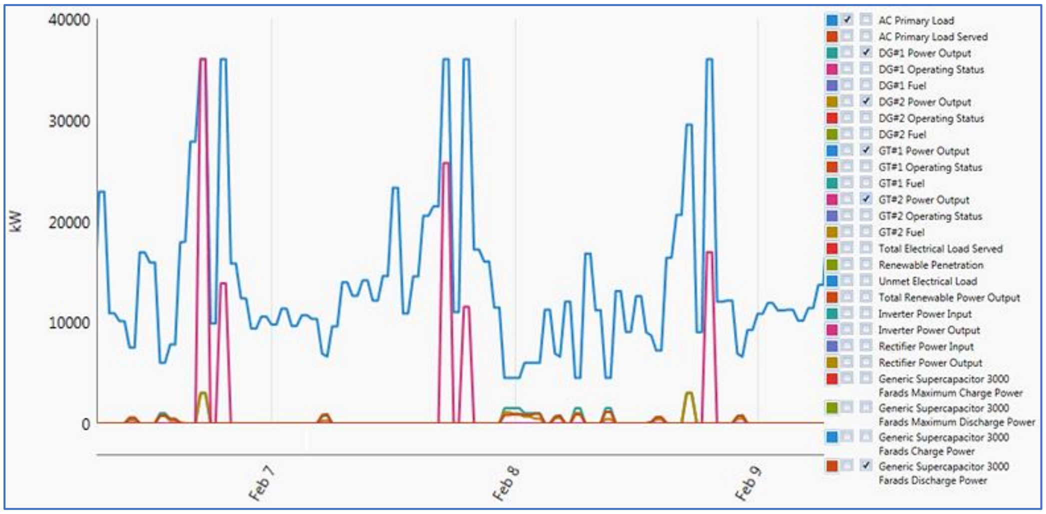


Figure 2.33. IPS 78 MW Plant Response to Load Profile with Load Following

The use of Homer Pro® software in demonstrating two different types of controllers provides insight into how power management systems and their controllers can have different effects on system attributes. For simplicity and the purposes of the current study, a choice between conventional PID and MPC controllers is incorporated into the simulator to demonstrate functionality of the simulator and effects on system attributes.

2.21.5 *Factorial Experiments and IPS Capability Response Surface Methodology*

The IPS costs required to achieve different mission capabilities can be visualized through factorial analysis. These capabilities consist of mobility, operability, ASuW, and ASW. From the modified MATE model value space, factorial analysis of attribute values is used to develop a response surface algorithm showing the main effects of mobility, operability and their interaction with respect to costs.

$$Costs = \$194{,}704{,}935 + \$70{,}451{,}684 * Mobility + \$73{,}142{,}830 * Operability \\ + \$28{,}954{,}145 * Mobility * Operability \tag{2.9}$$

This interaction is shown in the response surface depicted in Figure 2.34.

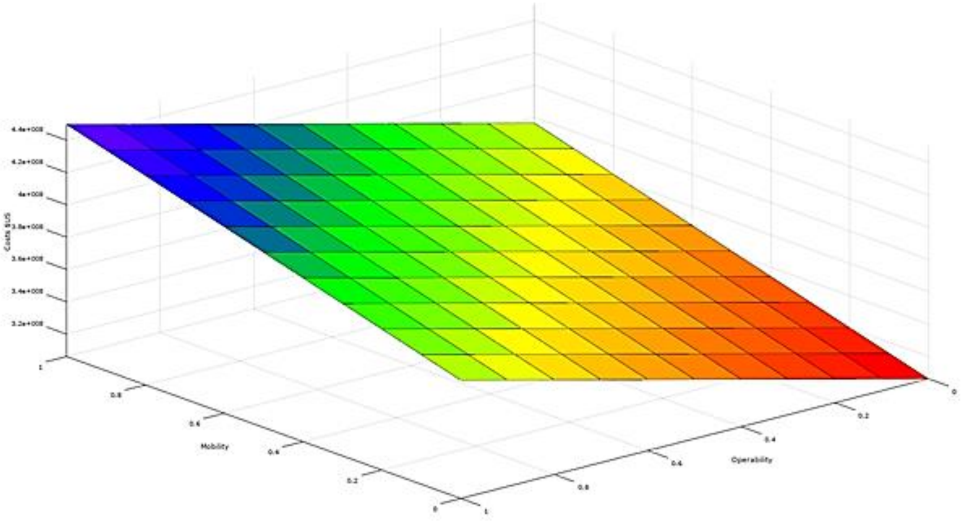


Figure 2.34. RSM Chart for Operability Mobility and Costs

This methodology can be used to visualize the interaction of other selected attributes from the MATE model but would require several response surface charts to be developed.

2.22 Conclusions

Through application of the modified MATE model for the IPS case study, design IDs 32 and 160 were determined to be optimal IPS design alternatives on the pareto front of performance, survivability and costs. Design number 32 represents a 36 MW IPS with 320 MW HESS configuration while number 160 represents a 78 MW IPS with 320 MW HESS.

The exercise of investigating and validating a suitable IPS architecture from optimal design alternatives adds validity and realism to the case study applied in the current research. Moreover, a tangible set of IPS design variables and attribute data can be used to exploit and validate other related models in development of the management flight simulator.

Deriving a set of variables and attributes involved decomposing and analyzing IPS architecture components against requirements. Arriving at a set of synthesized objective attributes can aid decision-making. Moreover, non-dimensional attributes can help provide for a common language among multiple disciplines.

Several tools and validation methods were applied in developing the modified MATE model and selecting a suitable IPS architecture including AHP, pair-wise comparison of attributes, sensitivity analysis, and Monte Carlo simulation. This demonstrates the many tools that are available in concept design and that the modified MATE, new value space and their emergent properties can be of value throughout the design cycle, as well as of value in developing the management flight simulator.

Both three-dimensional MATE tradespaces and response surface charts can provide useful visualization tools for tradeoff solutions and decision-making. These tools are limited in their ability to show the complete hierarchy of attributes in one view. However, the modified MATE model can serve as a reference model for attribute levels when parameters and components are changed later in the design. In displaying the new value space for attributes on one platform, the DSS is investigated.

Chapter 3 – Developing a Decision Support System

3.1 Introduction

This chapter builds on the previous chapter and investigates a decision-making framework that can provide visualization of several design attributes on one platform. The DSS is an extension of the modified MATE model and forms part of the larger integrated model and simulator in the current study. The focus of the current study is on the preliminary and detailed design tradespace where the MATE model is brought forward from the conceptual design stage.

The DSS takes advantage of the new value space identified in the previous chapter and considers aspects of Decision Theory and other factors in its development and use.

3.2 Motivation

Bringing the modified MATE model and a comprehensive set of design attributes that are inherently linked to requirements can have value throughout the design cycle. However, this model is limited in its ability by itself to succinctly show these attributes on one platform and to visualize changes in attributes during the design cycle. On the other hand, the modified MATE model can be used as a reference model in supporting an analytical DSS.

The DSS can help to prevent product failure, bring multiple disciplines together, and resolve competing demands for changes and redesign. Along with competing demands, teams require comprehensive multi-disciplinary design information in a one location for data-driven informed decision-making.

The effects of change propagation have not been addressed in developing models despite the capability of enterprise Product Data Management (PDM) systems to do so [48]. This chapter investigates change propagation and how it can be captured within the DSS.

The opportunity is favorable to implement DSS models with government initiatives to improve procurement strategies, product efficiencies and to advance data optimization techniques.

3.3 Objectives and Related Research Questions

Determining what the DSS and the larger integrated framework might look like is a question in the current study. In addressing this question, successive steps are taken in investigating potential frameworks and models across the design cycle and working toward a comprehensive and holistic integrated model. These steps include investigating why previous attempts to integrate models have failed and what assessment and success criteria looks like.

Specific questions addressed in this chapter include how early design analysis, risk reduction, improved collaboration, and decision-making can be achieved within a DSS.

3.4 Background

The aerospace industry appears to be leading in the application of systems engineering and DSS models; this does not appear to be common practice in other industries such as the marine industry. Nevertheless, the design of warships and its systems are viewed as analogous to complex aerospace systems and require a similar level of detail and rigor that may be best sought through adopting systems engineering practices and multi-discipline management tools.

The modified MATE framework discussed in the previous chapter is relatively straight forward in achieving an optimal marine IPS design on the pareto frontier; however, once the design is selected and additional stakeholders become involved, the amount of information can significantly increase where adhering to the design process can be difficult. Throughout this process, there will inevitably be the need for changes to the design, budget, resources and schedule. The drivers for these changes can be diverse and many but may be captured as risks within a DSS.

One way to deal with these risks is to monitor the associated system components, MATE design variables and attributes within a DSS model. The intent of this model is to monitor and help manage any variances in design variables and attributes throughout the design cycle.

In managing design attributes, there can be challenges in tradeoffs and in balancing competing demands. Moreover, how decisions are made can negatively affect outcomes; the DSS in the current study is a step toward addressing these issues.

3.5 Selected IPS Case Study Design

With a selected design from the MATE pareto frontier, trade-offs continue throughout the design development process where there are stakeholder competing demands, new constraints, environmental effects, and an evolving product design. The IPS optimal design selected from the case study in the previous chapter is ID 32. This architecture consists of two diesel generators, two gas turbines, an advanced control system, a 320 MW Ultra-Capacitor set, a ZED, and a raft configuration. The attributes for this design are provided in Table 3.1, these attributes will form the baseline for continued work in developing the simulator in the current study.

Table 3.1. Selected IPS Architecture Number 32

Design ID	Installed Power MW	Performance	Survivability	Cost $US	Schedule Slippage (Percent)	SRL
32	36	0.58	0.76	154,523,359	78	0.32

The design variables associated with the MATE process and design ID 32 are provided in Table 3.2. These include options that may be exercised within a DSS framework as part of design change management.

Table 3.2. Design Variables for Selected IPS Architecture ID 32

Design Variables	Options		Design ID 32
Total Installed Power	36 MW	78 MW	36 MW
DG Type	Conventional	WHR	Conventional
GT Type	Conventional	WHR	Conventional
PMS Type	MPC	PID	MPC
HESS Type	Ultracapacitor	Flywheel	Ultracapacitor
HESS Capacity	320 MJ	160 MJ	320 MJ
Compartmentalization	ZED	Conventional	ZED
Shock Hardening	Raft	ISO	Raft

3.6 Importance of The IPS Case Study for Integrated Model Development

The IPS case study helps validate functionality of the integrated model developed in the current study. It allows for in-depth analysis of design attributes and how they might be jointly managed by PM and SE disciplines. The IPS case study is complex enough to help validate the integrated model so that other complex systems may be applied using approaches discussed in the current study and using the existing structure of the model.

3.7 Criteria for Optimization and DSS Models

There are several existing optimization tools and models for decision-making. Areas requiring improvement in Multidisciplinary Design Optimization (MDO) models include the level of optimization and achieving the right fidelity [49].

Inadequate fidelity, improper matching of models, and immaturity of methods can make industry hesitant to adopt MDO models [49]. A taxonomy for matching the right tools and models to the level of required analysis and fidelity during the design cycle is depicted in Figure 3.1. The simulator in the current study may be thought of as residing within the taxonomy at the system, multi-attribute and preliminary design stage. Notwithstanding this, the IPS case study may be thought of as a SoS where attribute levels may be aggregated up to the overall system, or ship in this case.

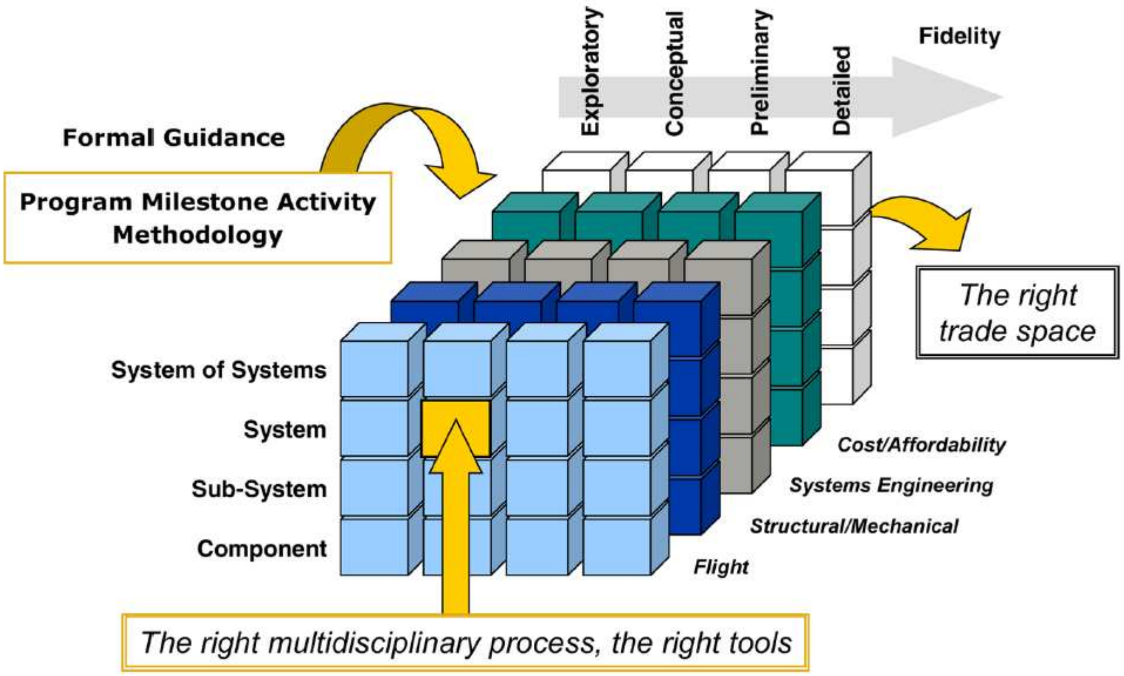


Figure 3.1. Taxonomy for Matching Multi-Disciplinary Tools and Models [49]

There are other criteria that can be applied in assessing the DSS framework in the current study, this criteria consists of simplicity, transparency, efficiency, accuracy, and portability [8].

Simplicity refers to the ease of implementation, transparency refers to the ease of understanding the model, efficiency is related to computational processing effort and speed, accuracy refers to the degree of approximation, and portability deals with integration of data from the various disciplines.

Many information systems present tabular data for product information that can be difficult to understand. As noted in one study, a graphical dynamic interface that presents the product’s change history help users to identify the correct configuration [48]. The DSS in the current study may help in this regard.

Stage-gates for decision making were introduced in the 1980’s as a disciplined approach for developing new products and getting them to market faster. Today’s more turbulent environment calls for a more flexible and adaptive approach, one the incorporates aspects of agile management. This adaptive approach includes the ability to respond to fluid information and changing customer requirements [50].

Use of the DSS and simulator provide for continuous review of attributes as part of an agile management approach. Automating parts of the DSS can reduce time in looking for information and analyzing it during stage-gate, and equally during continuous reviews.

Providing the right level of automation for the right function of a task can optimize the user's workload and situational awareness. It was found that high levels of automation in information analysis and action implementation can enhance team performance and reduce workload [51].

An important aspect in developing the DSS and simulator in the current study is to provide a level of automation and interactive user experience (UX). User interfaces can include dynamic controls for adjusting inputs into the simulator to better understand their impact on output parameters. Automation and UX not only addresses the criteria of simplicity and transparency but addresses the human interaction aspect in decision-making.

Other problems with current MDO methodologies include their inability to capture changing needs during product development and to include engineers 'in-the-loop' for feedback [49]. In the current study, this feedback also includes the PM and SE disciplines to be 'in-the-loop'. Capturing changing requirements and their impact on attributes are also addressed in the current study.

3.8 Decision-Making Process for Changes

Design and engineering change decision-making can be based on experience and good judgement, but this may not lead to optimum solutions. For complex systems, an improved process may involve the analysis of system components and their interaction to understand the effect of change and its propagation throughout a system.

In product design development, issues can often arise that require what-if scenarios and informed decision-making to arrive at an optimized and balanced solution. The typical and proposed design change processes in the current work are depicted in Figure 3.2.

In the typical design change process, the focus is on performance requirements and costs while the proposed process takes a more holistic approach through evaluation of design attribute levels and the monitoring of constraints and requirements. The trigger represents an event such as a change in attribute levels, trends or the requirement for a design change.

The approach in the current work for achieving optimal design changes involves the integration and use of models and tools within the DSS and simulator.

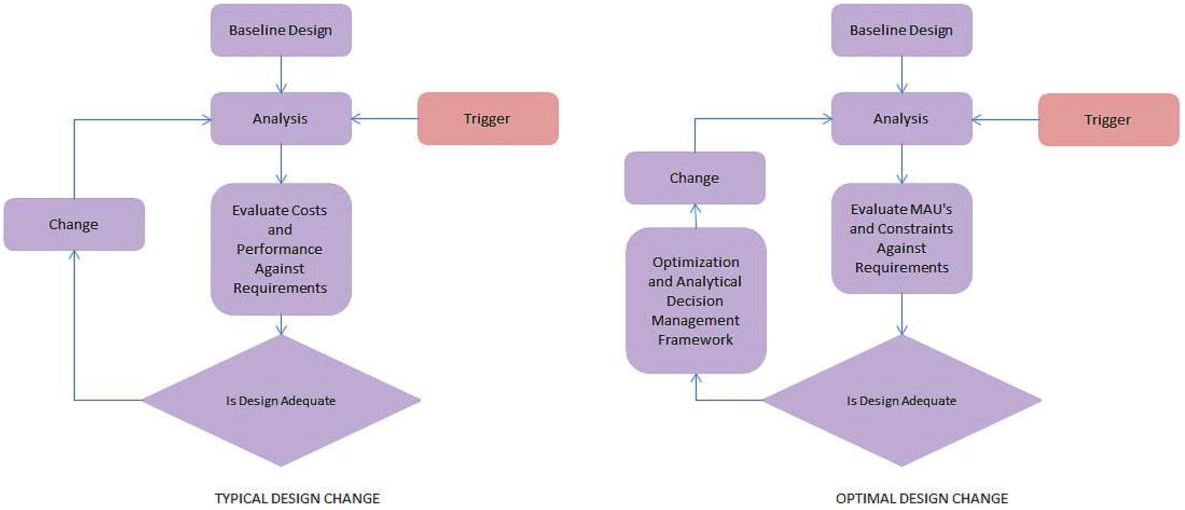


Figure 3.2. Design Change Decision-Making Processes

3.9 Typical Design Changes

In following an improved design change process and in validating models within the DSS and simulator, typical triggers for design changes are investigated in this chapter. The source for these triggers come from both the technical and program risks.

3.10 The Standard Risk Model

The SRM approach is a well-established and proven approach used in industry [52], the process is depicted in Figure 3.3.

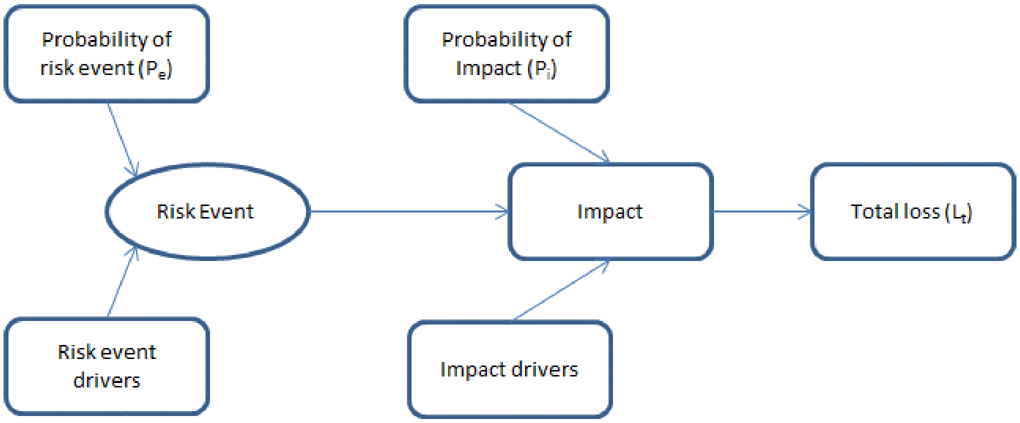


Figure 3.3. The SRM Process [52]

In the current work, risks are grouped into two main categories, one for program risks; the other for technical risks. While the probability of program risk events may be used for both risk categories, the probability of impact on the program and that on the affected system component are treated differently in the current work. The expected program loss in terms of schedule delay and costs can be calculated using the SRM. The expected loss from a system design perspective may require information from the modified MATE model, DSM, a component changeability assessment, and SRL measures. Typical triggers or risks to the program may be played out in what-if scenarios using the SRM as a starting point within the DSS.

In order to mitigate risks and decrease expected losses, risks should be identified, analyzed, prioritized and decreased. The risk management approach followed in the current study consists of the five-step risk management cycle process [52], as depicted in Figure 3.4.

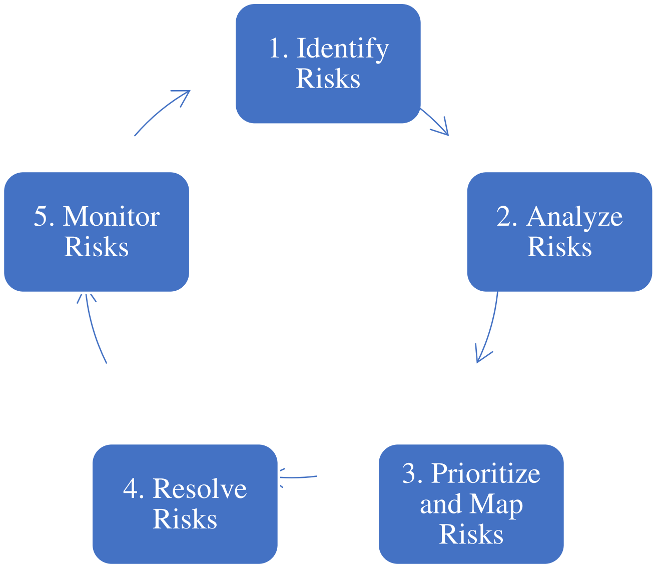


Figure 3.4. The Risk Management 5-Stage Cycle [52]

As risks with design changes can affect a primary system component as well as other associated components, the level of changeability and change propagation is of value in understanding the scope and implications of change.

3.11 The DSM and Linkages to the SRM

In many cases, the increased complexity of systems has made it difficult to achieve project success. It has also been a challenge to properly quantify and model the emergent behavior of complex systems and the coupling of system components [49]. Furthermore, deciding when to act in response to risk can be difficult. Within the DSS, a proactive approach is taken through the SRM and through systems engineering tools such as the DSM. Technical risks are mapped to primary system components where they can be further analyzed. The DSM and investigation into change propagation involves breaking down system components and their interfaces to simplify and better understand their complexity.

One of the key design principles in complex design is to make components that are likely to be changed throughout design more modular and robust. The DSM and partitioning of components is a method to help visualize system groups as candidates for modularity. The DSM can also be used to capture changeability measures for key components; this of interest in the current study to identify IPS component changeability risks as well as change propagation. For instance, a change to the IPS Diesel Generator (DG) set can affect several related components as well as associated design variables and attributes.

The diagonal of the DSM typically lists the system direct components while the off diagonals represent the indirect dependency between components. To account for change propagation, direct and indirect flow of change probability and impact probability can be analyzed, as depicted in Figure 3.5.

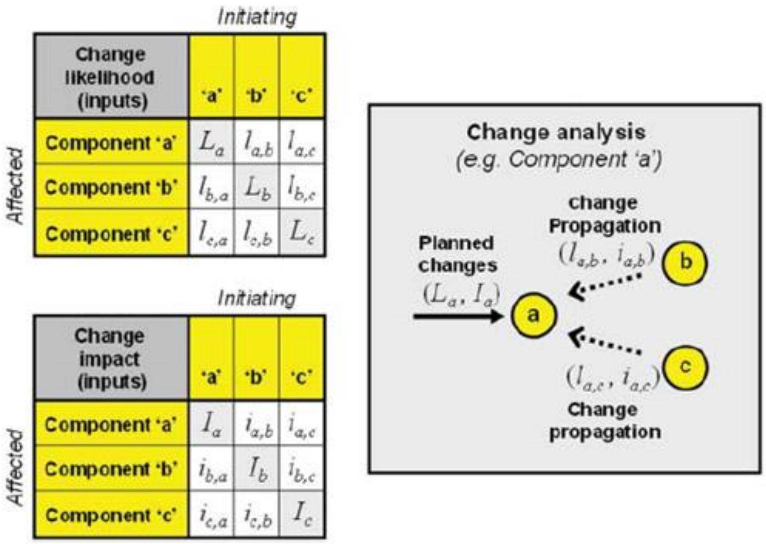


Figure 3.5. Direct and Indirect Components Affected by Change Risks [53]

The likelihood of direct change to component 'a' (L_a), as well as other directly affected components, is listed on the DSM diagonal. The current work takes a novel approach in linking the SRM probabilities to the DSM diagonals.

The SRM and its technical event and impact probabilities form a natural link into the DSM diagonals, this is automated in the current study. In the case of several risks being associated with a single system component, the highest risk value is chosen.

The likelihood of direct change propagation from ‘b’ to ‘a’ ($l_{a,b}$) describes how likely a change to component ‘b’ will lead to a change in component ‘a’. The likelihood of impact on redesign efforts follows the same logic. The column headings in the DSM represent initiating system components while row headings represent affected components. Taking interdependency of components and indirect change propagation into account leads to revised matrices that are based on change propagation trees as depicted in Figure 3.6 [54].

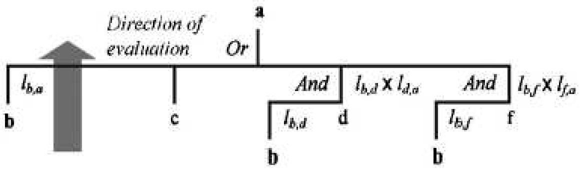
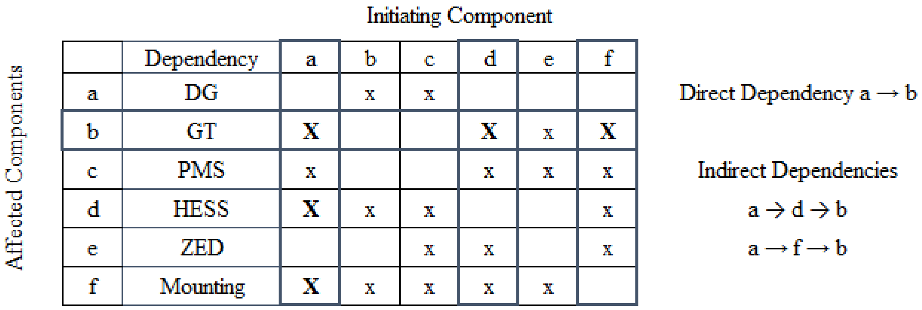


Figure 3.6. Component Change Propagation Tree [54]

The effect of change likelihood on component ‘b’ in Figure 3.6, given a change to component ‘a’, can be described.

$$L_{b,a} = 1 - \left(\left(1 - l_{b,a}\right) X \left(1 - l_{b,d}\, X\, l_{d,a}\right) X \left(1 - l_{b,f}\, X\, l_{f,a}\right)\right) \tag{3.1}$$

The direct and indirect propagation effects can be seen in the DSM highlighted rows and columns in Figure 3.7 for change propagation to component ‘b’ given a direct change to component ‘a’.



Initiating Component

Affected Components

	Dependency	a	b	c	d	e	f
a	DG		x	x			
b	GT	**X**			**X**	x	**X**
c	PMS	x			x	x	x
d	HESS	**X**	x	x			x
e	ZED			x	x		x
f	Mounting	**X**	x	x	x	x	

Direct Dependency a → b

Indirect Dependencies

a → d → b

a → f → b

Figure 3.7. Example of Direct and Indirect Change Propagation, Adapted [54]

Using similar logic, the risk and impact probability values are calculated using the risk propagation tree depicted in Figure 3.8, and equations 3.2 and 3.3.

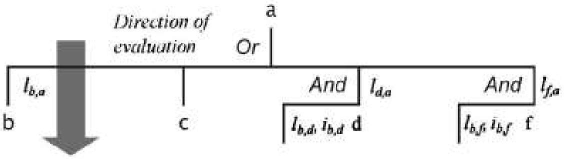
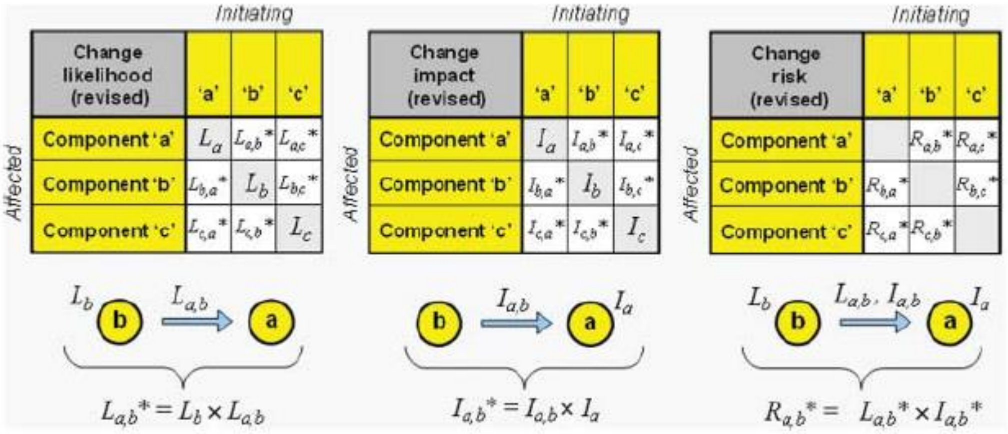


Figure 3.8. Risk Propagation Tree [54]

$$R_{b,a} = 1 - \left((1 - l_{b,a} \ X \ i_{b,a}) X \ (1 - l_{d,a} \ X \ l_{b,d} \ X \ i_{b,d}) X \ (1 - l_{f,a} X \ l_{b,f} \ X \ i_{b,f}) \right) \quad (3.2)$$

$$I_{b,a} = \frac{R_{b,a}}{L_{b,a}} \quad (3.3)$$

The resulting DSM matrices with change propagation take the form depicted in Figure 3.9 [53].



Change likelihood (revised)	'a'	'b'	'c'
Component 'a'	L_a	$L_{a,b}{}^*$	$L_{a,c}{}^*$
Component 'b'	$L_{b,a}{}^*$	L_b	$L_{b,c}{}^*$
Component 'c'	$L_{c,a}{}^*$	$L_{c,b}{}^*$	L_c

Change impact (revised)	'a'	'b'	'c'
Component 'a'	I_a	$I_{a,b}{}^*$	$I_{a,c}{}^*$
Component 'b'	$I_{b,a}{}^*$	I_b	$I_{b,c}{}^*$
Component 'c'	$I_{c,a}{}^*$	$I_{c,b}{}^*$	I_c

Change risk (revised)	'a'	'b'	'c'
Component 'a'		$R_{a,b}{}^*$	$R_{a,c}{}^*$
Component 'b'	$R_{b,a}{}^*$		$R_{b,c}{}^*$
Component 'c'	$R_{c,a}{}^*$	$R_{c,b}{}^*$	

Figure 3.9. Final DSM Changeability Matrices [53]

Change indices can be used to describe the effect of change on system components. For instance, the Incoming Change Likelihood (ICL) index describes how likely a component is expected to be changed due to change propagation and is calculated according to:

$$ICL = \frac{\Sigma \ Likelihood \ Row \ Entries}{Total \ Number \ of \ Components} \quad (3.4)$$

The Incoming Change Impact (ICI) index describes the impact on effort required in redesign due to change propagation and is calculated according to:

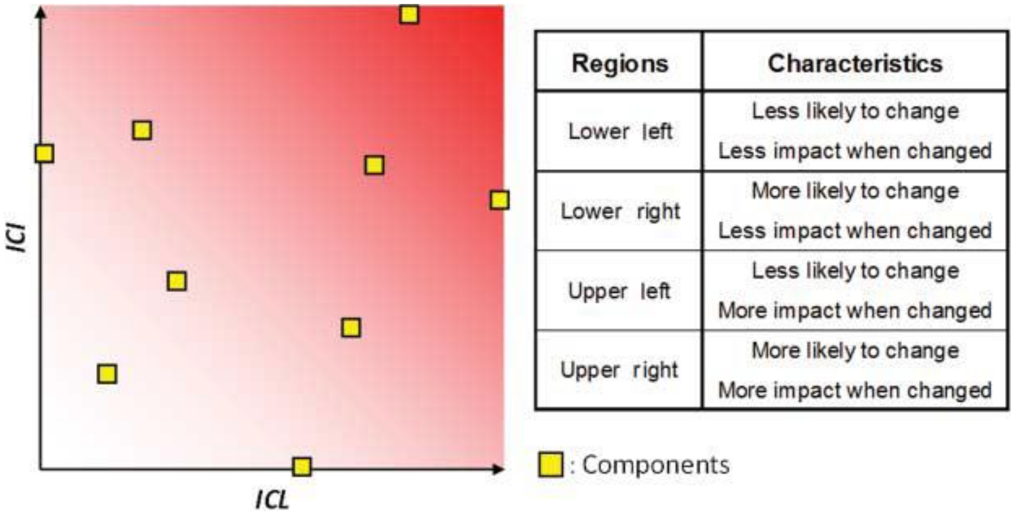
$$ICI = \frac{\Sigma\ Impact\ Row\ Entries}{Total\ Number\ of\ Components} \tag{3.5}$$

The Outgoing Change Risk (OCR) describes how a component can affect other systems in terms of change propagation and is calculated according to:

$$OCR = \frac{\Sigma\ Risk\ Column\ Entries}{Total\ Number\ of\ Components - 1} \tag{3.6}$$

Systems with a high OCR value have a strong influence on other components and therefore should be made less likely to change where the design principles of modularity and loose coupling may be appropriate. Conversely, systems with a low OCR are less likely to change and therefore may be more suited for standardization [53].

The indices described above may be normalized to provide a relative indication of components least and most affected by change in a system. The ICL and ICI indices may be plotted for system components as depicted in Figure 3.10.



Regions	Characteristics
Lower left	Less likely to change Less impact when changed
Lower right	More likely to change Less impact when changed
Upper left	Less likely to change More impact when changed
Upper right	More likely to change More impact when changed

Figure 3.10. Changeability of Components [53]

The changeability of components is included in the DSS to help assess the impact of both potential and realized engineering design changes. The normalized values for ICL and ICI provides for a common language when looking at changeability of components.

3.12 Management of Changes and New Measures to Manage Design Attributes

The modified MATE process described in the previous chapter provides for monitoring of the selected design, its MAU objectives and design vector values. When there is a potential change to the design, assessing its impact on design attributes requires a more dynamic DSS tool and performance management approach.

Six Sigma measures such as variation and Critical to Quality Metrics (CTQ) are adapted to the current study and DSS. The variation of attribute levels throughout the design cycle can be captured in control charts with appropriate CTQ metrics. While these metrics are typically used for chemical and manufacturing processes, they are applied to the design attributes in the current study.

Process Capability (C_{py}) is a common six sigma measure used to compare a process' natural variability against engineering tolerances and provides a measure of variability fit within tolerances [55] [56] [57].

$$C_{py} = \frac{USL - LSL}{6\sigma} \tag{3.7}$$

where *USL* is the upper specification limit, *LSL* is the lower specification limit and σ is the standard deviation.

The C_{py} measure is utilized in the current study to monitor the variability in attribute values over time, within the non-dimensional USL value of one and LSL value of zero. If engineering and program activities are stable, it is expected that there will be an acceptable variation in attribute values. On the other hand, an unacceptable variation may occur due to significant changes in design. There are however limitations with using Statistical Process Control (SPC) measures and include the requirement for more than 15 data points and the fact that charts typically track only one characteristic at a time [55]. With hundreds of changes possible in complex product management, this does not pose a limitation in the current study.

The higher the C_{py} value the better as it represents the number of times the process fits with the limits, values greater than one fit within tolerance limits. In addition to C_{py}, the C_{pky} value is a measure of the position of the process or attributes in relation to the tolerance limits. The lower of two C_{pky} values for upper and lower relative position-of-the-process is used in the current work.

$$C_{pky} = min\left(\left(\frac{USL-avg}{3\sigma}\right), \left(\frac{avg-LSL}{3\sigma}\right)\right) \tag{3.8}$$

Should C_{pky} be below one, the process will infringe upon specification limits. Both C_{py} and C_{pky} values are on interest in the current study in providing a measure of variability in attributes relative to limits, as depicted in Figure 3.11. These values are associated with IPS attributes, where low attribute C_{py} and C_{pky} values point toward design areas requiring investigation.

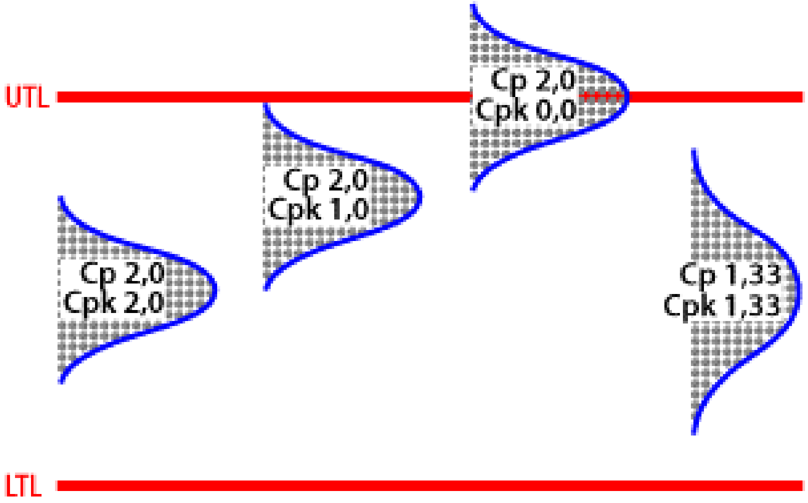


Figure 3.11. Process Variability Within Tolerance Metrics [56]

Control charts are used in the DSS and can provide a level of confidence in the stability of design attributes and may offer insight into design changeability of a system within USL and LSL constraints.

3.13 Design Attribute Payoff Tables, Bayes' Decision Theory and Other Decision Factors

Rationality in the different disciplines can often obey the rules of Bayesian theory; however, decision-making may not be so straightforward and other factors may have an impact [58].

These other factors can include the impact of changes on design attribute levels and system components. The typical monetary payoff tables used in Bayesian decision theory are augmented in the current study with design attribute payoff tables.

Better decision-making early in design can avoid increased costs and schedule delays later in the design cycle. The availability of broad data early in design can advance the Knowledge curve; use of the DSS and attribute payoff tables can help facilitate this.

Moreover, this early knowledge and prediction of risks and their impact can provide for early planning. The simulator itself serves as an early warning system with cues and triggers for deviations in design attributes and management curves.

In decision theory, the solution strategy depends on a priori probability with values and costs associated with the different decision options. With models built on decision theory, the numerical results do not require conscious decision-making. In conscious decision-making, the conscious mind must experience the outcome as positive or negative [59]. In the current study, these outcomes may include the state of design attributes and management curves.

The meaning of values and costs to different disciplines is a factor in optimal decision-making. While use of the simulator in the current study is viewed as a mechanism to aid unconscious decisions, the conscious mind may be in conflict. The conscious mind can involve both feelings and the different loyalties that engineers and managers may have.

While use of the simulator promotes Decision Theory, when confronted with the cognitive perception of gains and losses in utility or value of decisions, both the conscious mind and Prospect Theory can come into play. This is an important consideration in the gaming rules and structure of teams in the current study for overcoming the conflict between the conscious and unconscious mind.

The goal of optimal decision-making is to do it with minimal cognitive effort. However, in a stressful environment with time pressures, there can be a narrow focus on certainty of gains and less risk-taking. In these cases, there can be incomplete or ignored information where decisions are made quickly without looking at other tradeoffs and the balancing of demands. How information is presented, and the amount of information can affect decision-making.

The simulator captures comprehensive tradeoff information and makes it visually transparent in one place for the assessment of different solution options.

In Prospect theory, decisions are based on loss aversion, diminishing sensitivity and a reference point [60]. As depicted in Figure 3.12, the reference point for an attribute may be at a value of 0.3. A loss of 0.1 in its level may be perceived as twice as bad as an equivalent gain of 0.1. On the other hand, incremental gains in an already favorable attribute level can have a diminishing effect, dependent on the reference point.

Irrational decisions can be made on perceived potential gains and losses, dependent on the reference point. The simulator provides the different tradeoff decisions in tabular format with selection of the optimal decision based on objective attribute measures.

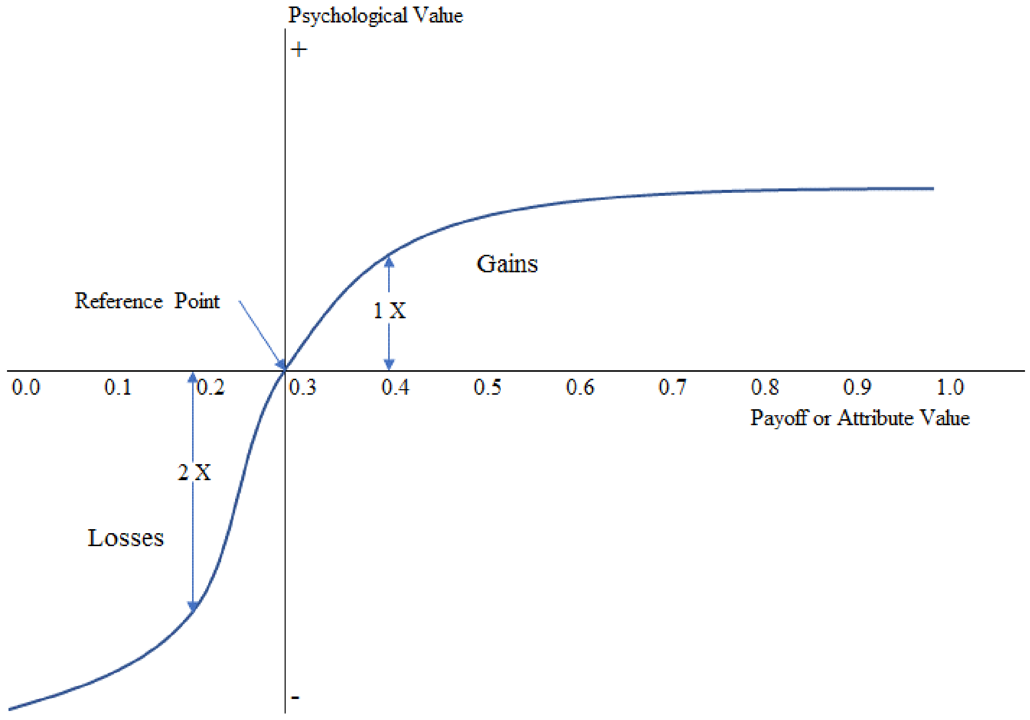


Figure 3.12. Attribute Payoffs and Prospect Theory, Adapted [60]

When problems occur in complex systems, the intuitive response is to find quick and easy solutions rather than long term effective solutions. This dilemma is apparent in the struggle between the systems engineer, project manager, engineering disciplines and other stakeholders in the project [7].

Resorting to quick solutions may be caused by a stressful environment with time pressures or reluctance to apply cognitive effort. Whatever the reason may be, when recurring similar problems arise, shifting-the-burden from finding a fundamental optimal solution to quick symptomatic solutions can occur [61]. When problems appear, the intuitive quick solution may not work in the long term.

As depicted in Figure 3.13, shifting-the-burden involves two balancing loops and one reinforcing loop [61]. The time delay or resistance in avoiding the fundamental solution leads to pursuing the quick solution. With this, side effects reinforce the problem including design issues. This forms a vicious reinforcing loop making it difficult to solve symptomatic problems. In terms of the current study, this reinforcing loop can create rework.

In the current study, the management flight simulator can reduce the delay for pursuing the fundamental optimal solution to symptomatic problems. It can do this through the automation of information, accessibility, transparency in results and ease of use.

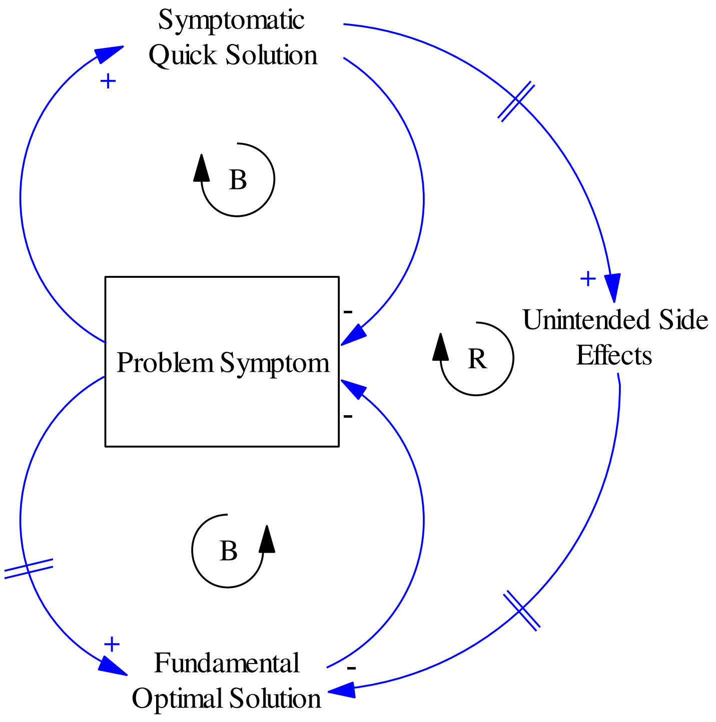


Figure 3.13. Shifting The Burden, Adapted [61]

3.14 Results

3.14.1 *Elements of the DSS*

The elements of the proposed DSS are depicted in Figure 3.14. Its functionality is demonstrated using data from the IPS case study. The DSS consists of the modified MATE, its new value space, commercial plant modeling updates for validating parameter values, attribute management, and interactive controls for adjusting system parameter and component types in playing out what-if scenarios in response to risks and potential design changes. In the DSS, the SRM and DSM are coupled to connect risks with associated primary system components. This approach to coupling models achieved portability in the integration of data from the different disciplines. The attributes of SRL, costs and RSS are available to both PM and SE for further analysis and decision-making.

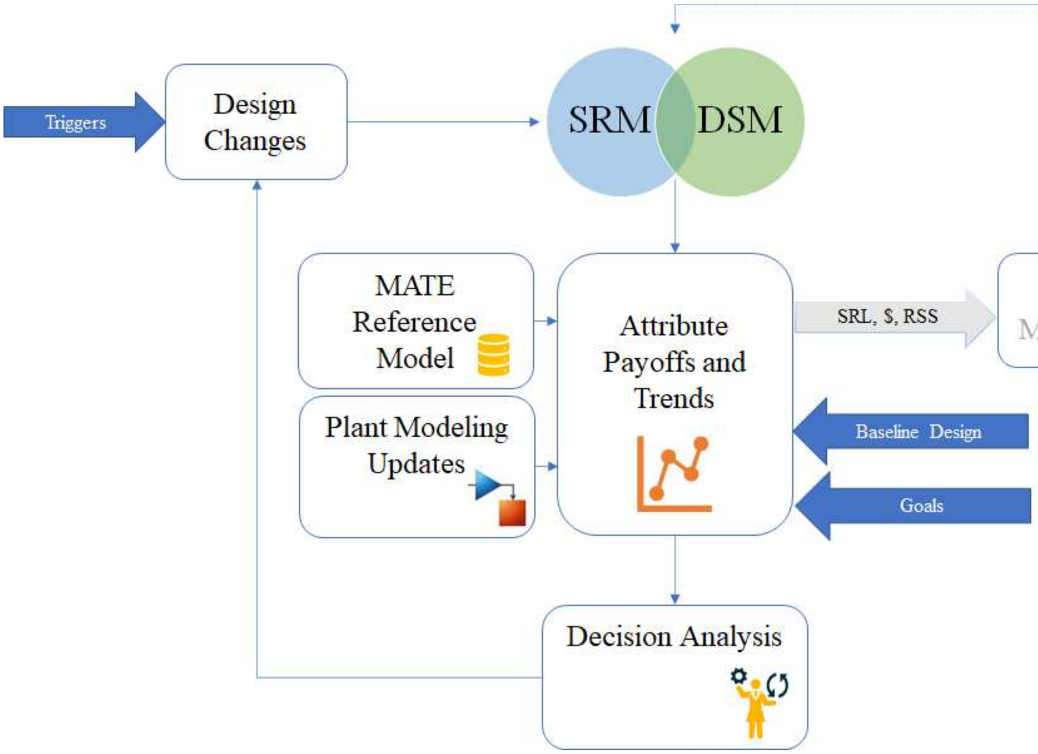


Figure 3.14. Elements of the DSS

3.14.1.1 *DSS and Design Change Triggers*

From an interview with a hydroelectric company, common technical factors that may trigger IPS design changes were identified, these include modeling and simulation results such as increased harmonics, lack of co-simulation tools, interference between systems, narrow design margins, and changes to total installed power requirements. Management factors were highlighted, including lack of communication between designers, new roles, and sequencing of the electrical design into overall design. External factors were noted, including political factors, fuel prices as they affect choice of engines, and changes to security measures.

In the same interview, it was noted that some components are easier to change than others. For instance, changing prime movers today may be easier than changing energy storage and control systems, especially with more complex control systems expected in the future.

From a broader set of interviews with shipyards, another hydroelectric company, electrical plant manufacture, and from a literature review [48] [62], the ten top risks or typical triggers are presented in Table 3.3.

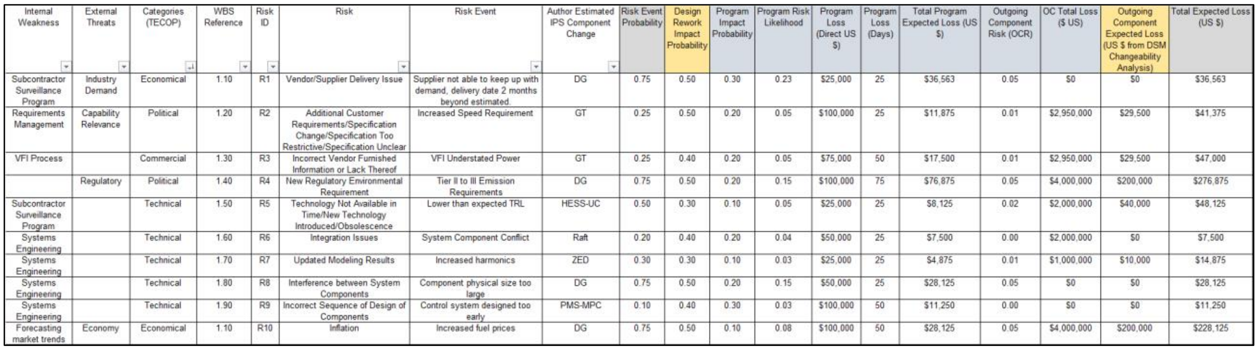
Table 3.3. Top Ten Typical Triggers or Risks for Design of an Electrical Plant

Shipyard Eastern Canada	Shipyard Atlantic Canada	Siemens Electrical	Quebec Hydro	Literature Review [48] [62]	Count	Typical Trigger/Risk	IPS Component Affected	Risk ID
1	1	1	1	2	6	Vendor/Supply Delivery Issue	DG	R1
1	1	1	1	2	6	Requirement/Specification Change	DG	R2
			1	2	3	Incorrect or Lack of Vendor-Furnished Information (VFI)	GT	R3
1	1		1		3	Environmental Regulation Change	DG	R4
		1	1	1	3	Immature Technology	HESS	R5
		1	1	1	3	Integration Issue	PMS	R6
		1	1		2	Model Updates (Harmonics)	ZED	R7
1			1		2	Interference Between Components	DG	R8
			1	1	2	Incorrect Sequence in Design of Components	PMS	R9
			1		1	Fuel Price Change (Inflation)	DG	R10

3.14.1.2 *DSS and The SRM*

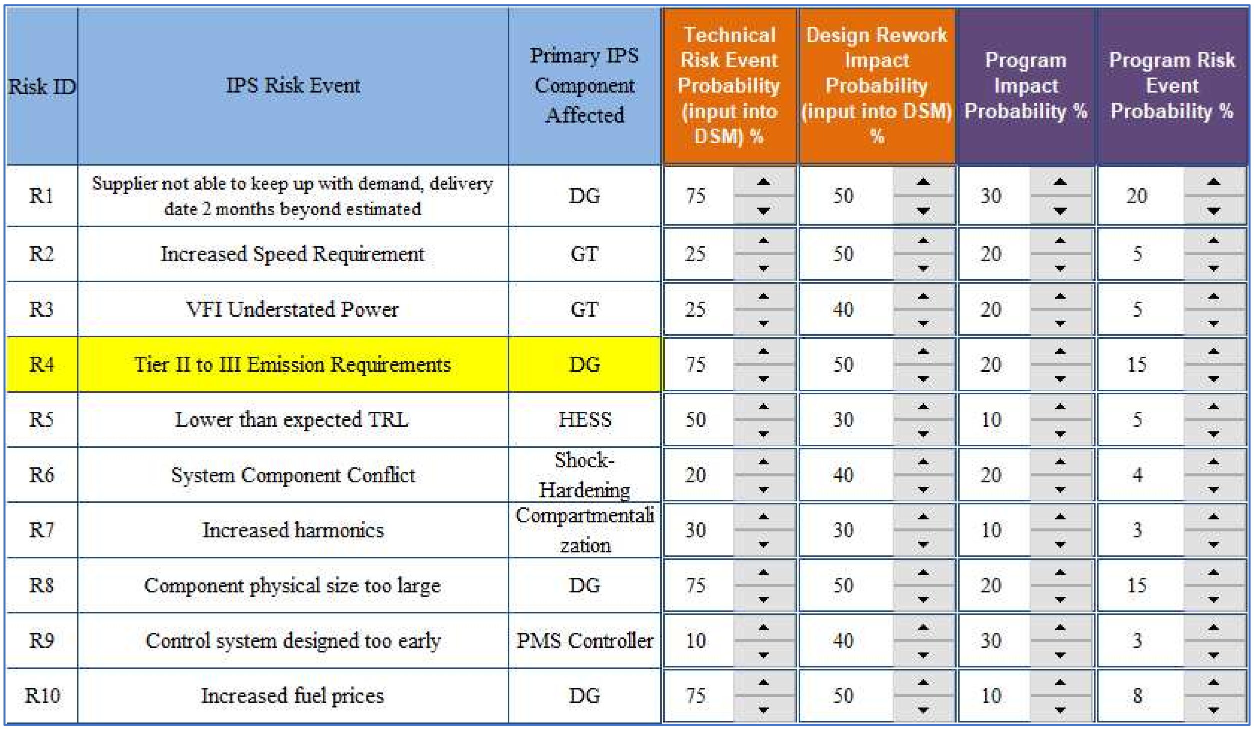
These top ten triggers were entered into the integrated SRM, depicted in Table 3.4, with estimated probabilities for risk events and for the program impact; the risk and loss at the system level were calculated through the DSM model.

Table 3.4. Adopting Typical Risks Within The SRM



Internal Weakness	External Threats	Categories (TECOP)	WBS Reference	Risk ID	Risk	Risk Event	Author Estimated IPS Component Change	Risk Event Probability	Design Rework Impact Probability	Program Impact Probability	Program Risk Likelihood	Program Loss (Direct US $)	Program Loss (Days)	Total Program Expected Loss (US $)	Outgoing Component Risk (OCR)	OC Total Loss ($ US)	Outgoing Component Expected Loss (US $ from DSM Changeability Analysis)	Total Expected Loss (US $)
Subcontractor Surveillance Program	Industry Demand	Economical	1.10	R1	Vendor/Supplier Delivery Issue	Supplier not able to keep up with demand, delivery date 2 months beyond estimated.	DG	0.75	0.50	0.30	0.23	$25,000	25	$36,563	0.05	$0	$0	$36,563
Requirements Management	Capability Relevance	Political	1.20	R2	Additional Customer Requirements/Specification Change/Specification Too Restrictive/Specification Unclear	Increased Speed Requirement	GT	0.25	0.50	0.20	0.05	$100,000	25	$11,875	0.01	$2,950,000	$29,500	$41,375
VFI Process		Commercial	1.30	R3	Incorrect Vendor Furnished Information or Lack Thereof	VFI Understated Power	GT	0.25	0.40	0.20	0.05	$75,000	50	$17,500	0.01	$2,950,000	$29,500	$47,000
	Regulatory	Political	1.40	R4	New Regulatory Environmental Requirement	Tier II to III Emission Requirements	DG	0.75	0.50	0.20	0.15	$100,000	75	$76,875	0.05	$4,000,000	$200,000	$276,875
Subcontractor Surveillance Program		Technical	1.50	R5	Technology Not Available in Time/New Technology Introduced/Obsolescence	Lower than expected TRL	HESS-UC	0.50	0.30	0.10	0.05	$25,000	25	$8,125	0.02	$2,000,000	$40,000	$48,125
Systems Engineering		Technical	1.60	R6	Integration Issues	System Component Conflict	Raft	0.20	0.40	0.20	0.04	$50,000	25	$7,500	0.00	$2,000,000	$0	$7,500
Systems Engineering		Technical	1.70	R7	Updated Modeling Results	Increased harmonics	ZED	0.30	0.30	0.10	0.03	$25,000	25	$4,875	0.01	$1,000,000	$10,000	$14,875
Systems Engineering		Technical	1.80	R8	Interference between System Components	Component physical size too large	DG	0.75	0.50	0.20	0.15	$50,000	25	$28,125	0.05	$0	$0	$28,125
Systems Engineering		Technical	1.90	R9	Incorrect Sequence of Design of Components	Control system designed too early	PMS-MPC	0.10	0.40	0.30	0.03	$100,000	50	$11,250	0.00	$0	$0	$11,250
Forecasting market trends	Economy	Economical	1.10	R10	Inflation	Increased fuel prices	DG	0.75	0.50	0.10	0.08	$100,000	50	$28,125	0.05	$4,000,000	$200,000	$228,125

The probability values for both technical and program risks may be automated within the DSS where the technical risk values may be used as input into the DSM. The interactive SRM for the DSS is depicted in Figure 3.15. This dashboard provides a user interface to update probability values.



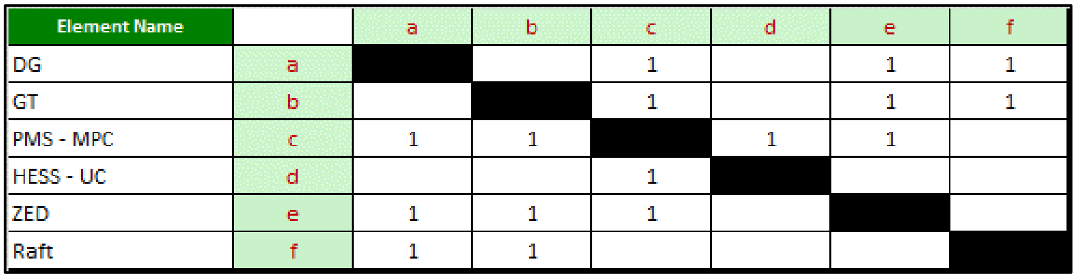
Risk ID	IPS Risk Event	Primary IPS Component Affected	Technical Risk Event Probability (input into DSM) %	Design Rework Impact Probability (input into DSM) %	Program Impact Probability %	Program Risk Event Probability %
R1	Supplier not able to keep up with demand, delivery date 2 months beyond estimated	DG	75	50	30	20
R2	Increased Speed Requirement	GT	25	50	20	5
R3	VFI Understated Power	GT	25	40	20	5
R4	Tier II to III Emission Requirements	DG	75	50	20	15
R5	Lower than expected TRL	HESS	50	30	10	5
R6	System Component Conflict	Shock-Hardening	20	40	20	4
R7	Increased harmonics	Compartmentalization	30	30	10	3
R8	Component physical size too large	DG	75	50	20	15
R9	Control system designed too early	PMS Controller	10	40	30	3
R10	Increased fuel prices	DG	75	50	10	8

Figure 3.15. Automated SRM Within The DSS

3.14.1.3 *DSS and The DSM*

The basic IPS DSM is shown in Table 3.5 with component interactions represented by a value of 1.

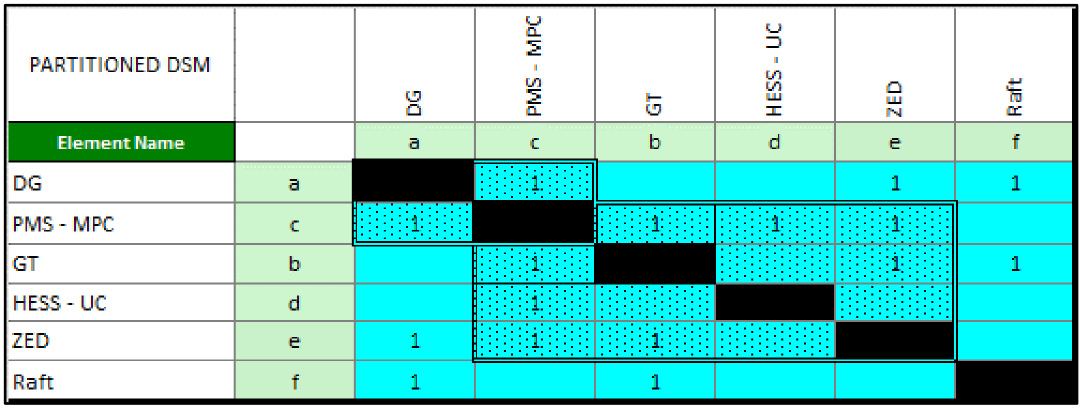
Table 3.5. Basic IPS DSM



Element Name		a	b	c	d	e	f
DG	a	■		1		1	1
GT	b		■	1		1	1
PMS - MPC	c	1	1	■	1	1	
HESS - UC	d			1	■		
ZED	e	1	1	1		■	
Raft	f	1	1				■

In accordance with systems engineering best practices, as well as following MBSE principles, the DSM is partitioned to show modularity and high-level component integration through clusters, as shown in Table 3.6.

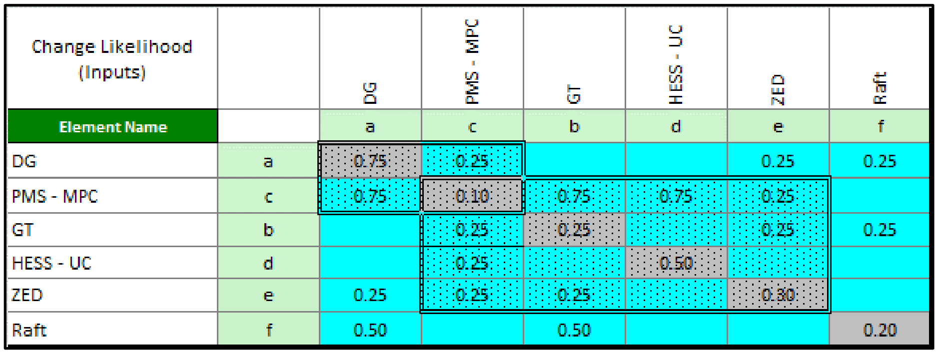
Table 3.6. IPS Partitioned DSM



PARTITIONED DSM		DG	PMS - MPC	GT	HESS - UC	ZED	Raft
Element Name		a	c	b	d	e	f
DG	a	■	1			1	1
PMS - MPC	c	1	■	1	1	1	
GT	b		1	■		1	1
HESS - UC	d		1		■		
ZED	e	1	1	1		■	
Raft	f	1		1			■

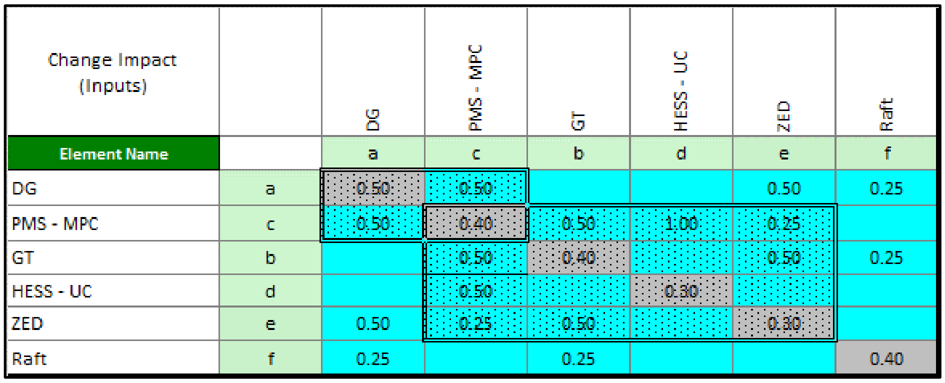
The process of determining changeability risks for components in a system, as described in separate work [53] [54], is adopted in the current IPS application. Tables 3.7 and 3.8 capture the probabilities for directly affected components on the diagonals as well as the indirectly affected adjacent components. The current study proposes the SRM and its values as a natural link into the DSM diagonals of technical change probability and impact.

Table 3.7. IPS Change Event Probabilities



Change Likelihood (Inputs)		DG	PMS - MPC	GT	HESS - UC	ZED	Raft
Element Name		a	c	b	d	e	f
DG	a	0.75	0.25			0.25	0.25
PMS - MPC	c	0.75	0.10	0.75	0.75	0.25	
GT	b		0.25	0.25		0.25	0.25
HESS - UC	d		0.25		0.50		
ZED	e	0.25	0.25	0.25		0.30	
Raft	f	0.50		0.50			0.20

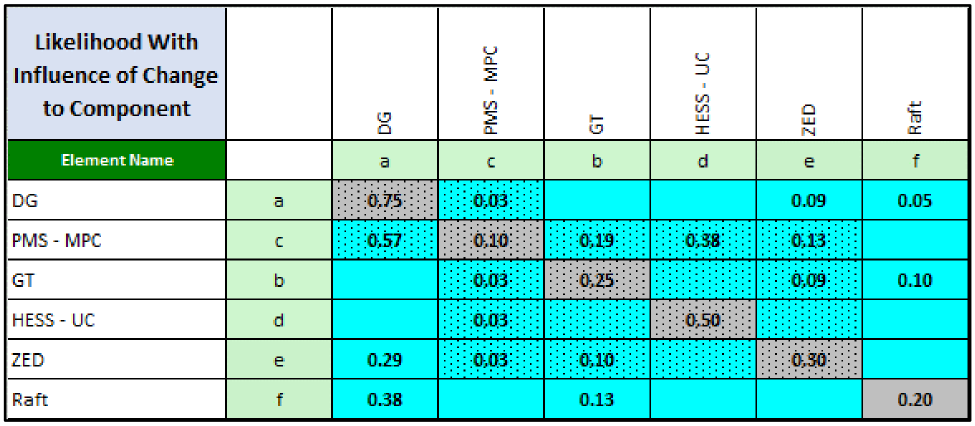
Table 3.8. IPS Component Impact Probabilities



Change Impact (Inputs)		DG	PMS - MPC	GT	HESS - UC	ZED	Raft
Element Name		a	c	b	d	e	f
DG	a	0.50	0.50			0.50	0.25
PMS - MPC	c	0.50	0.40	0.50	1.00	0.25	
GT	b		0.50	0.40		0.50	0.25
HESS - UC	d		0.50		0.30		
ZED	e	0.50	0.25	0.50		0.30	
Raft	f	0.25		0.25			0.40

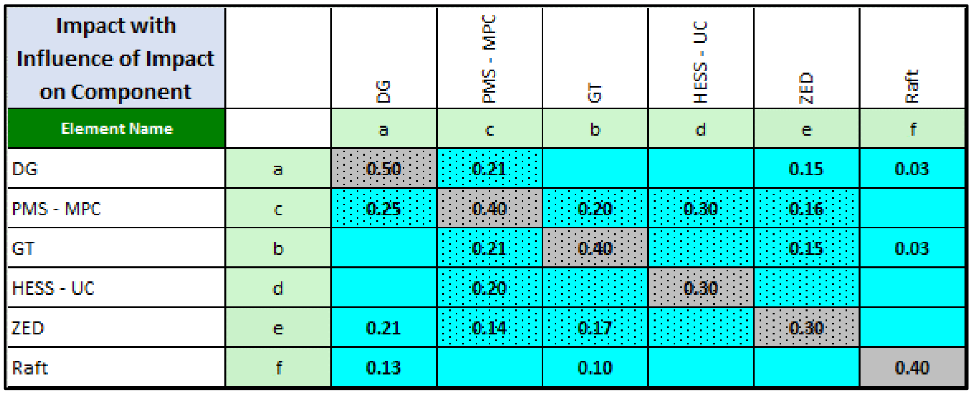
With the use of change propagation trees and values from the preceding tables, the combined component probability for change events, impacts and risks are shown in Tables 3.9, 3.10 and 3.11 respectively.

Table 3.9. IPS Combined Probability of Change to a Component



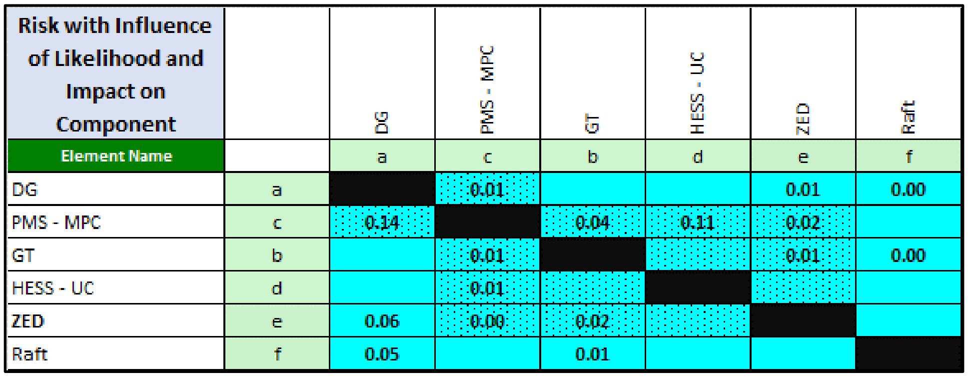
Likelihood With Influence of Change to Component		DG	PMS - MPC	GT	HESS - UC	ZED	Raft
Element Name		a	c	b	d	e	f
DG	a	**0.75**	**0.03**			**0.09**	**0.05**
PMS - MPC	c	**0.57**	**0.10**	**0.19**	**0.38**	**0.13**	
GT	b		**0.03**	**0.25**		**0.09**	**0.10**
HESS - UC	d		**0.03**		**0.50**		
ZED	e	**0.29**	**0.03**	**0.10**		**0.30**	
Raft	f	**0.38**		**0.13**			**0.20**

Table 3.10. IPS Combined Probability of Impact on a Component



Impact with Influence of Impact on Component		DG	PMS - MPC	GT	HESS - UC	ZED	Raft
Element Name		a	c	b	d	e	f
DG	a	0.50	0.21			0.15	0.03
PMS - MPC	c	0.25	0.40	0.20	0.30	0.16	
GT	b		0.21	0.40		0.15	0.03
HESS - UC	d		0.20		0.30		
ZED	e	0.21	0.14	0.17		0.30	
Raft	f	0.13		0.10			0.40

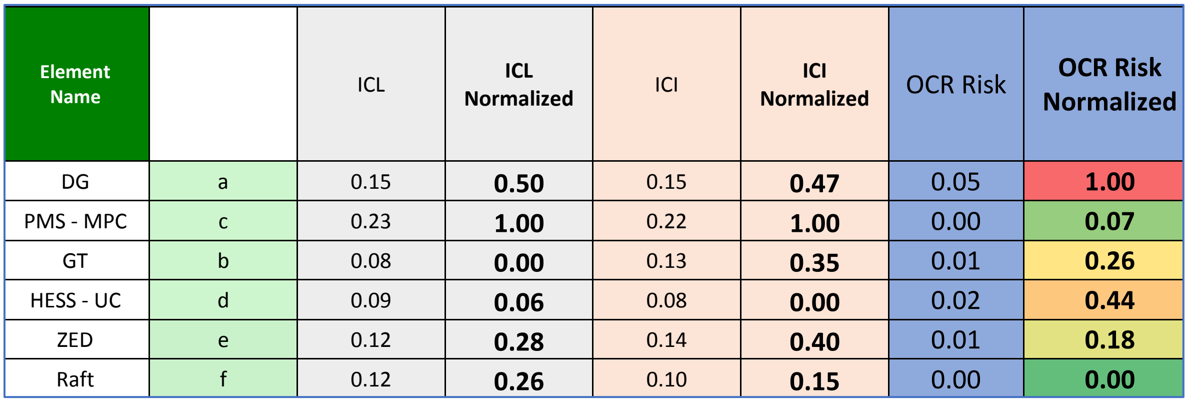
Table 3.11. IPS Combined Risks of Change to a Component



Risk with Influence of Likelihood and Impact on Component		DG	PMS - MPC	GT	HESS - UC	ZED	Raft
Element Name		a	c	b	d	e	f
DG	a	■	0.01			0.01	0.00
PMS - MPC	c	0.14	■	0.04	0.11	0.02	
GT	b		0.01	■		0.01	0.00
HESS - UC	d		0.01		■		
ZED	e	0.06	0.00	0.02		■	
Raft	f	0.05		0.01			■

To show the relative level of changeability of IPS components, the probability and risk values are normalized and ranked as shown in Table 3.12.

Table 3.12. IPS Normalized Outgoing Combined Risk for a Component



Element Name		ICL	**ICL Normalized**	ICI	**ICI Normalized**	OCR Risk	**OCR Risk Normalized**
DG	a	0.15	**0.50**	0.15	**0.47**	0.05	**1.00**
PMS - MPC	c	0.23	**1.00**	0.22	**1.00**	0.00	**0.07**
GT	b	0.08	**0.00**	0.13	**0.35**	0.01	**0.26**
HESS - UC	d	0.09	**0.06**	0.08	**0.00**	0.02	**0.44**
ZED	e	0.12	**0.28**	0.14	**0.40**	0.01	**0.18**
Raft	f	0.12	**0.26**	0.10	**0.15**	0.00	**0.00**

The normalized OCR value of 1.00 for the DG indicates that is has a strong influence on other components.

The ICL and ICI values for components are plotted in Figure 3.16. It is evident that the DG and PMS-MPC are most susceptible to change based on event and component impact probabilities, as estimated in the SRM and updated within the DSM. The PMS-MPC component resides in the upper right quadrant of the dynamic component changeability chart and is viewed as the most difficult to change.

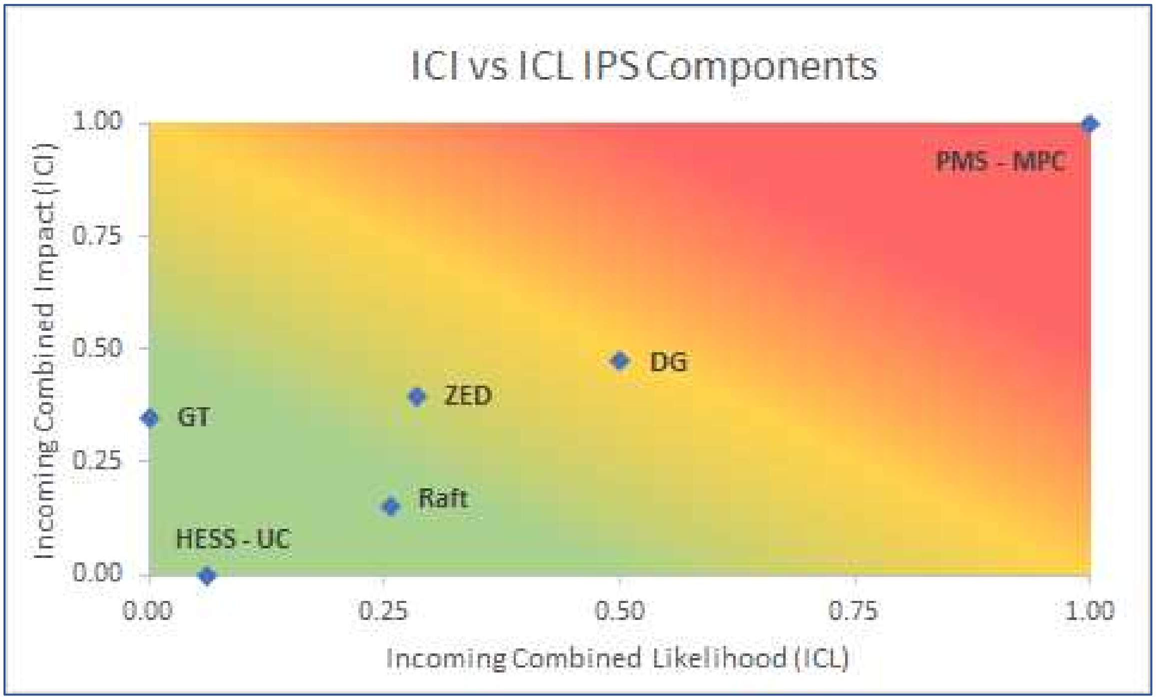


Figure 3.16. ICI vs ICL for IPS Components

3.14.1.4 *DSS and Design Attribute Values*

Table 3.13 shows the hierarchy of attributes considered in the IPS case study. The IPS can be affected by the risk triggers. For risk R4, it is likely that a new regulation will force redesign of the DG system to accommodate IMO Tier III emission requirements. This change is significant in that it requires reconfiguration of the IPS where several design variables and attributes will be affected. Of interest, this change leads us back to one of the MATE pareto frontier architectures that incorporate a DG with WHR. This is the value of bringing the MATE model forward into the design cycle as a reference model.

Table 3.13. IPS Modified MATE Attributes With Design Changes

		Performance									Survivability						Program		
		Mission								Enviro	Mission				Safety		Cost	Schedule	Risks
		0.30		0.50					0.10		0.30	0.30		0.20	0.20				
		0.33	0.67	0.34	0.06	0.13	0.12	0.35	1.00		1.00	0.33	0.67	0.20	0.50	0.50			
		Mobility		Operability					ASuW		Mobility	ASW		ASuW	Code	Reliability			
		0.1	0.2	0.17	0.03	0.07	0.06	0.18	0.10	0.10	0.30	0.10	0.20	0.20	0.10	0.10			
		Maximum Speed	Range	Power Quality	Capacity Factor	Space	Weight	Transient Load Response Time	Rail Gun Performance	Energy-Efficiency Design Index	Blackout	Torpedo/Mine	Shock	Missile/Gun	NSC and NVR	Reliability	Total Costs	Schedule Slippage Due to TRL	System Readiness Level (SRL)
	Attribute	X1	X2	X3	X4	X5	X6	X7	X8	X9	S1	S2	S3	S4	S5	S6	P1	P2	P3
	Variable-Attribute Relationship	non-linear	assume linear	binary	linear	linear	linear	binary	assume linear	lookup table	lookup table	lookup table	lookup table	lookup table	binary	binary	linear	linear	linear
	Units of Measure	nmi/h	nmi	%	%	m^3	kg	n/a	rounds/min	n/a	n/a	n/a	n/a	n/a	n/a	na	$M	%	n/a
	Least Acceptable (LSL)	25	2500	5	17	1030	360000	slow	12	59	0.86	0.44	0.22	0.44	0.25	0.5		150%	0.25
	Least Acceptable Normalized (LSL)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0			
	Most Desirable (USL)	30	4000	2	50	250	130000	fast	24	37	1	1	1	1	1	1		0%	1
Month	Most Desirable Normalized (USL)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1			
	Baseline Design 32	25.0	3281	2	38.6	289	158226	fast	24	51	0.98	0.75	0.75	0.75	1.00	1.00	154.5	78%	0.32
0	Baseline Design 32 Normalized	0.00	0.52	1.00	0.65	0.95	0.88	1.00	1.00	0.41	0.86	0.55	0.68	0.55	1.00	1.00			
	CR1.0 Revised Design 32	25.7	3253	2.00	35.6	296	160476	fast	24	50	0.98	0.75	0.75	0.75	1.00	1.00	157.5	118%	0.26
1	CR 1.0 Revised Design 32 Normalized	0.13	0.50	1.00	0.56	0.94	0.87	1.00	1.00	0.45	0.86	0.55	0.68	0.55	1.00	1.00			
	CR 1.1 Modeling Results	26.1	3235	2.00	33.9	301	161976	fast	24	50	0.98	0.75	0.75	0.75	1.00	1.00	159.3	114%	0.28
2	CR 1.1 Modeling Results Normalized	0.22	0.49	1.00	0.51	0.93	0.86	1.00	1.00	0.48	0.86	0.55	0.68	0.55	1.00	1.00			
	CR 1.2 Modeling Results	26.3	3226	2.00	33.0	304	162726	fast	24	50	0.98	0.75	0.75	0.75	1.00	1.00	160.2	103%	0.30
3	CR 1.2 Modeling Results Normalized	0.26	0.48	1.00	0.49	0.93	0.86	1.00	1.00	0.49	0.86	0.55	0.68	0.55	1.00	1.00			
	CR 1.3 Modeling Results	25.7	3253	2.00	35.6	296	160476	fast	24	50	0.98	0.75	0.75	0.75	1.00	1.00	157.4	84%	0.30
4	CR 1.3 Modeling Results Normalized	0.13	0.50	1.00	0.56	0.94	0.87	1.00	1.00	0.45	0.86	0.55	0.68	0.55	1.00	1.00			
	CR 1.4 Modeling Results	25.7	3253	2.00	35.6	296	160476	fast	24	50	0.98	0.75	0.75	0.75	1.00	1.00	154.5	73%	0.40
5	CR 1.4 Modeling Results Normalized	0.13	0.50	1.00	0.56	0.94	0.87	1.00	1.00	0.45	0.86	0.55	0.68	0.55	1.00	1.00			
	Configuration Change CR 2.0 DG WHR for Tier III Design ID 96	25	3373	2	38.6	334	170225	fast	24	50	0.98	0.75	0.75	0.75	1.00	1.00	186.6	132%	0.3
6	Configuration Change 2 DG WHR for Tier III Normalized Design ID 96	0.00	0.58	1.00	0.65	0.89	0.83	1.00	1.00	0.47	0.86	0.55	0.68	0.55	1.00	1.00			

Variation in attribute values caused by changes can be visualized over time, a representative control chart for the mobility attribute is depicted in Figure 3.17. To determine whether the variability of attributes is within control can be assessed with the variability measures of C_{py} and C_{pky}.

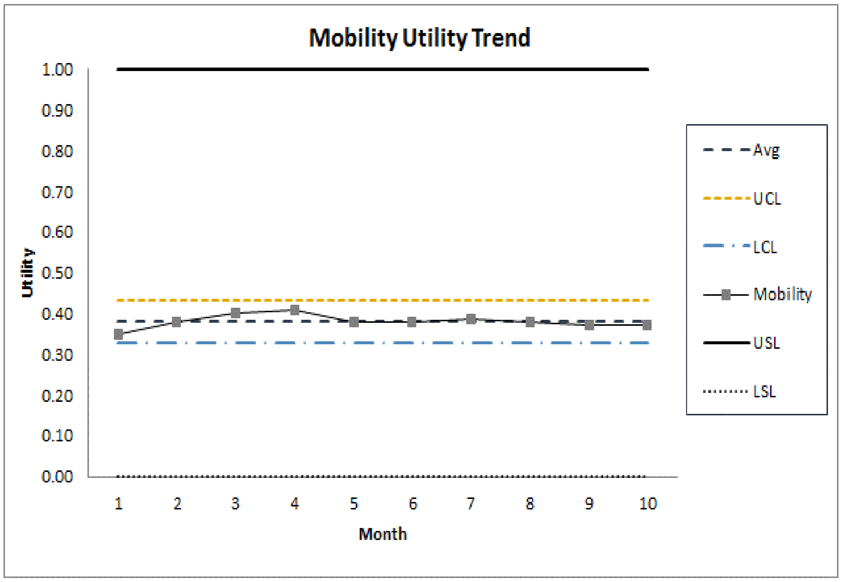
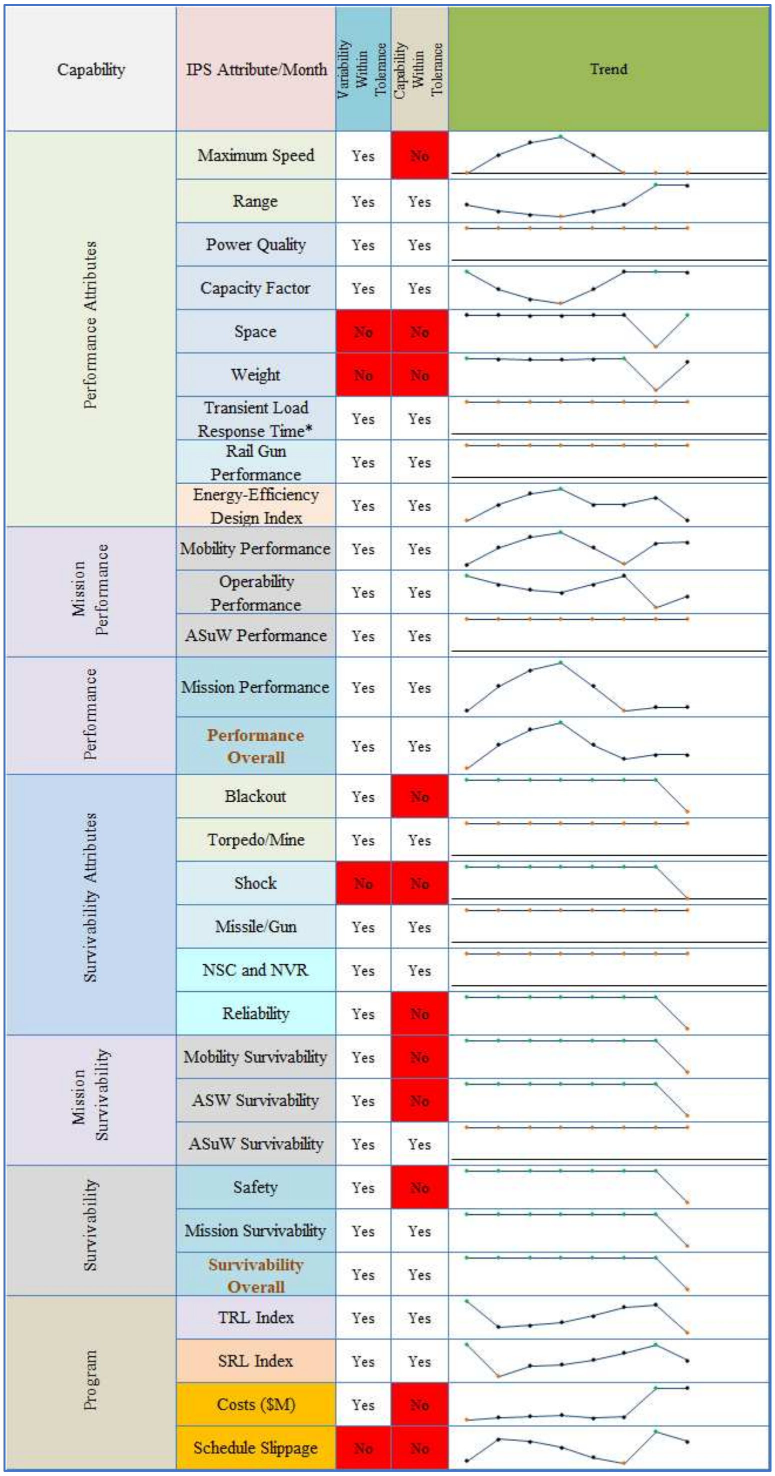


Figure 3.17. Representative Attribute Control Chart

The DSS incorporates all IPS attributes of interest in one view, as depicted in Figure 3.18.



Capability	IPS Attribute/Month	Variability Within Tolerance	Capability Within Tolerance	Trend
Performance Attributes	Maximum Speed	Yes	No	
	Range	Yes	Yes	
	Power Quality	Yes	Yes	
	Capacity Factor	Yes	Yes	
	Space	No	No	
	Weight	No	No	
	Transient Load Response Time*	Yes	Yes	
	Rail Gun Performance	Yes	Yes	
	Energy-Efficiency Design Index	Yes	Yes	
Mission Performance	Mobility Performance	Yes	Yes	
	Operability Performance	Yes	Yes	
	ASuW Performance	Yes	Yes	
Performance	Mission Performance	Yes	Yes	
	Performance Overall	Yes	Yes	
Survivability Attributes	Blackout	Yes	No	
	Torpedo/Mine	Yes	Yes	
	Shock	No	No	
	Missile/Gun	Yes	Yes	
	NSC and NVR	Yes	Yes	
	Reliability	Yes	No	
Mission Survivability	Mobility Survivability	Yes	No	
	ASW Survivability	Yes	No	
	ASuW Survivability	Yes	Yes	
Survivability	Safety	Yes	No	
	Mission Survivability	Yes	Yes	
	Survivability Overall	Yes	Yes	
Program	TRL Index	Yes	Yes	
	SRL Index	Yes	Yes	
	Costs ($M)	Yes	No	
	Schedule Slippage	No	No	

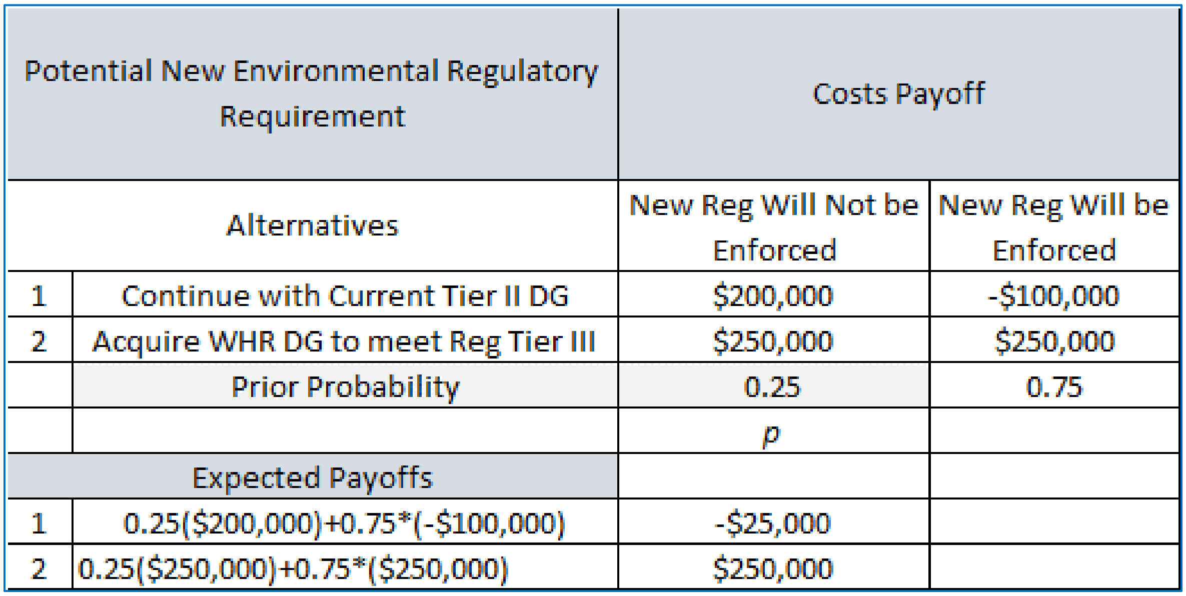
Figure 3.18. DSS Visualization of Design Attribute Levels and Trends

Based on the design change scenario, users may adjust SRM risk values and IPS parameters and component types in response to potential changes, this includes updates to parameter values from external plant models. The levels and trends of attributes may be monitored and managed accordingly. Thresholds may be assigned to C_{py} and C_{pky} values where cues or triggers are activated when actual values are below these threshold values.

3.14.1.5 *DSS and Decision Analysis*

In decision analysis, the typical monetary payoff assessment for design change alternatives is used, an example for risk R4 in the current study is provided in Table 3.14.

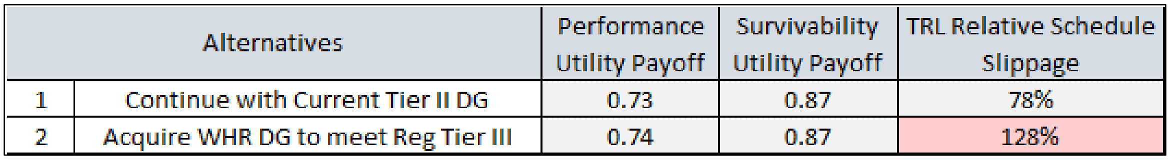
Table 3.14. Bayes' Monetary Payoff Table for IPS Notional Risk R4



Potential New Environmental Regulatory Requirement		Costs Payoff	
Alternatives		New Reg Will Not be Enforced	New Reg Will be Enforced
1	Continue with Current Tier II DG	$200,000	-$100,000
2	Acquire WHR DG to meet Reg Tier III	$250,000	$250,000
	Prior Probability	0.25	0.75
		p	
Expected Payoffs			
1	0.25($200,000)+0.75*(-$100,000)	-$25,000	
2	0.25($250,000)+0.75*($250,000)	$250,000	

While this analysis points toward pursuing alternative 2, it is of value to also assess design attribute payoff tables, an example of some high-level attributes is provided in Table 3.15. In this case, there is an increase to schedule slippage by following alternative 2.

Table 3.15. Design Attribute Payoff Table for IPS Notional Risk R4

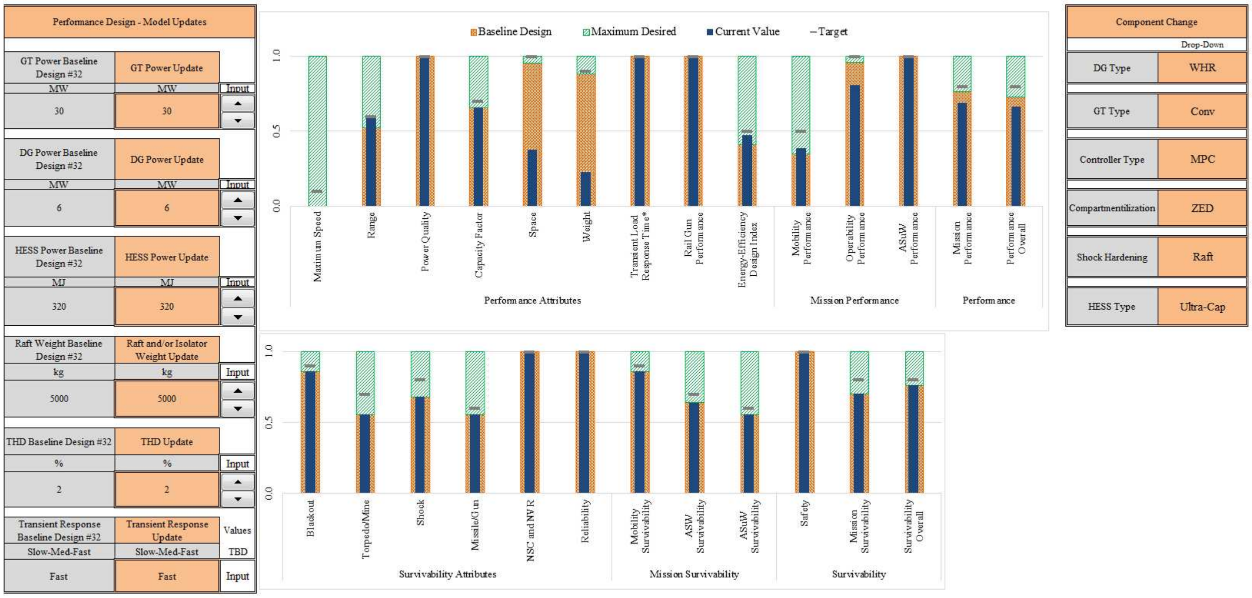


Alternatives		Performance Utility Payoff	Survivability Utility Payoff	TRL Relative Schedule Slippage
1	Continue with Current Tier II DG	0.73	0.87	78%
2	Acquire WHR DG to meet Reg Tier III	0.74	0.87	128%

3.14.1.6 *The DSS and Dynamic Interactive Controls for What-If Decision-Making*

Discrete Event Simulation (DES) is a computer simulation of a dynamic system where the system state changes over time depending on discrete events [63]. The sub-models of the simulator represent DES models that involve human-in-the-loop (HIL) updating of data for decision-making. Discipline-specific teams cause a discrete event by changing physical system parameters and component types in response to risks and potential design changes.

The DSS includes interactive controls for adjusting design variables, system component types, and risk values to visualize the impact from changes on design and program attribute payoffs and component changeability. As depicted in Figure 3.19, this dynamic platform provides meaningful information that may be gained through what-if scenarios.



Performance Design - Model Updates

GT Power Baseline Design #32	GT Power Update	
MW	MW	Input
30	30	
DG Power Baseline Design #32	DG Power Update	
MW	MW	Input
6	6	
HESS Power Baseline Design #32	HESS Power Update	
MJ	MJ	Input
320	320	
Raft Weight Baseline Design #32	Raft and/or Isolator Weight Update	
kg	kg	Input
5000	5000	
THD Baseline Design #32	THD Update	
%	%	Input
2	2	
Transient Response Baseline Design #32	Transient Response Update	Values
Slow-Med-Fast	Slow-Med-Fast	TBD
Fast	Fast	Input

Component Change

	Drop-Down
DG Type	WHR
GT Type	Conv
Controller Type	MPC
Compartmentilization	ZED
Shock Hardening	Raft
HESS Type	Ultra-Cap

Figure 3.19. DSS Interactive Design Attribute Dashboard

3.14.1.7 *Assessment of DSS Model Criteria*

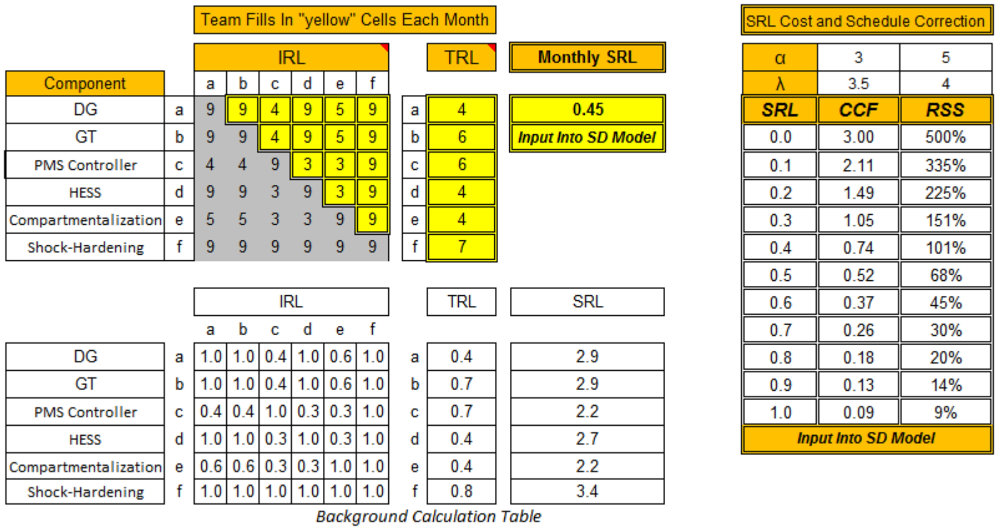
The functionality of a framework for a DSS was validated with IPS notional design changes, as triggered by risks within the SRM. The criteria for developing the DSS was assessed by the author, as provided in Table 3.16.

Table 3.16. Assessment of DSS Criteria

DSS Models	Simplicity	Transparency	Efficiency	Accuracy	Portability	User Experience (UX)
Integrated Standard Risk Model	✓	✓	✓		✓	✓
DSM Changeability Model			✓		✓	✓
Modified MATE Model	✓	✓	✓		✓	
System Optimization Plant Modeling (MATLAB®, Homer Pro®)			✓	✓	✓	
Design Attribute Capability and Performance	✓	✓	✓	✓	✓	✓
Bayes' Decision Analysis With Attribute Payoff Tables	✓	✓	✓		✓	

3.14.2 *SRL Model*

In the current study, SRL values may be updated through the model depicted in Figure 3.20. This requires manual periodic input of system component TRL and IRL values. From this, SRL, CCF and RSS values are automatically updated and linked to the simulator inputs.



Team Fills In "yellow" Cells Each Month

Component		IRL a	IRL b	IRL c	IRL d	IRL e	IRL f		TRL	Monthly SRL
DG	a	9	9	4	9	5	9	a	4	0.45
GT	b	9	9	4	9	5	9	b	6	*Input Into SD Model*
PMS Controller	c	4	4	9	3	3	9	c	6	
HESS	d	9	9	3	9	3	9	d	4	
Compartmentalization	e	5	5	3	3	9	9	e	4	
Shock-Hardening	f	9	9	9	9	9	9	f	7	

		IRL a	IRL b	IRL c	IRL d	IRL e	IRL f		TRL	SRL
DG	a	1.0	1.0	0.4	1.0	0.6	1.0	a	0.4	2.9
GT	b	1.0	1.0	0.4	1.0	0.6	1.0	b	0.7	2.9
PMS Controller	c	0.4	0.4	1.0	0.3	0.3	1.0	c	0.7	2.2
HESS	d	1.0	1.0	0.3	1.0	0.3	1.0	d	0.4	2.7
Compartmentalization	e	0.6	0.6	0.3	0.3	1.0	1.0	e	0.4	2.2
Shock-Hardening	f	1.0	1.0	1.0	1.0	1.0	1.0	f	0.8	3.4

Background Calculation Table

SRL Cost and Schedule Correction

α	3	5
λ	3.5	4
SRL	***CCF***	***RSS***
0.0	3.00	500%
0.1	2.11	335%
0.2	1.49	225%
0.3	1.05	151%
0.4	0.74	101%
0.5	0.52	68%
0.6	0.37	45%
0.7	0.26	30%
0.8	0.18	20%
0.9	0.13	14%
1.0	0.09	9%

Input Into SD Model

Figure 3.20. The Simulator SRL Model

3.15 Conclusion

With IPS design number 32 selected, there is value in monitoring risks as they affect design attributes and components throughout the design cycle. This can be achieved through DSS framework that brings multiple disciplines together on a common platform using a common language with the goal to maintain design integrity, design intent and communicate variations in design attributes. This common language of non-dimensional attributes and changeability values also helps to reduce complexity of the system. Moreover, the view of a set of comprehensive attribute values expands the traditional view of Decision-Theory and Bayes' table of payoffs.

Typical changes were investigated for the IPS adding realism to the case study and substance to validation of the simulator. At the same time, typical or anticipated changes for any system can provide for early planning, knowledge and risk reduction.

The unique combining of the SRM, DSM and component changeability charts is a step toward aligning PM and SE practices as well as developing an integration strategy for the simulator.

The DSS with its UX interface can improve team collaboration, efficiency, effectiveness and situational awareness for improved decision-making. It can help decision makers from resorting to shifting-the-burden. The DSS is a viable option in answering the need for data-driven, risk-informed decision-making early in the design cycle.

Chapter 4 – Knowledge and Human Factors in Decision-Making

4.1 Introduction

While the DSS integrates risks, system interdependencies and attributes for decision-making, this chapter investigates knowledge, social and human factors involved in design change management. Several social and human factors in decision-making are considered in developing a process for users to play out design change scenarios within the DSS and simulator. Some of these factors were discussed in the previous chapter including Prospect Theory and shifting-the-burden in decision-making. In this chapter, supporting theories include Game Theory, Theory of Knowledge and Learning Theory.

In this chapter, the DSS is viewed as a tool for learning and to generate knowledge for informed decision-making early in the design cycle. It is also viewed as a tool bring PM and SE disciples together on a common platform to better manage design changes and attributes. The integration of multiple disciplines and how they might interact in response to two different types of design changes is investigated in the current chapter using Social Network Analysis (SNA) and a SNA survey conducted with a west coast shipyard.

4.2 Motivation

It is not apparent that design change management and its social dimension have been adequately addressed in developing a data management and decision-making information tool [48].

If knowledge can be quantified and an approach developed to advance knowledge in the design cycle, then design costs and schedule delays may be reduced. After an extensive review of knowledge management theory and research, it is not apparent that there exists a quantitative measure for measuring knowledge; the current study attempts to develop this measure.

The motivation in the current chapter is to show the importance of knowledge and social interactions in decision making and how these elements might be leveraged in development of the simulator.

4.3 Objectives and Research Questions

By understanding knowledge management and the social aspects involve in resolving design problems, insight into the integration elements for the DSS and simulator can be gained.

Research questions on an integration strategy for PM and SE, a response strategy to better adapt to design changes and ways to improve collaboration are addressed from the social dimension in this chapter.

4.4 Background

On the human factors side, different perceptions, biases, memory and knowledge limitations can negatively affect decision-making. Moreover, decision-making that involves several different disciplines can be affected by time, personality and group pressures, as well as not having all the required information readily available to make these decisions. This was evident in decisions in the past that led to engineering disasters such as the Titanic, Apollo, and Space Shuttle disasters. In many cases, solutions to problems are decided through a top-down senior management approach that puts little weight on engineering data.

From a human factors perspective, causes for poor program performance may include interpersonal conflict, loss of conceptual slack under a high pace environment that include numerous disruptions, and fear of project failure [64].

There can be several other pressures within the program and engineering management environment such as contract pressures in meeting deadlines, organizational changes, political influences, and incomplete or inaccurate information.

Human factors associated with learning and decision-making include pattern recognition, historical data, and the ability to play out what-if scenarios. The DSS addresses these factors through its user interface and visualization component.

4.5 Recognizing Types of Design Changes

There can be two types of design changes; ripple changes that eventually end, and avalanche changes that are multipliers and un-ending [65]. In other work, change categories included emergent design problems and customer-initiated changes [66]. These types of changes can influence system attributes at varying levels of degree. The DSS attribute control charts and component changeability chart can provide useful insight into what type of change is at play. Patterns and cues in these charts can signal high-risk avalanche type changes.

These high-risk changes may be associated with changes to system components while low-risk incremental changes may be associated with system parameter changes. These types of changes and how teams interact in response to them are investigated in this chapter.

4.6 Pattern Recognition and Perception

Klein’s theory of Recognition-Primed Decision Making (RPD) describes how individuals make incremental changes based on observing patterns in dynamic environments [67]. Given a problem, RPD involves recalling a similar situation and its course of action. RPD describes how people make decisions based on their experience and the constraints of the problem. This may work well where there are experienced people in the organization. On the other hand, people with less experience or who are new to the organization may not be in position to make effective decisions. Recalling a similar situation of course of action may be difficult in time-constrained high-pressure environments like a shipyard. In these cases, the DSS and its record of past design changes and decisions, for both similar projects and existing projects, can enhance RPD.

In the Naturalistic Decision-Making (NDM) environment, interpreting patterns can also be based on the individual's experiences [68]. For complex design projects, the level of the NDM environment can vary where decision-makers can be faced with decisions later in the design development process when changes are more difficult and costly to implement. During complex design, situations can often include a change in design where decisions are made under the pressures of cost, time, contractual constraints. These dynamic situations can involve problems of high severity, uncertainty and time pressures where decision-making involves assessment, actions and adjustments, this is known as Naturalistic Decision-Making (NDM). In the NDM environment, researchers found that decision makers rely heavily on intuition and that methods to help strengthen this intuition are needed [67]. These methods can include use of the DSS and simulator where what-if scenarios can challenge existing mental models, build new ones and strengthen intuition.

Aspects of both RPD and NDM can be at play in decision-making within a stressful environment of tight time constraints. These theories are viewed as related to both Prospect Theory and shifting-the-burden concepts where decisions need to be made quickly and may not totally resolve the problem. Having readily available comprehensive data and information can facilitate better informed decisions in stressful time-constrained situations.

On the other hand, good team performance in decision-making can be about learning, discovery, and insights, and therefore NDM can be considered a form of positive cognitive psychology [69]. Performance improvement can depend on both the reduction of errors and increasing insights and expertise [68].

It is proposed that the DSS and simulator can provide for learning, early insights with its ability to play out what-if scenarios and provide a tool for effective decision-making.

4.7 Knowledge

In the late 1990's, most executives stated their key responsibility as being to leverage organizational knowledge [70]. This included management of the knowledge economy and deciding when to develop knowledge and how it might be combined with that of external contractors. Knowledge economy theory considers the life cycle of knowledge as a commodity, when to develop professional knowledge, and how to combine sources of knowledge such as internal resources as well as external consultants [70].

It is proposed that leveraging organizational knowledge is still relevant today and even of greater importance with increased complexity of products, projects and the accompanying increase in data and information.

In the shipyard environment, all stakeholders play a role in exchanging and generating knowledge. In the current study, internal and external organization relationships are viewed as affecting knowledge generation as well as maturity of VFI.

According to the Oxford dictionary, Knowledge may be defined as:

"Facts, information, and skills acquired through experience or education; the theoretical or practical understanding of a subject" [71].

For the purposes of the current study, Knowledge may be defined as the information within design processes and the experience and education gained through gaming change scenarios in supporting decisions and action.

Knowledge management has stemmed from theory and research in several fields including information economics, strategic management, organizational culture, organizational behavior, organizational structure, quality management, and artificial intelligence [70].

The Theory of Knowledge, also referred to as epistemology, involves the intersection of mental models, the actual state of the real world and a justification system of values and beliefs. Aspects of this theory include coherency of constructs, correspondence in making predictions, comprehensiveness in incorporating different domains, and conduciveness in achieving goals [72].

The simulator may be viewed as supporting these aspects of knowledge theory. The SD model within the simulator provides constructs in the form of causal loop diagrams, the behavior of management curves is predicted, several disciplines can be involved, and goals are achieved through adjusting policy and process levers. The justification of beliefs can be supported by the mental models generated within the simulator as well as through a comparison with real world results.

Knowledge may become useful information when codified into symbolic forms such as charts, images and text [70]. In the current study, the DSS and simulator provide several dynamic charts including changeability of components, attributes levels, trends and patterns.

Knowledge can take the form of explicit or tacit knowledge. Explicit knowledge in ship design takes the form of drawings, technical specifications, documents and plans. Tacit knowledge may include experience, expertise, lessons learned and knowledge of typical design changes from past similar projects. Tacit knowledge involves learning through on the job training and putting theory into practice.

Knowledge sources include documents, past design information, Vendor Furnished Information (VFI), new technologies and informal knowledge from meetings and working groups [73]. While these are recognized as sources of explicit and implicit knowledge, the current study is focused on generating tacit knowledge through teaming, the gaming of design change strategies and on-the-job training.

Knowledge-based systems have been noted in aiding a flexible design where what-if scenarios can be exercised, and early decisions made [74]. The DSS and simulator in the current study may be viewed as a knowledge-based system as it meets these requirements.

4.7.1 *Knowledge Management Process*

The knowledge management process can be ambiguous and difficult to describe with the many factors involved [70]. These factors include experience, perception, intuition, values and beliefs. While these factors can be difficult to quantify and measure, system dynamics is a field that is leveraged in the current study to help understand the knowledge management process and the factors that influence it.

4.7.1.1 *Knowledge Generation*

Implicit learning can involve unconscious learning of dynamic statistical patterns and features, which leads to the development of tacit knowledge. This learning and development of tacit knowledge may help with the retention and transfer of expertise [67]. In knowledge management theory, strategies are proposed to make tacit knowledge in people explicit so that it may be shared. Use of the DSS and simulator provides a strategy to generate and share tacit knowledge. In generating this knowledge, the Knowledge curve may be advanced early in the design cycle using key action mechanisms.

Knowledge creation may also be founded in creativity theory that promotes non-conformity and thinking outside the box [70]. Knowledge creation may also be supported through gaming what-if scenarios, shifting the culture towards creativity and promoting new ideas and learning. Knowledge creation may also be achieved when tacit knowledge is socialized among customers, partners and key stakeholders within the organization.

There can be counter-balancing effects to knowledge generation. This may be founded in organizational behavior that may include a culture of group think or fear of embarrassment in speaking out. Other counter-balancing effects may include the NDM environment where there are pressures to make decisions quickly, often with limited information.

The stressful environment in complex project management including shipbuilding can inhibit knowledge generation and transfer. These inhibitors include lack of infrastructure, high staff turn-over, high workload, and high rework [75].

4.7.1.2 *Knowledge Transfer*

While knowledge and information transfer can be achieved through information systems, it can be related to the absorptive capacity of an organization to identify and exploit knowledge [70]. Like knowledge generation, knowledge transfer may also be inhibited by the counteractive effects of culture, values and the organizational environment. These effects are considered in developing the simulator SD model in the current study.

The conditions for knowledge to flow include content, culture, processes, and infrastructure [75]. Knowledge content can consist of the types of information that are important to the organization. In the current study, the explicit content within the DSS and simulator and the tacit knowledge learned through gaming change scenarios are considered important in developing the simulator.

The increased amount of information, software applications, and complexity in ship design requires effective collaboration, knowledge management and a learning culture for project success.

4.8 Learning

The learning organization may enhance knowledge creation, storage and transfer. The learning process may be explained by the theory of double-loop learning, this theory describes how tacit knowledge through learning can remain in an organization [76]. The learning process can be linked to the social network, culture, values and willingness of an organization to learn.

Learning can include discovery of rework and errors where knowledge can be discovered through looking for it [77]. However, this method of learning from mistakes can be expensive.

Mental models include our beliefs about the causes and effects that a system operates in and help frame the problem. Bringing learned information into mental models provides for double-loop learning.

It is proposed that mental models within double loop learning can be enhanced through gaming scenarios within the DSS and simulator to gain knowledge in a virtual world. This iterative agile approach for learning and project success reflects Revan's law of action learning.

$$L = P + Q \tag{4.1}$$

where learning (L) occurs through programmed knowledge (P) and insightful questioning (Q) [78]. This law includes learning from both successes and failures without fear of reprisals in an environment where all should have an equal voice. Revan also proposed that for an organization to survive, its rate of learning must equal the rate of change in the external environment [78].

It has been recognized that single loop feedback lacks the influence of mental models and cause-and-effect relationships in decision-making [76]. The benefits of action learning include the increased likelihood of knowledge transfer to other situations and double loop learning where teams not only learn new facts but also investigate their own underlying assumptions and mental models, thereby learning how to learn [78]. As depicted in Figure 4.1, the simulator forms the second inner loop for double-loop learning.

For learning to occur in these two loops, it has been noted that work effectiveness and quick cycling around the loops is required as the real-world environment changes [76].

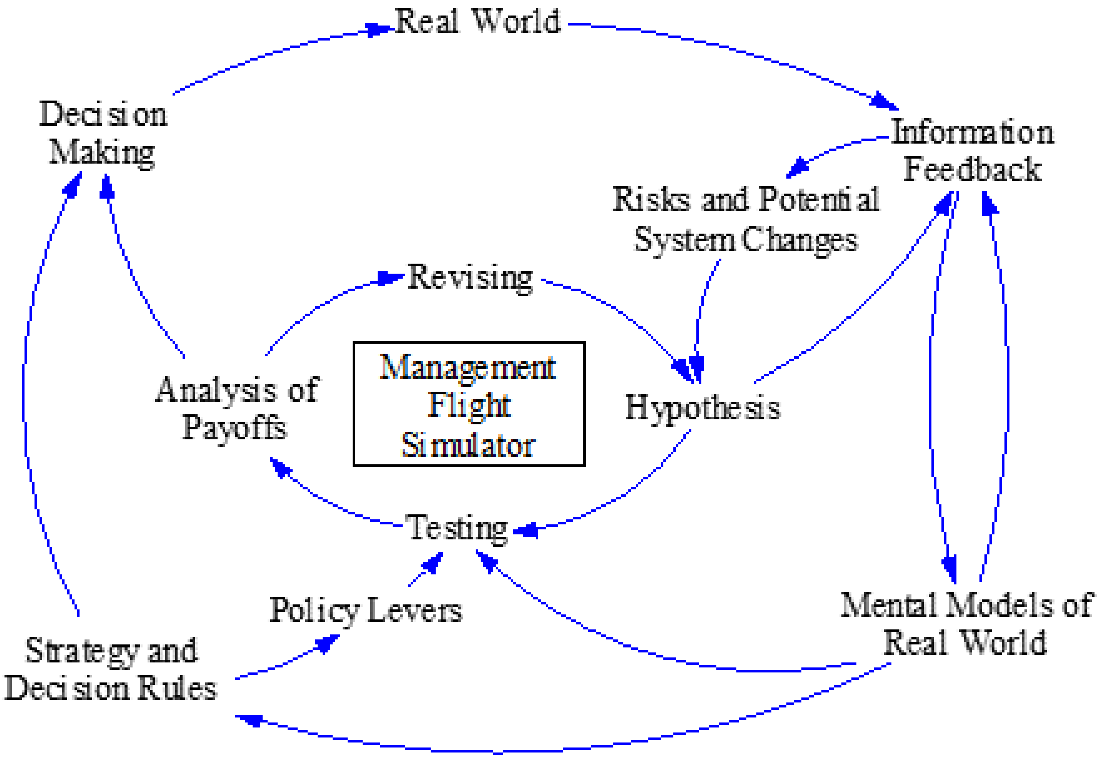


Figure 4.1. Double Loop Learning and the Simulator. Adapted from [76]

Work effectiveness is addressed in the SD sub-model through several system dynamic feedback loops. The quick cycling around the loops can be achieved through action learning and the elements of sprints and scrums used in agile management.

Learning involves both the real and virtual worlds as they both inform development of mental and formal models [76]. In the current study, the mental models within the inner loop are displayed within a virtual management flight simulator. The outer loop includes the mental models formed by individuals and may include aspects of RPD. These two loops form the basis of double loop learning.

The current study adopts double loop learning through knowledge management, insightful questioning through teaming and the gaming of strategies in resolving design problems. The concept of double-loop learning is used in bringing together both traditional information from the DSS and consequential mental models from the SD model.

Overcoming the barriers to learning requires a synthesis of multi-discipline methods [76]. In the current study, this supports the synthesis of several processes and models within the DSS and simulator.

While double-loop learning may occur to a limited degree with use of existing processes, models and tools, it is restricted to use of discipline-specific disparate models and tools. Moreover, these tools can be difficult to use and time-consuming, including challenges in understanding and analyzing their results.

The simulator in the current study is aimed at multiple disciplines using it on a shared platform with results that are non-dimensional and easy to understand. These results include linked technical and programmatic measures that can be shared across the organization. The mechanics behind the use of the simulator are not intuitive and will require a systems engineer to facilitate its use with cross-functional teams. Nevertheless, the attractiveness of the simulator through dynamic visualization of results and its user experience can help avoid shifting-the-burden toward easier tools that provide irrational and non-inclusive decisions. Moreover, results that capture technical, organizational and project performance on one platform can help speed up the process of information gathering for decision-making.

4.9 Human Factors and Requirements for the DSS and Simulator

Based on a review of human factors that influence decision-making, additional specifications for the DSS and simulator include:

i. Visualization of patterns, trends and cues for the management of design and program management attributes. The use of patterns and trends is well-suited to addressing the limitations in perception and memory;
ii. Typical risks from past similar projects and anticipated risks. This is viewed as a key element in advancing the Knowledge curve;
iii. Automation of technical tasks. The DSS and simulator user interface should reduce the level of effort in assessing risks and the impact of design changes; and
iv. The DSS and simulator should provide a learning environment for all stakeholders, to build on tacit knowledge and mental models. This includes the aspect of double-loop learning.

4.10 Game Theory in Using the DSS and Simulator

It is proposed that aspects of game theory in using the DSS can help manage collaborative decision-making. Game theory originates from games such as chess where they are mathematically expressed and where players must think ahead and devise strategies. In game theory, the game is described by the players, strategies and possible payoffs, as depicted in Figure 4.2. Using game theory for decision-making can be useful in managing multi-discipline collaborative design. Compared with other multi-objective optimization methods, game theory methods have been shown to converge faster with better robustness [79].

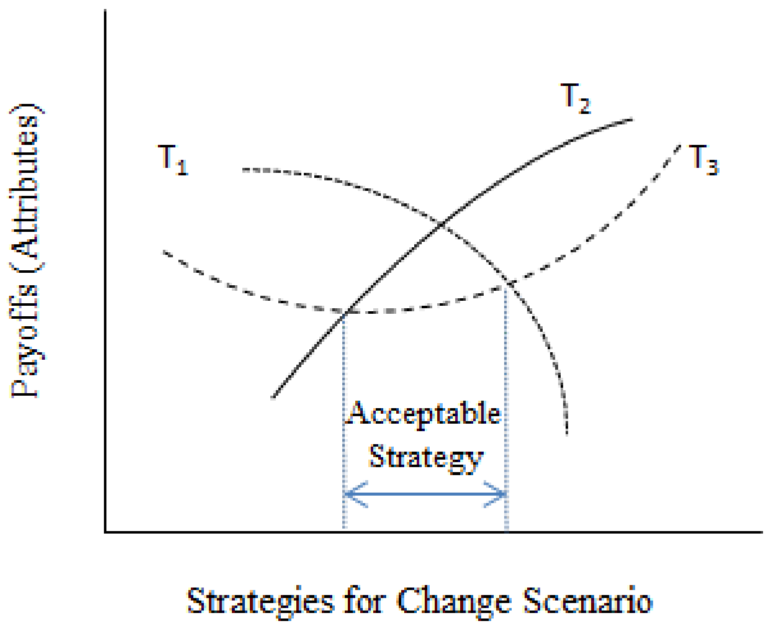


Figure 4.2. Team Strategies and Convergence of Payoffs [79]

In game theory, the players may adopt a non-cooperative model based on a Nash equilibrium or a cooperative model based on a pareto optimal solution [79]. In the current work, it is presumed that the cooperative model is adopted and that players are willing to compromise to improve the overall payoffs. On the other hand, non-cooperation may reflect reality in the ship design environment.

For the IPS case study, several different engineering disciplines can control a subset of design variables in a game and adjust their variables in seeking optimized output design attributes. For instance, plant modeling engineers may revise time-response variables, electrical system engineers may revise power capacity, and propulsion engineers may revise the type and size of engines. The program management stakeholders may influence the design through schedule and cost restraints. Similarly, production may influence the design through the constraints of produce-ability of the product and its installation.

The team (T) players considered in the current work include:

T_1: Program Manager

T_2: Electrical Engineering team

T_3: Mechanical and Propulsion Engineering team

T_4: Supply Chain team

T_5: Planning and Scheduling team

T_6: Production

In order to understand the team relationships, strategies and payoffs in a game, the matrix in Figure 4.3 is used without any implicit calculations.

$$\begin{bmatrix} S_{11} & S_{12} & S_{13} & \cdots & S_{1m} \\ S_{21} & S_{22} & S_{23} & \cdots & S_{2m} \\ S_{31} & S_{32} & S_{33} & \cdots & S_{3m} \\ S_{41} & S_{42} & S_{43} & \cdots & S_{4m} \\ S_{51} & S_{52} & S_{53} & \cdots & S_{5m} \\ S_{61} & S_{62} & S_{63} & \cdots & S_{6m} \end{bmatrix} \begin{Bmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \\ T_5 \\ T_6 \end{Bmatrix} = \begin{Bmatrix} P_1 \\ P_2 \\ P_3 \\ P_4 \\ P_5 \\ P_6 \end{Bmatrix}$$

Figure 4.3. Matrix of Team Strategies and Payoffs [79]

In this matrix, the vector of payoffs (P1, P2, P3,.., Pm)^T represent the IPS attributes described within the DSS. The matrix kernel consists of strategies adopted by each team and includes the adjustment of design variables and components for a change scenario.

The contribution of each team may be at different levels of importance for each change scenario where the strategy of less important teams may be removed. The importance of each team in a scenario may be determined in accordance with the organization’s change process rules and validated through a SNA.

Defining team authority and roles is important to both PM and SE integration and decision-making. These roles also are important in the type of design change being addressed.

After completion of a game, the change strategy can be saved as a scenario as part of advancing knowledge. The gaming of change scenarios can promote team collaboration early in the design and establish rule sets for certain scenarios.

To understand the level of interaction of players and their interaction for each scenario, SNA is adopted. It is proposed that the graphical results of this analysis can provide a visual cue of the importance of each player for a given scenario and help validate the organizational structure intended for participation in the change process.

4.11 Human Factors in Decision-Making

As noted in a separate study, engineers as professionals have their own code of ethics, with a loyalty beyond the employer, while managers typically follow the corporate code of ethics that is more orientated to cost and schedule performance [80]. While managers can be more susceptible to organizational pressures, these pressures can be felt at all levels in the organization.

Use of the simulator in the current study can provide objective measures of attributes and measures that may help in achieving unbiased assessments of design solutions.

Research has been conducted in social psychology on how the perceptions of people, their ability to infer mental states of others and their emotional reaction can affect decision-making [81]. The ability to infer the mental states of others or predict their behavior is often referred to as Theory of Mind.

Manipulating imagined future episodes can be effective in increasing intention to help others and in promoting prosocial behavior. This episodic simulation intersects with Theory of Mind in facilitating prosocial behavior.

The simulator in the current study can provide for episodic simulation through what-if scenarios and visualization of results. Moreover, the gaming of these what-if scenarios can help in understanding the different perspectives and mental states of others. This can be of value in navigating the social environment and understanding the behavior or perspectives of others in responding appropriately.

Connected to the Theory of Mind and inferring the mental states of others is the social interaction of teams and how they work together under different types of change scenarios.

4.12 Social Network Analysis

The approach in the current study is to conduct a SNA through a survey of teams involved in ship design for two different types of change scenarios.

Agent-based Systems (ABS) modeling has become popular in the social sciences where individual entities and their interaction can be represented [82]. The SNA sub-model represents an ABS that is used to describe the emergence of structures and changes in social measures among multi-disciplinary teams.

The knowledge economy operates on the complexities of human connections that affect the flow of information and knowledge [83]. Patterns in the network connections can provide insight into how teams are performing. In the current study, these networks are analyzed through surveys for Social Network Analysis (SNA) with application of Inflow® software.

The flow of knowledge may be seen through SNA in terms of information sharing within networks and clusters. In the context of the DSS and simulator, information flow may be seen through collaboration, risk management and understanding changes as they affect system and program attributes.

In the current study, a SNA survey of discipline-specific team leaders involves asking them who and how often they go to for information with respect to two different types of design changes. While the focus in the current study is limited to information flow for SNA, other surveys could be conducted where different types of networks may be analyzed. This includes extending the survey with questions related to expertise and competency within the organization, thus leading to a knowledge management network.

Performance, learning, and innovation can be improved through determining connectivity within the organization. Understanding the network can help an organization better adapt to change, be it internally or externally related.

Moreover, understanding the interaction between stakeholders can help validate the intended change management process as well as the intended organizational structure for decision-making. While SNA can help to validate processes and organizational structure, it can also highlight organization cultural barriers to effective decision-making.

Social Network Analysis (SNA) can help identify where critical information flow is and from there, information can be categorized, and roles changed to accommodate a more balanced and integrated flow of information exchange.

Critical links can be identified, and contingency planning can take place to ensure more efficient running of the organization. The analysis can be used to adjust the organization so that groups are not fragmented by physical, functional, hierarchical, or organizational boundaries.

It has been recognized that more collaboration is needed in organizations today and that this collaboration for the most part occurs through informal networks [84]. There can be four types of nodes or players in a network, these include bottlenecks or star players, boundary spanners, information brokers, and peripherals.

Information flow through SNA can be useful in terms of quantifying collaboration, integration of cultures and work groups, and accountability [84]. The SNA metrics used in the current work include Density, Characteristic Path Length (CPL) and Power.

Density measures the pairwise (dyadic) connections (ties) of a sample population.

$$Density = \frac{average\ strenght\ of\ ties}{number\ of\ possible\ ties} \tag{4.2}$$

As depicted in Figure 4.4, in a dense network team members are in a good position, having several paths available for accessing information.

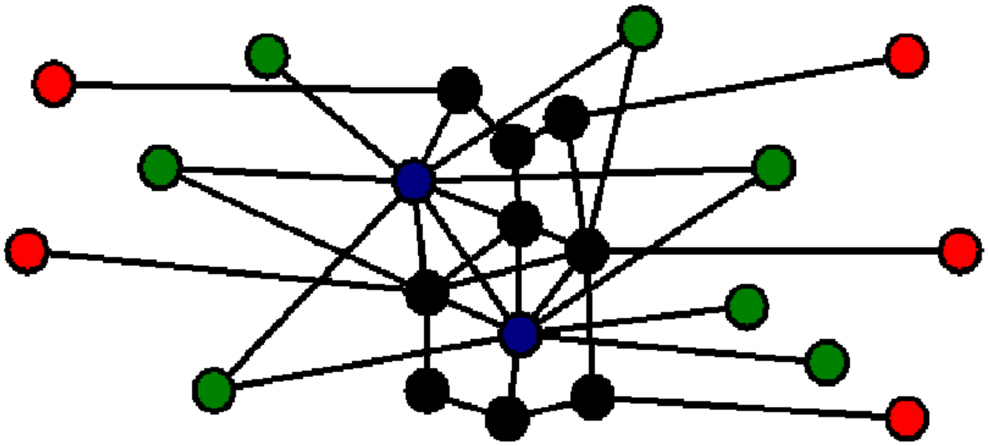


Figure 4.4. Example of a Dense Network [84]

The less dense or sparse network in Figure 4.5 might be adequate for employee growth but not for team performance. This less dense network may represent the different PM and SE disciplines and teams within an organization.

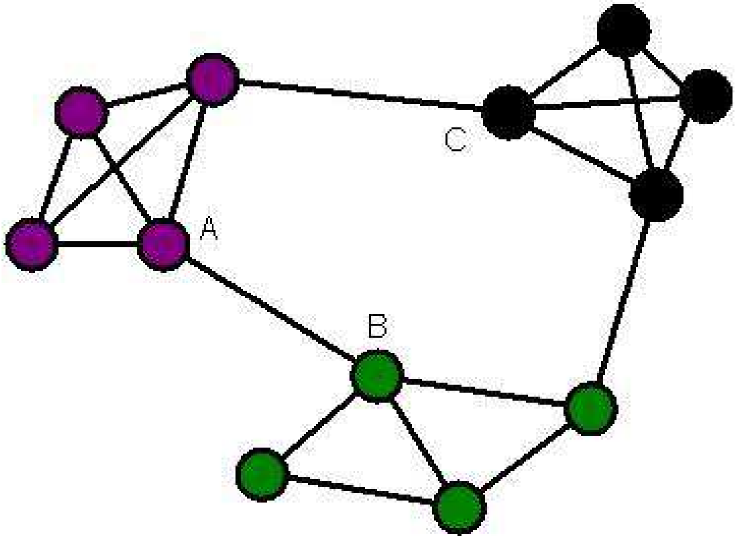


Figure 4.5. Example of a Less Dense Network [84]

In either dense or sparse networks, there can be boundary spanners between neighborhoods. These spanners can be vital to keeping the network together, nodes A, B, and C depict boundary spanners. These boundary spanners may be viewed as integrators or facilitators for information flow throughout the organization. In the current study, these roles may be assumed by systems engineers.

For complex projects, one the objectives of the SE process is to minimize undesirable consequences. This can be achieved through the contribution of experts across the different disciplines and coordinated by the systems engineer. The systems engineer is typically involved in every aspect of a project and establishes an interaction network with stakeholders [7]. It has also been found that middle management plays a key role in conflict resolution and escalation of any issues up to senior leadership [70]. The systems engineer can also play the role of facilitator in the gaming of design change scenarios and in helping to resolve conflict by instilling rules.

This role may also be viewed as one of an information broker where the systems engineer can track down and validate information. This can also include validating information within the DSS.

The average characteristic path length (CPL) indicates how easily information can be accessed, the shorter the path; the more easily information is obtained.

The measure of Power is related to organizational structure; in a hierarchical structure the leader would have ultimate Power at a value of one. With a more horizontal interconnected structure, increased collaboration and relationships distribute Power more evenly.

Inflow® software provides visualization and analysis of teams and their relationships with respect to the metrics of interest. The automatic arrange feature of the software is used to determine these relationships. This feature shows the relationship structure based on the Kamada-Kawai method and its graph drawing algorithms. Graphically, the closer the relationship or information flow; the closer are the people (nodes) within the network.

The change scenario and process rules may dictate the weighting of certain key stakeholders in the decision-making process. This may be straight forward for the case of a collaborative project team; on the other hand, the preferences and influence of team leads may lead to biases or group think decision. SNA is considered in the current study as an approach to validate the weightings of key decision-makers. These weightings are associated with SNA Power metrics.

4.13 Gaming and Conflict Resolution

Project characteristics can lead to conflicts among team members. These characteristics include risks, lack of standards and practices, lack of information, a high workload, and having to make decisions under tight timelines.

On the other hand, successful conflict management can lead to increased productivity and positive relationships among multiple disciplines. If managed correctly, differences of opinion can lead to increased creativity and better decision-making. The psychological and social approach to conflicts can be aided by various techniques including predictive tools, best practices and a roles and responsibility matrix [85]. The structured approach in gaming change scenarios within the simulator can help facilitate the positive effects of conflict management.

In the current study, resolution of team conflicts may be resolved by considering SNA power metrics, a focus on convergence of solutions to optimal attribute levels and by applying decision rules. Of interest among SNA metrics is the level of Power where the standard deviation of power across teams is investigated. It is proposed that a low standard deviation corresponds to teams that have more of an equal voice for both questioning and effective decision-making. The structured gaming approach within the simulator follows the four principles of an agile methodology including people interaction, a product focus, collaboration, and responding to changes [85].

4.14 Results

To obtain SNA data, two different types of design change scenarios were solicited to a west coast shipyard. The first scenario involves changing a diesel generator set to one with waste heat recovery due to imposed more stringent environmental regulations, this was risk R4. The second scenario concerns an error in Vendor Furnished Information (VFI) that requires an increase in the power rating of the Gas Turbines (GT). The first scenario is a component type change while the second scenario is a parameter type change.

The shipyard design project team consists of six sub-teams that support the organization's value chain. Inflow® software results are provided in Appendix C, with a summary of key SNA metrics provided in Tables 4.1 and 4.2.

Table 4.1. West Coast Shipyard SNA Power for Two Change Scenarios

Team	Description	Power Scenario 1	Power Scenario 2
T1	Program Management	0.34	0.60
T2	Electrical Engineering	0.32	0.36
T3	Mechanical and Propulsion	0.31	0.36
T4	Supply Chain	0.80	0.36
T5	Planning and Scheduling	0.36	0.60
T6	Production	0.36	0.36

Table 4.2. West Coast Shipyard SNA High-Level Metrics for Two Change Scenarios

Scenario	Network Density (Percent)	Standard Deviation of Team Power	Characteristic Path Length
1 Component Change	60	0.19	1.4
2 Parameter Change	73	0.13	1.3

From these results, information flow appears to be more restricted for the first scenario as compared to the second scenario. The network for the first scenario is depicted in Figure 4.6.

In the first scenario, the network pattern is one where teams are well connected on both sides of team T4 (Supply Chain); however, T4 may be viewed as a bottleneck to the flow of information within the network. The role and authority of T4 in this case may be related to the associated change in product type. On the other hand, there appears to be strong communication in pairs for the engineering teams, program management and the supply team, and production and planning teams.

In SNA analysis, the first scenario resembles a quasi ‘kite network’ where T1, T5 and T6 communicate and collaborate but they do not have a direct connection with T2 and T3.

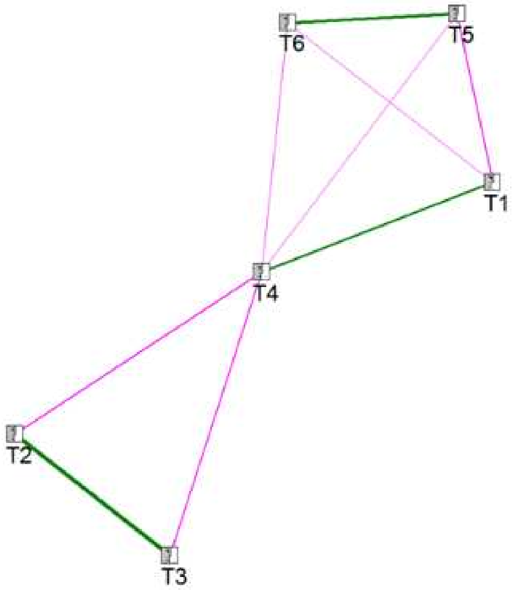


Figure 4.6. Social Network for the First Change Scenario

The network for the second scenario is depicted in Figure 4.7. For this scenario, which involves incorrect VFI and a required parameter change, there appears to be increased connectivity of the teams. This may reflect the view of all teams on the importance of VFI flow throughout the network and organization's value chain.

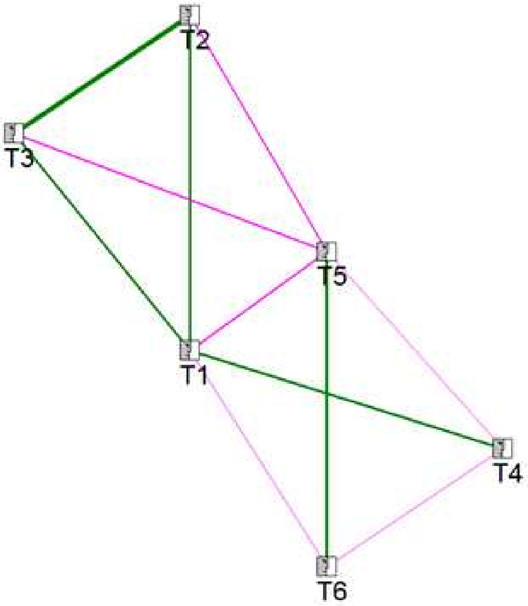
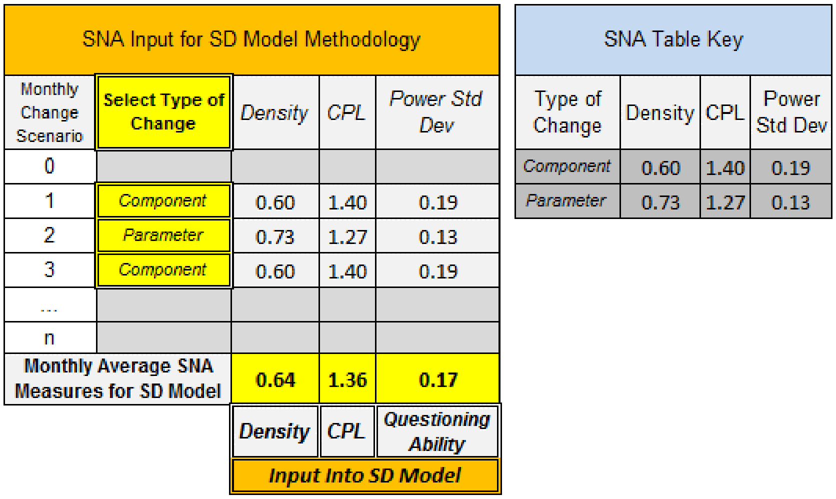


Figure 4.7. Social Network for the Second Change Scenario

With each type of change scenario exercised, corresponding SNA metrics are tabulated within the SNA model depicted in Table 4.3 and used as input into the simulator.

Table 4.3. SNA Model



SNA Input for SD Model Methodology				
Monthly Change Scenario	**Select Type of Change**	*Density*	*CPL*	*Power Std Dev*
0				
1	*Component*	0.60	1.40	0.19
2	*Parameter*	0.73	1.27	0.13
3	*Component*	0.60	1.40	0.19
...				
n				
Monthly Average SNA Measures for SD Model		**0.64**	**1.36**	**0.17**
		Density	***CPL***	***Questioning Ability***
		Input Into SD Model		

SNA Table Key			
Type of Change	Density	CPL	Power Std Dev
Component	0.60	1.40	0.19
Parameter	0.73	1.27	0.13

4.15 Conclusion

Through understanding knowledge management and the social team interactions in decision making, insight is gained into the integration elements required for the DSS and simulator. Some of the factors for knowledge generation, degradation and transfer were identified in this chapter, these factors will be considered in developing a knowledge management SD curve within the simulator. The simulator can provide for double loop learning and an agile approach in the gaming of design change scenarios.

Through a survey with a west coast shipyard, a SNA was conducted for two different types of design changes. The SNA metrics of density, CPL and power are of value in describing the behavior and interaction of teams in decision-making. These metrics are also of value for developing interrelationships and identifying influencing factors related to knowledge, integration and the culture management curves within the SD model.

Chapter 5 – Design Changes, New Technology and Information Flow

5.1 Introduction

The DSS and the gaming of design change scenarios can advance knowledge and reduce project risks, costs and delays. Game theory provides an approach for teams to play out change scenarios and develop strategy solutions. The way teams interact in response to different types of changes can be described through SNA.

This chapter investigates the design change management process and how changes and new technology can be addressed earlier in the design cycle to reduce risks, costs, delays and rework. This chapter presents a response strategy and governance structure to respond to design changes and new technology insertion. The related Theory of Constraints (TOC) and Theory of Inventive Problem Solving (TRIZ) are discussed.

The governance structure includes the monitoring and management of design attributes in adapting to changes and new technology. Set-based design is introduced as an approach to manage these attributes. Set-based design and the Ease-of-Change management curve are also discussed in this chapter as tools to help achieve a robust design. In this chapter, it is proposed that the system Ease-of-Change management curve can be moved up by applying set-based design, engineering principles and leveraging the Design Structure Matrix (DSM) for system component changeability.

The requirements of information management for design decisions is investigated. The MacLeamy design process curve is introduced as well as the concept of how early information and knowledge can help to achieve early design analysis and decisions.

This chapter includes the results from a survey with a west coast shipyard on the challenges experienced with design change and information management.

5.2 Motivation

The public inquiry into cost overruns in the Scottish Parliament construction project revealed poor management of 15,000 design changes [64]. Overlapping design changes caused significant engineering problems. More effort is required to develop tools and manage knowledge to enhance the design change process and to improve quality in production [65].

Costs and time could be saved if it were possible to make quick, yet accurate assessments about the impact of change prior to implementing change [86].

The Airbus 380 super jumbo aircraft suffered cost overruns and schedule delays due to late engineering incompatibilities in the design of the electrical harnesses. While it is difficult to plan for every contingency, it has been shown that a focus on critical points in the design and increased team communication can help avoid these problems [87]. These critical points may be identified in attribute levels and changeability of components.

Advancing new technology in the design cycle has been a challenge in the design cycle, like challenges with introducing design changes. With warship and IPS design, the design-build program can last several years where technology may become obsolete and where just-in-time mature technology is desired.

5.3 Objectives and Research Questions

The objective in the current chapter is to describe an approach using the DSS that can help adapt to design changes and new technology. This includes the ability to anticipate changes and predict their impact on the existing design.

Related research questions are addressed including how early knowledge, design analysis and risk reduction can be achieved with the simulator.

5.4 Background

In complex and extreme projects within a turbulent environment, there can be evolving objectives, tight time constraints, a quick implementation strategy, and stress caused by high uncertainty and frequent changes [85].

In 1970, Ingalls Shipbuilding won a contract to design and build 30 warships but by the mid-1970s, incurred large cost overruns and delays. The project involved a highly complex warship of new and immature technology. Ingalls believed cost overruns were caused by thousands of customer-imposed changes and their interference in the shipyard processes [76]. They also believed that these changes and their ripple effects magnified the delays several times. However, the ripple effects could not be demonstrated with traditional project management tools. In response, Ingalls turned to system dynamics and a SD model to quantify the delay and disruption created by customer-imposed design changes.

The simulator in the current study incorporates a DSS and SD model that are aimed at enhancing the design change decision process including the tracking of both changes and how decisions are made.

The shipyard procurement process for the case study follows both just-in-time engineering and just-in-time procurement where technical specifications and drawings are sequentially issued as part of requests for proposals (RFP) under a competitive process. The sequencing of the RFP is aligned with the ship system build strategy and captured within planning and scheduling enterprise software.

Costs and technology are committed through purchase orders (PO) and supported by defense customer sub-contracts and milestone payments as part of the overall spend plan.

5.5 The Change Management Process and Early Design Changes

The design change management process and the approach in the current study includes the evaluation of the performance of several attributes. This is supported by the DSS for tradeoff analysis and early decision-making. Together with early knowledge, this approach can increase ease-of-change in a system for a robust design.

Similar design change models have been developed that show reduced costs by advancing the design change process early in the design. The Macleamy design process curve is a time-effort curve that shows this relationship [88]. This curve has been used in the building architecture engineering construction (AEC) industry in response to low productivity projects where there has been poor interaction between separately contracted professionals. The MacLeamy time-distribution curves have been used to show how increasing effort in Building Information Models (BIM) can pay off during the construction phase [88]. The BIM models consist of tools, processes and technology that promote collaboration and sharing of information by the entire project team. As depicted in Figure 5.1, this can result in advancing the design process and in reducing costs. The concept of the MacLeamy curves has been leveraged in the current study where the DSS and simulator can equally provide advanced information and knowledge for decision-making.

In the MacLeamy Curves, it is not clear how the underlying design process interrelationships and the use of BIM tools can lead to decreased costs. The current study investigates the underlying relationships of several management processes including design change management. Of interest is the Ease-of-Change management curve and how it can be moved up for a robust design.

The number of both proposed and implemented design changes across the design cycle forms reference data for developing the SD model. Through interviews with a local shipyard, an estimate in the number of these changes for the past design and build of a similar marine IPS was obtained.

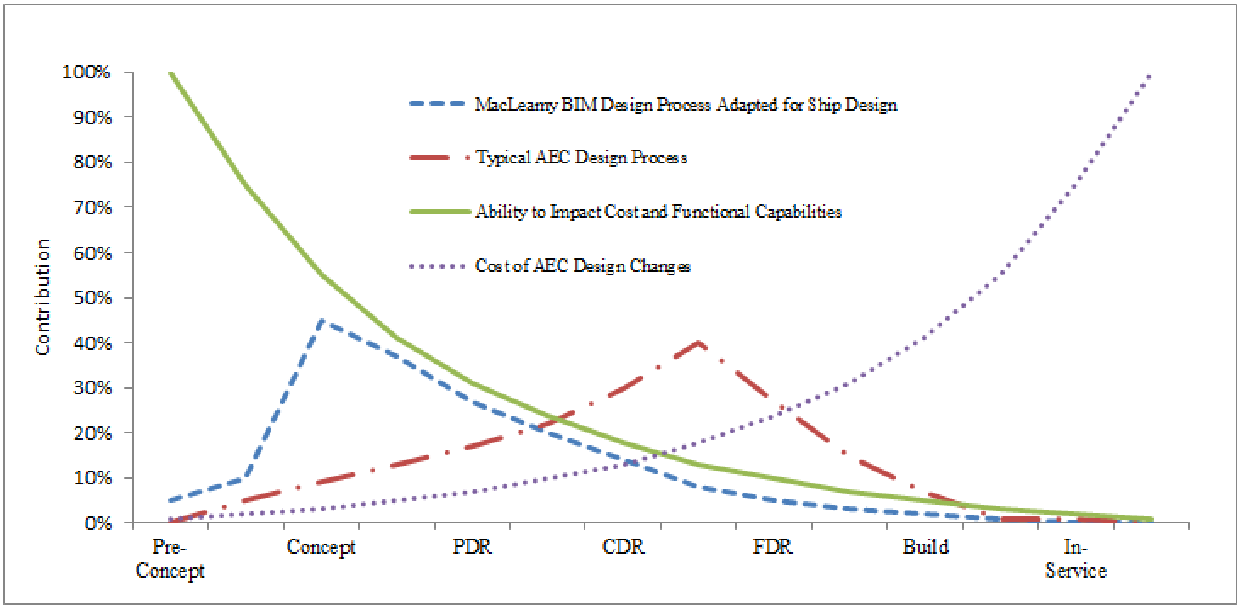


Figure 5.1. MacLeamy Curves. Adapted from [88]

The cost of design changes typically increases throughout the design cycle. The rough order of magnitude (ROM) for this increase during the production phase can be as high as 80 times compared to that experienced early in the design. For the purposes of validating functionality and relative costs over time, an average typical cost per change is used in the current study. The average cost per change for the U.S. automotive industry was estimated in one study at approximately $5000.00. [89]. The relationship between design changes and increased costs is investigated in the current study.

5.6 Advancing New Technology in the Design Cycle.

Risk is inherent in all projects, but it is especially prevalent in those that deal with new technologies and rapidly changing industries [52]. Moreover, in extreme projects most risks are not identified in time and it is not possible to plan a risk response in good time [85].

With complex project cost overruns and schedule delays attributed to challenges with design changes and advancing technology, a more effective response strategy and governance structure is needed. The proposed response strategy and governance structure to help manage potential design changes and new technology using the flight management simulator is depicted in Figure 5.2.

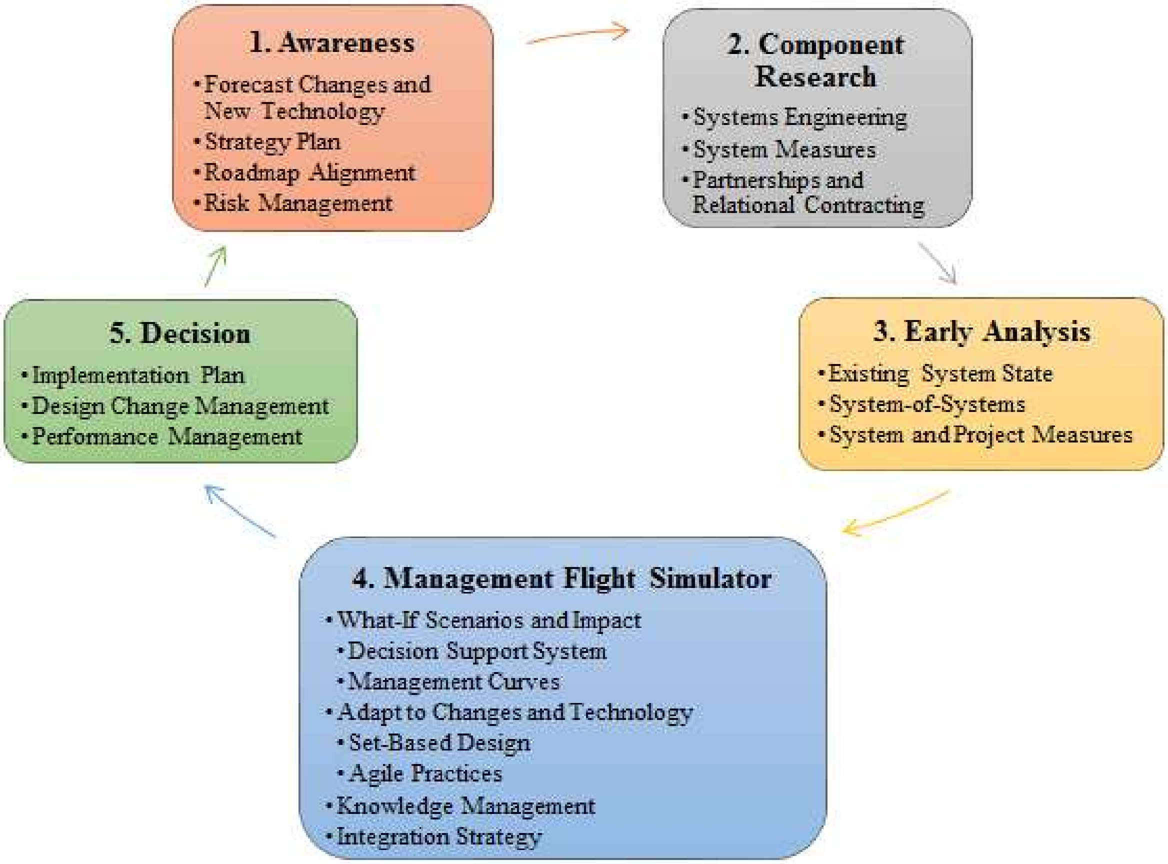


Figure 5.2. Design Change and New Technology Roadmap Governance

During the awareness stage, potential design changes and new technology can be anticipated and captured within the SRM.

The Gartner's Hype Cycle provides an indication of how new technologies emerge over time [90]. This cycle can be customized for emerging naval technologies and combined with technology maturity and supportability curves, as depicted in Figure 5.3.

During long duration projects such as a warship build, just-in-time operationally relevant technology is desired. As with the existing design changes, tradeoffs with new technology include an assessment of risks and attribute levels. At the same time, the maturity, supportability and affordability of new technology must be weighed in these decisions for their insertion during the design cycle.

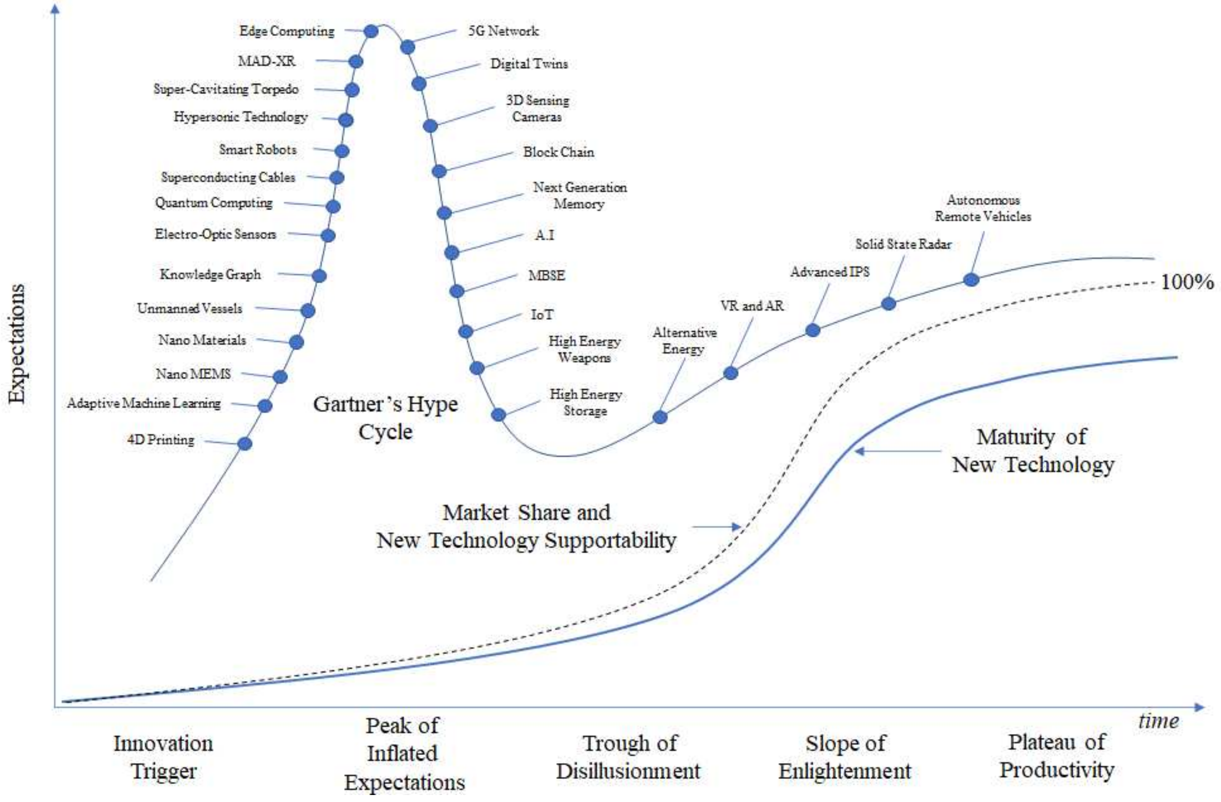


Figure 5.3. New Technology Maturity. Adapted from [90]

In the component research stage, the design change or new technology under consideration is analysed in terms of technology readiness level (TRL) and its performance, survivability, cost and operational capability attributes. Information on the constituent attributes of size, weight and power (SWaP) is also collected. This information helps to define the performance trajectory of new technology and its potential to meet the envelope of larger system acceptable performance parameters. While disruptive technologies may not initially meet performance requirements, they can eventually enter the zone or envelope of existing system acceptable performance.

Determining a window for implementing new technology can be difficult if not investigated early in the design. In the current study, a proactive approach is taken using the SRM and systems engineering tools such as DSM and design change propagation trees. It is also recognized that establishing relationships with vendors of new technology is equally important early in the design for capturing component information.

The management flight simulator provides for set-based design, a robust design, agile management through risk reduction and what-if scenarios, and informed decision-making. Moreover, the simulator can help predict the impact of changes and new technology on an existing system design.

5.7 Set-Based Design and Ease-of-Change Management

While there have been advancements in design space exploration and multidisciplinary optimization, most naval ship design efforts today rely on manual point-design [91].

The system property of flexibility can be defined as a measure of ease for which the system can be changed over time. It has been viewed as an emergent property that can be better understood by examining both the social and technical domains [92].

In the current study, measuring flexibility in design can take two different points of view. The first is one is where the DSM and changeability of components are considered. The other is one is where the position of attributes within their respective range values is considered; this reflects the set-based design approach for a robust and flexible design.

Set-based design has been reported as more effective than single point design [4]. It has also been noted that with robust design, systems can be more reliable under different conditions [93]. In set-based design, attributes are represented as ranges instead of point values and there are explicit views of trade-off values prior to decision making. In point design, teams inefficiently move from one alternative to the next in search of a solution.

Set-based design has not been formalized in terms of describing how to define sets, how to reason about them and eliminate options to arrive at solutions. It was recommended that set-based design have a mathematical foundation and clear methods to define sets and assess their values. [94]. The DSS addresses this need through the management of design attribute levels within their respective ranges. The goal for teams is to position attributes above their lower threshold for a robust design where the system can more easily adapt to changes. Set-based design is intended for windows of design feasibility, increasing the level of innovation and optimization throughout design [4].

While a goal-based approach to increasing attributes above their lower threshold can help with adapting to changes and new technology, this approach has the added benefit of maintaining design integrity, design intent and preserving margins during the design cycle.

In the current study, the attribute variance measures of C_{py} and C_{pky} provides insight into the trend and convergence of attributes over time. These measures may also help in assessing acceptable strategies and solutions, as depicted in Figure 5.4.

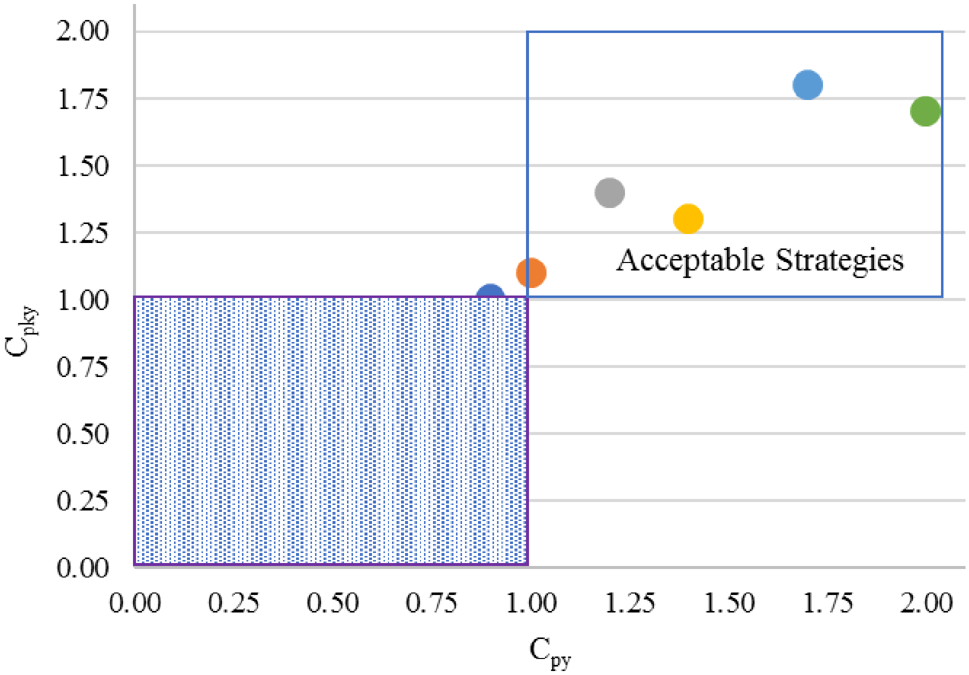


Figure 5.4. Attribute Variance Measures for Decision-Making

The management of attribute variance measures can help maintain a stable and robust design where the specific attribute values should be monitored to assure robustness of the overall design.

The TRIZ (Theory for Inventive Problem Solving) is a rule-based method to guide design and understand the impact of new technology and changes to a system. The TRIZ process is based on convergence toward a solution through iterative steps that govern design by the laws of evolution including system physical laws [95].

As depicted in Figure 5.5, DSS and set-based design provide a structured approach that mirrors TRIZ, including the convergence of attributes in design solutions over the course of the design cycle.

This approach includes striving for a robust design by way of a converged range of attributes above their lower acceptable threshold. TRIZ recognizes that the pattern of design evolution must follow underlying physical laws. This is also recognized in development of the design support system in the current study.

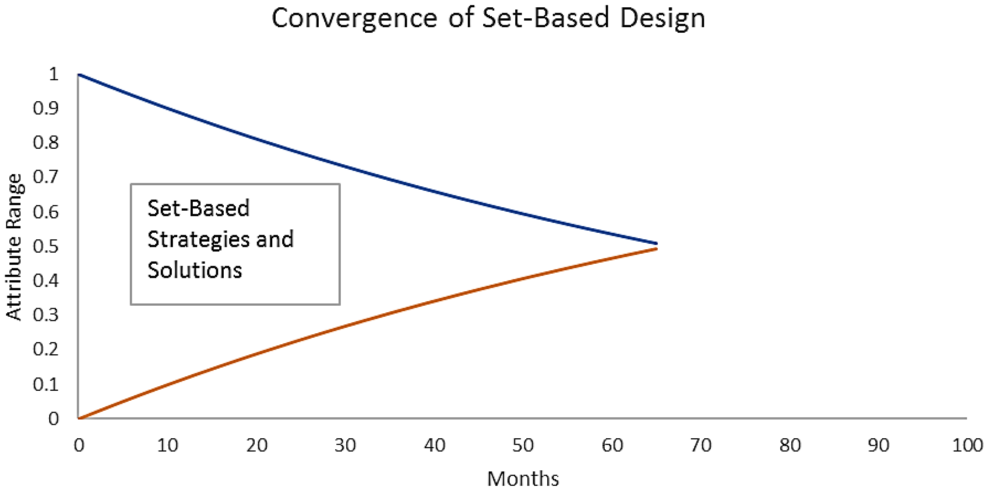


Figure 5.5. DSS Set-Based Design and Convergence of Design Solutions

TRIZ also recognizes that creative solutions to design problems may already exist. In the current study, these solutions may exist among design variants in the MATE reference model Similar to TRIZ, the current study promotes the use of several models and tools in design including the integration requirements of systems thinking, integrated models and simulation, and set-based design for robustness.

While the current study proposes a set-based design approach adhering to attribute thresholds, it is understood that there may be scenarios where an attribute may have to be relaxed in order to achieve realistic solutions. This may be viewed in terms of the Theory of Constraints where an attribute acts as a bottle neck to resolving a design problem. In these situations, the attributes of other systems within the larger SoS may have to be negotiated with other teams.

The enabling requirement of set-based goal-based design robustness is a high-level requirement that is related to SoS. Attribute management of the IPS design is for one system that is part of several ship systems. SoS common attributes such as SWaP and mission capability attributes can be shared across several systems. The SoS concept is important when conducting trade-off analysis where collective attribute management should be considered. This is important when considering overall design margins such as weight and electrical demands.

Closely related to the proposed set-based design approach for robust design is the operating window (OW) for robustness and failure mode avoidance for systems in operation. During design, the range of the OW for reliability can be determined from the physical laws of design variables and their values that achieve required performance [96]. Increasing likelihood of reliability, availability and safety throughout the product lifecycle may be achieved through maintaining attribute levels above their lower thresholds for improved performance and survivability. This may also be viewed as maintaining design integrity of the system functions and specifications. Additionally, the management of attributes, design changes and technology insertion can help assure design intent.

Changes may take the form of new technologies. Technologies can be of two types, sustaining or disruptive technologies. Sustaining technologies can improve system performance while still adhering to set-based specifications. On the other hand, disruptive technologies are those that may not meet near-term specifications but may eventually enter the zone of acceptable performance [97].

As depicted in Figure 5.6, disruptive changes and technologies may enter the zone or range of acceptable set-based attribute performance. In this case, understanding the maturity of technologies and their likelihood of meeting requirements later in the design cycle becomes important. Other considerations include increasing costs for changes later in the design and design change windows where a range of attributes can accommodate such changes.

The effort to extract defects through rework and changes can be up to 1000 times original developmental costs [4]. There have been more conservative estimates of the escalating costs of design changes ranging from 10 times original costs early in the design to 100 times these costs at the start of production [89]. These more conservative estimates are depicted in Figure 5.6.

Also depicted are the number of implemented changes for a real project based on a similar design-build of a marine IPS. One of the goals in the current study is to reduce the number of design changes, thereby reducing costs.

In the current study, system attribute variance and component changeability measures influence the ease-of-change levels. Low levels provide an opportunity to apply engineering principles such as modularity to components early in the design. High levels of ease-of-change provide an opportunity to standardize components.

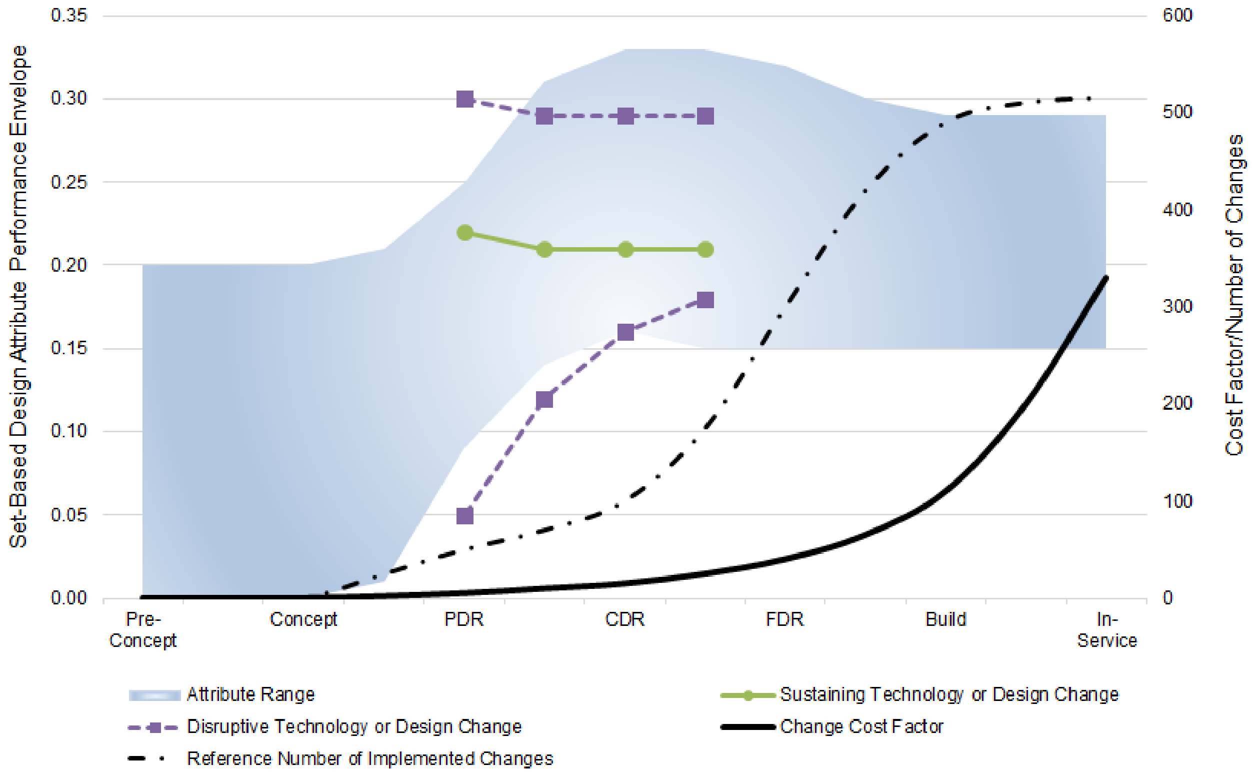


Figure 5.6. Technology Insertion, Design Changes and Cost Considerations

5.8 Information Management and Design Changes

It has been noted that better management of product information requires the alignment of design management processes, information systems, and the management of models for decision-making [48].

In a separate study, the review of rail and aerospace industry challenges in managing design changes pointed toward several issues worth considering in the current work [48]. The top five challenges resulting from a survey of 39 organizations were noted as follows:

i. inaccurate product information;
ii. managing the product change process;
iii. flow of information between information systems;
iv. time spent searching for information; and
v. duplicate product information.

With inaccurate information and increased time spent looking for information, the aspect of shifting-the-burden and resorting to quick solutions comes into play.

Some of the organizations surveyed shared their concerns with highly intensive information, obsolescence as a key driver for product changes, and the lack of application architectures for information flow [48].

In order to validate these challenges for the ship design and shipbuilding industry, a survey was conducted with a west coast shipyard.

Information enterprise systems can share common data fields, but many fields can be different. These systems support the design and management of system products and product information but there is a lack of standard terminology across information systems for achieving closer integration and smooth flow of information [48].

The current study investigates information flow and the need for transformational variables to link the different simulator models. The non-dimensional design attributes, changeability measures and management curves provide for standard terminology and a common language.

Integrated Product and Process Development (IPPD) is a management technique to help integrate acquisition activities using Integrate Product Teams (IPT) or cross-functional teams to support design, production and supporting processes.

The success of IPPD information systems depend on several objective features [98]:

i. support to analysis in early design stages;
ii. early knowledge of the design space;
iii. invoke permanent team structure;
iv. manipulate data as much as possible to simulate design tasks in early design stages;
v. optimized decision processes based on objective design attributes; and
vi. concurrent coupled design schedules for greater knowledge of design in early design stages

The first five features in this list are considered in development of the DSS and simulator.

5.9 Vendor Furnished Information

Decisions made early in the design cycle can have the greatest impact while at the same time there is little product information and high uncertainty [10]. The maturity of the design at a point in time can include having the required VFI, design processes and systems in place, required completion of design deliverables, and mature technology readiness levels.

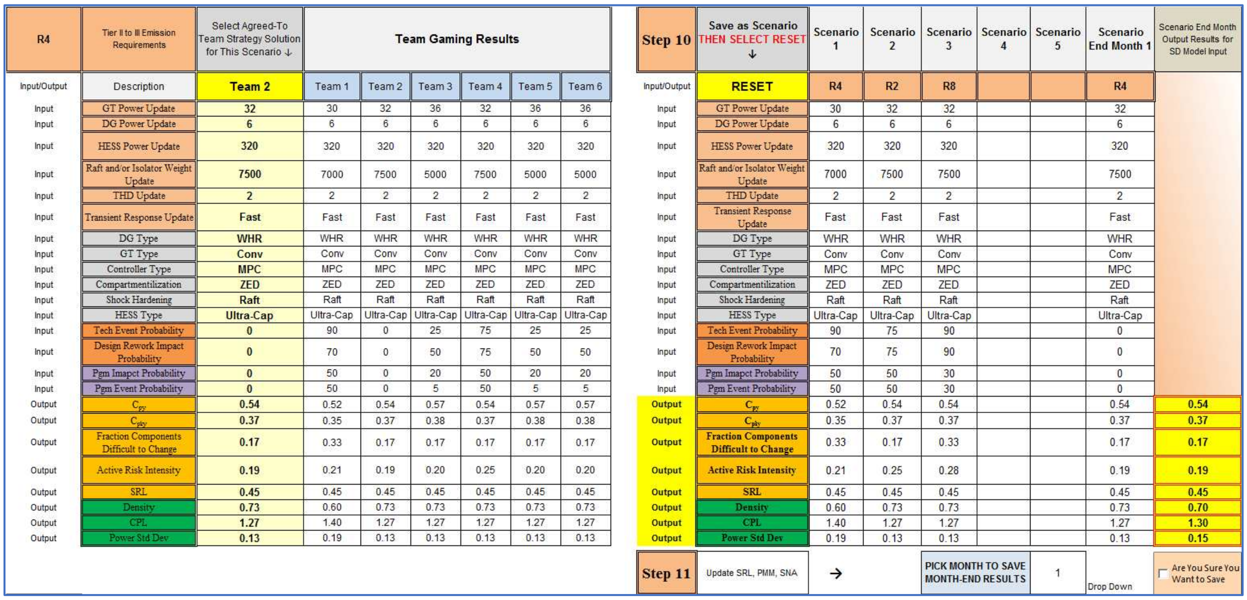
For the U.S Navy, elements for assessing design maturity include the maturity of VFI, technology level, and completion of required drawings and specifications. A design maturity of at least 85 percent for a stable design is desired prior to production; lower than this has been known to increase costs, design changes and cause out-of-sequence work [10].

In developing SDM model management curves, the predicted Design Maturity curve can be monitored for achieving a maturity of 85 percent prior to production.

5.10 Results

In the gaming of design change scenarios, the DSS attribute variances values, component changeability upper right quadrant fraction, SRM average risk intensity, SNA measures, and SRL values can be aggregated at the end of each month. These measures are automatically captured in DSS tables, as depicted in Table 5.1. In these tables, teams can game and select the best solution to design change problems.

Table 5.1. Gaming of Design Change Scenarios



R4	Tier II to III Emission Requirements	Select Agreed-To Team Strategy Solution for This Scenario ↓	Team Gaming Results					
Input/Output	Description	Team 2	Team 1	Team 2	Team 3	Team 4	Team 5	Team 6
Input	GT Power Update	32	30	32	36	32	36	36
Input	DG Power Update	6	6	6	6	6	6	6
Input	HESS Power Update	320	320	320	320	320	320	320
Input	Raft and/or Isolator Weight Update	7500	7000	7500	5000	7500	5000	5000
Input	THD Update	2	2	2	2	2	2	2
Input	Transient Response Update	Fast	Fast	Fast	Fast	Fast	Fast	Fast
Input	DG Type	WHR	WHR	WHR	WHR	WHR	WHR	WHR
Input	GT Type	Conv	Conv	Conv	Conv	Conv	Conv	Conv
Input	Controller Type	MPC	MPC	MPC	MPC	MPC	MPC	MPC
Input	Compartmentilization	ZED	ZED	ZED	ZED	ZED	ZED	ZED
Input	Shock Hardening	Raft	Raft	Raft	Raft	Raft	Raft	Raft
Input	HESS Type	Ultra-Cap	Ultra-Cap	Ultra-Cap	Ultra-Cap	Ultra-Cap	Ultra-Cap	Ultra-Cap
Input	Tech Event Probability	0	90	0	25	75	25	25
Input	Design Rework Impact Probability	0	70	0	50	75	50	50
Input	Pgm Imapct Probability	0	50	0	20	50	20	20
Input	Pgm Event Probability	0	50	0	5	50	5	5
Output	C_{py}	0.54	0.52	0.54	0.57	0.54	0.57	0.57
Output	C_{ply}	0.37	0.35	0.37	0.38	0.37	0.38	0.38
Output	Fraction Components Difficult to Change	0.17	0.33	0.17	0.17	0.17	0.17	0.17
Output	Active Risk Intensity	0.19	0.21	0.19	0.20	0.25	0.20	0.20
Output	SRL	0.45	0.45	0.45	0.45	0.45	0.45	0.45
Output	Density	0.73	0.60	0.73	0.73	0.73	0.73	0.73
Output	CPL	1.27	1.40	1.27	1.27	1.27	1.27	1.27
Output	Power Std Dev	0.13	0.19	0.13	0.13	0.13	0.13	0.13

Step 10	Save as Scenario THEN SELECT RESET ↓	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario End Month 1	Scenario End Month Output Results for SD Model Input
Input/Output	RESET	R4	R2	R8			R4	
Input	GT Power Update	30	32	32			32	
Input	DG Power Update	6	6	6			6	
Input	HESS Power Update	320	320	320			320	
Input	Raft and/or Isolator Weight Update	7000	7500	7500			7500	
Input	THD Update	2	2	2			2	
Input	Transient Response Update	Fast	Fast	Fast			Fast	
Input	DG Type	WHR	WHR	WHR			WHR	
Input	GT Type	Conv	Conv	Conv			Conv	
Input	Controller Type	MPC	MPC	MPC			MPC	
Input	Compartmentilization	ZED	ZED	ZED			ZED	
Input	Shock Hardening	Raft	Raft	Raft			Raft	
Input	HESS Type	Ultra-Cap	Ultra-Cap	Ultra-Cap			Ultra-Cap	
Input	Tech Event Probability	90	75	90			0	
Input	Design Rework Impact Probability	70	75	90			0	
Input	Pgm Imapct Probability	50	50	30			0	
Input	Pgm Event Probability	50	50	30			0	
Output	C_{py}	0.52	0.54	0.54			0.54	0.54
Output	C_{ply}	0.35	0.37	0.37			0.37	0.37
Output	Fraction Components Difficult to Change	0.33	0.17	0.33			0.17	0.17
Output	Active Risk Intensity	0.21	0.25	0.28			0.19	0.19
Output	SRL	0.45	0.45	0.45			0.45	0.45
Output	Density	0.60	0.73	0.73			0.73	0.70
Output	CPL	1.40	1.27	1.27			1.27	1.30
Output	Power Std Dev	0.19	0.13	0.13			0.13	0.15
Step 11	Update SRL, PMM, SNA	→		PICK MONTH TO SAVE MONTH-END RESULTS		1	Drop Down	☐ Are You Sure You Want to Save

In validating issues with the design change process and information management, a survey was conducted for a west coast shipyard. Most respondents indicated that there were problems in the transfer and accuracy of product information and that high-level system attributes should be included in assessing the impact of design changes. Table 5.2 provides a summary of the results from the west coast questionnaire as it relates to the design process, information flow and accuracy, and the need for higher level design attributes such as those proposed in the DSS for the IPS case study.

These validation results further support the need for a DSS that includes multiple high-level attributes. Survey results highlighted the need for a defined change management process that includes all factors affecting the final decision. Results also supported the need for accurate and mature VFI.

Table 5.2. Summary Results from West Coast Shipyard Design Team Survey – Design Change Process and Information Quality

Engineering - Program Management Questions	Rating: 1	Rating: 5	Mean	Std Dev
How do you rate the ability of your organization to track product changes throughout the lifecycle?	Good	Very Difficult	2.9	0.2
How well do you know the product change process?	Very Well	Not Well	2.0	0.0
How do you rate discrepancies in product information amongst stakeholders?	Few and Low Impact	Many and High Impact	3.5	0.5
How do you rate problems with product information flow between information systems?	Low	High	4.0	0.0
How do you rate the need to include higher level product information such as performance, survivability and program attributes and the impact due to product design changes?	Not Needed	Needed	2.8	0.8

Through interviews with an east coast shipyard design team, low VFI maturity and late design changes were noted as concerns; their estimated values for the design and build of a similar marine IPS are depicted in Figure 5.7. These values are useful as reference mode data in developing the SD model.

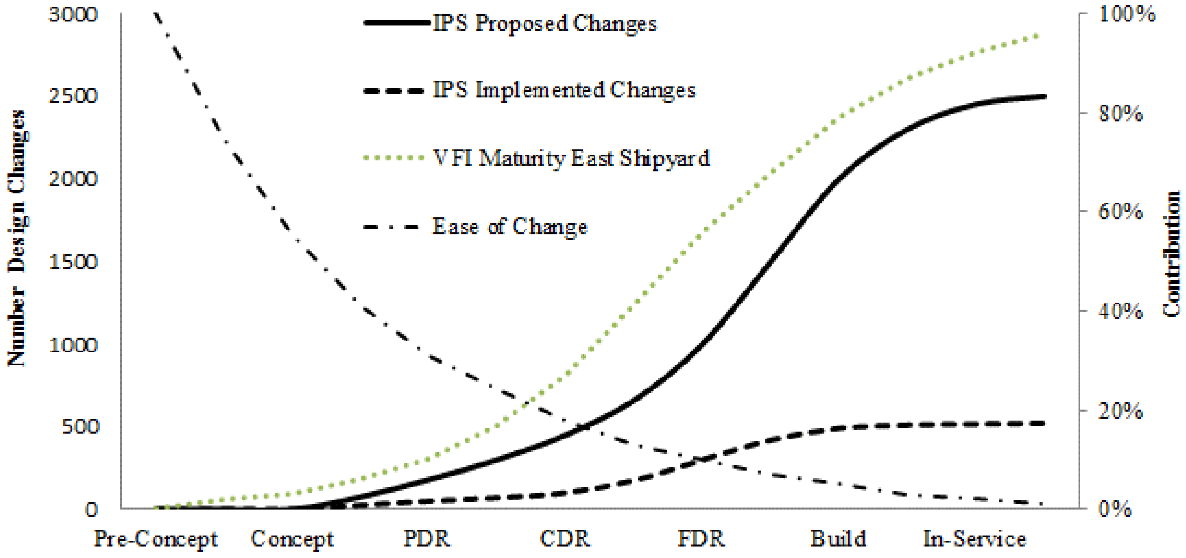


Figure 5.7. East Coast Shipyard Changes and VFI Maturity Relative to Ease-of-Change

Of interest is the VFI Maturity curve where it closely follows the shape of the typical Knowledge curve, as depicted in Figure 5.8. VFI maturity is viewed as a contributing factor to explicit knowledge.

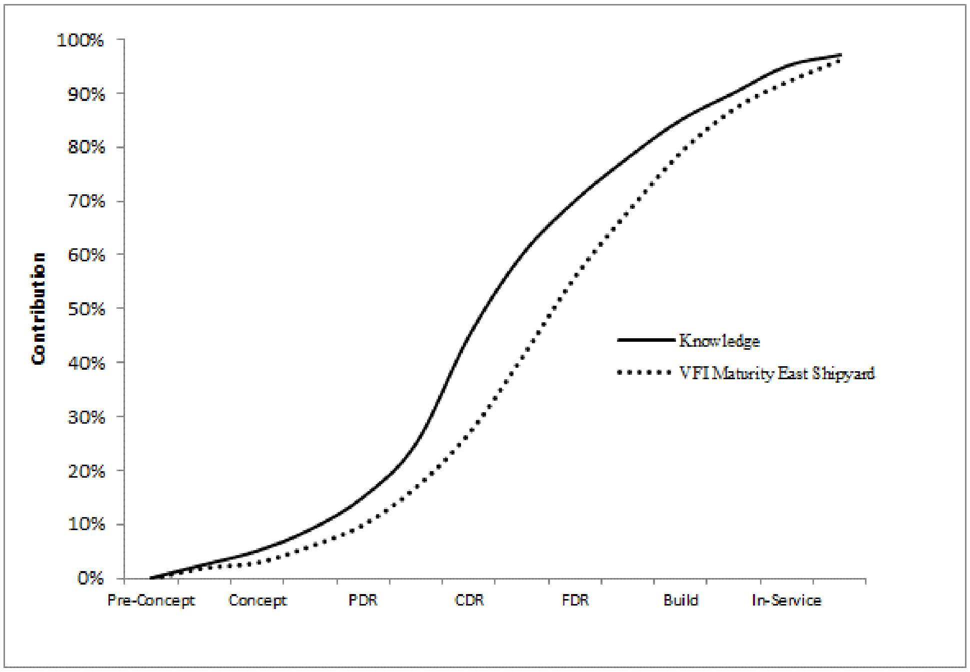


Figure 5.8. VFI Maturity East Shipyard and Typical Knowledge Curve

The lack of knowledge and immature VFI early in the design can negatively impact the ability to effectively manage design changes. The lack of this knowledge may stem from inadequate communication among teams and weak relationships with vendors but may also be caused by the lack of contractual arrangements in place to obtain early VFI. Often VFI is provided on a pro bona basis with vendors that expect to be included in the procurement process. Building early relationships with vendors to obtain VFI is known as relational contracting.

5.11 Conclusions

The west coast shipyard survey highlighted the need for accurate VFI, improved information flow among stakeholders and a DSS to understand the impact of changes on design attributes.

Information flow and management requirements were identified that can help in development of the simulator. Some key requirements include readily available information, accurate product information (VFI), objective attribute information for optimized decisions, and simulation of design tasks. Information systems that meet these requirements may be viewed as ones that can generate early knowledge and increase efficiency and effectiveness in decision-making. Moreover, these systems may avoid shifting-the-burden and help in moving toward fundamental long-term solutions.

Set-based design is viewed an approach to help achieve a robust design and move the Ease-of-Change curve up. The variance in attribute levels and component changeability can influence the position of this curve.

The strategy to strive for design attributes to be above their lower threshold is viewed as an effective approach in adapting to design changes, new technology insertion and preserve design margins. With this approach, the design process and the flow of information are viewed as key success factors for maintaining design integrity and design intent.

Chapter 6 – Cross-Functional Processes, Process Improvement and Policy Levers

6.1 Introduction

This chapter is aimed at advancing the simulator through the linking of key cross-functional processes and associated model elements. While literature proposes philosophical requirements for integration of these disciplines, there does not appear to be a practical approach offered. In the current study, the integration of processes, people, policy, models and tools are investigated.

Understanding how to integrate cross-disciplinary tools and models can be enabled through the review of project management and systems engineering processes. The review of underlying cross-functional processes is important in forming a basis and structure for development of the simulator. The common themes and lessons learned from past project successes and failures can help to identify policy levers of influence and provide insight into what to link across models. Casual relationships in cross-functional processes can include design life-cycle management curves and associated levers of influence.

6.2 Motivation

One of the major factors in complex project and product failure is the non-integration of disciplines, processes, models and tools. This continues to be the case for many projects despite earnest efforts in applying disparate decision-making models and tools. With the right integration approach, a more holistic and practical integrated model can be developed.

The motivation in the current chapter is to demonstrate the importance of cross-functional processes, factors and levers for product and project success. Moreover, identification of key processes is important in laying a foundation of core elements within the simulator.

6.3 Objectives and Questions

Integrating both project and systems engineering processes is a necessary step in achieving both integration of the organizational disciplines, the physical system and the models that are important to project and product success. Selecting the appropriate cross-functional processes is viewed as an enabler to effective integration.

When tailoring processes to a project, factors include culture, complexity, technology uncertainty, location of teams and language [99]. These are some of the factors considered in developing the simulator for bringing project management and systems engineering together.

Other factors include the effect from maturity of key processes, the current study considers best practices in adopting a Business Process Maturity Model (BPMM) [100].

6.4 Background

Through a literature review, a common theme with project and product failures is the lack of the right integration of discipline-specific processes, models, and tools, including a basis for a common language. Related themes include the need to utilize the broad knowledge base, to better communicate and collaborate, and the need to identify and understand cause-and-effect relationships. In these relationships, techno-socio-economic and cultural factors have not been adequately addressed to improve decision-making. For decision-making throughout the design cycle, a more flexible and adaptive approach is needed.

The decision management process is viewed as an overarching process that is used across elements within the simulator. The decision and risk management processes have been stated as the essence of program management where they synergistically create good tension and an opportunity for integration through team-based decisions and risk management processes [5].

6.5 Cross-Functional Processes

There are seven cross-functional processes in the current study that relate to the typical management curves of knowledge, ease-of-change, costs and technology commitments and costs-incurred. These processes include knowledge, change, risk, strategy, integration, communication, and supply-VFI management. The risk and strategy management processes are viewed as coupled processes that address the triggers and strategies in addressing design changes. The integration, communication and knowledge management processes are viewed as strongly related to each other. The supply-VFI management process is viewed as important in achieving explicit knowledge early in the design cycle, VFI and design maturity.

The maturity of these processes can affect the integration of PM and SE as well as product and project success.

6.5.1 *Knowledge Management*

Knowledge management is considered the critical variable and enabler in the current study. The application of the knowledge management process can help achieve project success and contribute to organizational learning [99]. Prior knowledge can be leveraged to improve project success and includes lessons-learned and typical system changes from past similar projects. In systems engineering, knowledge management is a process to create capability for the organization in exploiting opportunities and in reusing knowledge [7].

In the current study, knowledge management covers a broad area that transcends across the different disciplines.

6.5.2 *Change Management*

From a project management perspective, integrated change control is a process for reviewing change requests, approving changes and managing changes [99]. Change requests require revised cost estimates, schedules and analysis of risk response alternatives. This process is closely related to the systems engineering change and configuration management process.

In systems engineering, the change process helps to manage and control changes to system elements and configuration over the product lifecycle.

6.5.3 *Risk Management*

The Standard Risk Model (SRM) has been adopted in the current study. Both project management and systems engineering risk management processes use similar steps such as analysis, mitigation and the monitoring of risks. Systems engineering makes the distinction with managing technical risks that may interact with project risks [7]. The current study encompasses the management of both project and technical risks.

6.5.4 *Strategy Management*

The strategy management process allows an organization to adapt effectively to change and deliver effective capability to the customer. This process consists of three stages: strategy formulation, strategy implementation, and strategy evaluation [101]. In all three stages, PM and SE disciplines should be involved.

6.5.5 *Integration Management*

Studies reveal that only 16 percent of organizations are fully integrated and that over 60 percent of complex projects fail in terms of cost overruns and delays [5].

From a project management perspective, the goal of the integration process is to identify, define and coordinate activities across the project lifecycle. It includes balancing competing demands, alternatives and managing interdependencies. Closely related to integration management is knowledge management, monitoring and control, and integrated change control processes [99].

From a systems engineering perspective, the integration process integrates and synthesizes a set of system elements into an architecture and design [7]. It includes verification and validation as an iterative process for design changes.

Integration of disciplines has been viewed as an enabler to project success with the key elements of integration consisting of rapid decision-making, collaborative work, information sharing, and a culture of risk management [5]. In the current study, the integration of disciplines and processes is viewed as step toward increasing collaboration and decreasing unproductive tension between PM and SE.

Evolving trends in the integration management process include automated tools, knowledge management and agile management [99]. These trends and tools are investigated and incorporated into the simulator in the current study. Other considerations include automation of decision-making, tracking of decisions and understanding how decisions are made. This requires analysis of the communication management process and the information translated across the PM and SE domains.

6.5.6 *Communication Management*

The communication management process involves an exchange of information and forms a bridge between diverse stakeholders. In this process, effort is required in preventing misunderstanding and miscommunication [99]. Better communication between the disciplines of engineering and program management may prevent project and product failures.

The breakdown of communications can be a threat to design integrity, the Challenger disaster is an example of how serious the consequence of failed communication can be.

The 2010 Deepwater Horizon oil rig disaster was a result of several factors including poor design considerations, lack of understanding of technical information, and a focus by management on cost-cutting measures [102]. Poor decision-making includes a lack of understanding of risks associated with systems and a culture of withholding information from the public and government. The communication gap between engineers and managers can often cause incomplete and the thinning out of information as it gets passed up the chain of command.

To close the communication gap between disciplines, steps can be taken to create an environment for increased communication flow. In the current study, these steps include teaming and gaming change scenarios within the simulator and a realization of team social network interactions and performance.

Communication may also be improved through clear delineation of roles and responsibilities, providing an environment for information flow, practices that help communication, and an appeal process for decisions [80]. This includes governance rules for the gaming of change scenarios in the current study and identification of roles and authorities.

Additionally, co-location of teams may help in providing structured communication and a more tightly coupled organization [103]. Co-location is considered a policy lever within the simulator developed in the current study.

6.5.7 *Supply-VFI Management*

The supply-VFI management process is not well described within standards but the acquisition plan is well described in the program management standard [104]. The procurement plan supports both program and systems engineering in meeting requirements, system attributes, cost and schedule requirements. This plan can include options to purchase vendor furnished information (VFI) early in the program in order to gain knowledge and advance design maturity.

6.6 Work Performance

The organization can be analyzed through SD modeling to predict work performance, the extent of rework and the quality of work. This provides a different perspective on the work performance that may be compared to traditional performance management practices.

6.6.1 *Rework*

Engineering work in the current study includes engineering tasks that consist of drawing reviews and technical specification development, both of which are required to proceed with procurement of equipment. On top of this, additional engineering work is required for engineering changes, new technology insertion and rework during the design cycle.

Rework may occur due to errors associated with the lack of knowledge, competency, immature information, and program pressures. Performance in the organization depends on reducing these errors and increasing insights [68]. Other causes of rework include incompatible specifications, changing requirements, manufacturing issues, quality of design documentation, and environmental pressures [4].

Set-based design has proven effective in reducing rework [4]. This is of interest to the current study where set-based design can be achieved through the management of design attributes within the DSS model.

Like the consequences of late design change decisions, rework late in the design can also significantly increase costs [4]. While it's difficult to shift work forward, the approach in the current study is to use set-based design and levers of influence to provide more flexibility in design and to reduce incurred costs for design changes.

From concept to production, extracting defects through rework and changes can be up to 1000 times original developmental costs [4]. Many of the existing models and tools proposed to reduce rework have had limited impact as they do not address the root causes of rework.

6.6.2 *Performance Measurement*

Despite project management best practices and Earned Value Management (EVM) techniques, complex projects continue to experience cost overruns and delays. In the current study, project management is viewed as a dynamic system with influencing factors that are not typically defined and captured within normal practice.

Traditional program management performance measurement tools have failed to solve persistent project problems [76] [77]. The associated measures are viewed as lagging and can lead to late awareness of problems and poor project performance.

As highlighted in one study, program success has been narrowly defined in terms of costs and schedule and that the technical elements of design and risk management are required as leading indicators of cost and schedule performance [5].

Monitoring complex projects is difficult using traditional measures and do not consider the techno-socio-cultural factors [77]. System dynamics modeling is a well-established modeling approach for project management and can include these factors as well as the aspects of rework, feedback loops, and an understanding of adverse consequences in decision-making.

6.6.3 *Organizational Culture*

With increasing complexity in technologies, there has been increased focus on organizational culture and its connection with leadership [105]. Culture can be revealed in social and organizational situations including risk and design change management. It can also influence the performance and effectiveness of an organization.

Culture may be thought of as a pattern of shared basic assumptions that the group learns as it solves problems [105]. From this perspective, strategizing solutions to problems can be a form of learning as well as a mechanism to increase knowledge gain.

The learning culture can help generate and increase the use of knowledge. To achieve this culture, factors include charismatic leadership, teamwork and cooperation, training, empowerment, feedback, and an environment of trust for open communication [7].

These factors are restated in other literature, including practices in teamwork, and a safe environment for questioning and sharing information. Culture can be an elusive concept based on mindsets and patterns that are not easily measured. It has been viewed as the tacit social order of an organization that shapes behavior, attitudes and norms [106]. Culture can also be viewed as a barrier to the execution of strategy and the implementation of timely design changes. As noted by Peter Drucker, “culture eats strategy for breakfast”.

6.7 Improvement Levers

6.7.1 *Policy Levers*

Within the DSS, technical levers for adjusting system parameter and component types were discussed in previous chapters. Based on review of project failures, successes, and PM-SE integration requirements the focus of the current study is on seven policy and seven process improvement levers. The policy levers include on-the-job training, gaming intensity, application of engineering principles, learning effort, team colocation, paying for advanced VFI, and relational contracting effort. These are considered key levers that can influence the position and behavior of management curves.

6.7.2 *Process Improvement Levers*

The state of processes in an organization can affect work performance. While PM and SE have their own standards for describing processes, there does not appear to be a standard for describing cross-functional processes.

In the current study, key cross-functional processes are described in terms of supporting the simulator. Levers for improving these processes are proposed by way of process improvement initiatives. These initiatives may be triggered by the state or maturity of existing processes within an organization. The current study adopts a process maturity model (PMM) metric, with its levels listed in Table 6.1.

Table 6.1. Process Maturity Model Metrics [100]

Maturity Level	SD Model Level	Person Depend-ent	Documented Process	Partial Deployment	Full Deployment	Measured and Automated	Continuously Improving
Level 0	0.2	Yes	—	—	—	—	—
Level 1	0.4	—	Yes	—	—	—	—
Level 2	0.6	—	Yes	Yes	—	—	—
Level 3	0.8	—	Yes	—	Yes	—	—
Level 4	0.9	—	Yes	—	Yes	Yes	—
Level 5	1.0	—	Yes	—	Yes	Yes	Yes

6.8 The Effect of Levers on SD Entities

6.8.1 *Effect of Process Improvement Levers on SD Entities*

As listed in Table 6.2, is the effect from adjusting process improvement levers on rates and primary stock entities within the SD sub-model.

6.8.2 *Effect of Policy Levers on SD Entities*

As listed in Table 6.3, is the effect from adjusting policy levers on rates and primary stock entities within the SD sub-model.

Table 6.2. Effect of Process Improvement Levers on SD Entities

Process Improvement Lever	Effect →	Rate or Factor→	Effect →	Primary Stock Affected
Knowledge	+	Knowledge Gain	+	Knowledge
Communication	+	Knowledge Use	-	Proposed Changes
Change	+	Proposed Changes	+	Proposed Changes
Integration	+	Organization Integration	+	Strategies
Strategic	+	Strategy Reduction	-	Strategies
Risk	+	Risk Mitigation	-	Active Risks
Supply/VFI	+	VFI Acquisition	-	VFI Required

Table 6.3. Effect of Policy Levers on SD Entities

Policy Lever	Effect →	Rate or Factor→	Effect →	Primary Stock Affected
OJT	+	Knowledge Gain	+	Knowledge
Gaming Intensity	+	Organization Integration	+	Strategies
Engineering Principles	-	Ease-of-Change Depletion	+	Ease-of-Change
Learning Effort	+	Tasks Completion	-	Tasks-to-Do
Team Colocation	+	Organization Integration	+	Strategies
Paying for Early VFI	+	VFI Acquisition	-	VFI Required
Relational Contracting	+	VFI Acquisition	-	VFI Required

6.9 Conclusion

Through the review of PM and SE cross-functional processes and project success and failure factors, policy and process improvement levers were identified in this chapter that can influence the design life-cycle management curves.

The knowledge management process transcends across PM and SE and is viewed as a critical enabler in the current study. The risk management process can be a leading indicator of program performance. This process is uniquely coupled to the strategy management process as both are used to resolve design change problems. The integration process was also highlighted as a key process for automation of project and product elements.

The PMM measure was introduced and will be used in managing seven process improvement levers within the simulator.

The cross-functional processes discussed in this chapter represent entities within the simulator that provide a foundation for its development. This chapter provided insight into the causal relationships between cross-functional processes, work performance, and organizational effectiveness. These relationships and levers can be used in developing the program management side of the simulator.

Chapter 7 – Integration of PM-SE, Simulator Models and Processes

7.1 Introduction

It is not apparent that there has been research into a single standard, common language or practical approach to integrating PM and SE. With the many disparate models and tools, there can be confusion on what to integrate for product and project success. Moreover, the improper matching of models and immaturity of methods can make industry hesitant to adapt integrated MDO models [49]. One approach to alleviate this confusion is to apply systems thinking, systems science and systems engineering methodologies in the development of an integrated model.

There has been research into PM and SE integration where it was recognized that the relationship between integration, unproductive tension, and organizational performance is unclear but that the use of integration tools could be beneficial in bringing these two disciplines together [5]. In the same research, philosophical requirements for integration were offered but there remains no practical approach or working model for achieving this integration.

The current research provides a practical approach to PM and SE integration through development of a management flight simulator. This simulator captures both the technical system integration aspects and the project management practices for product and project success.

The integration of selected models within a management flight simulator allows for teams can game design change strategies in response to risks and issues. This simulator includes the DSS with its system normalized technical and quality measures, visualization of levels and trends in attributes for set-based design, and a system dynamics (SD) sub-model. This simulator can help maintain design integrity, promote a collaborative environment, lead to better decision-making, and ensure program and product success.

This chapter provides the basis for an integration strategy and framework that brings SE and PM together. The integration strategy includes taking a systems thinking, systems science and SE approach to this integration. Aspects of Control Theory are discussed in helping to understand how the management flight simulator can help to resolve change problems and remain stable as a system.

The technical and programmatic sides of projects are not well coupled, hampering decision-making [3]. The linkages between simulator technical and programmatic sub-models are presented by way of a digital thread or knowledge graph of transformational variables.

The simulator is discussed in its ability to adapt to complexity. Supporting laws are discussed for adapting to complexity, including Ashby's Law of Requisite Variety and Jaque's Law of Cognitive Capacity.

7.2 Motivation

In the current study, the simulator can track design changes, their impact and essentially the reasoning behind decisions. Through interactive controls and visualization of the impact of changes on both the system and management curves, the simulator provides multiple disciplines the 'big picture' of system, organizational and project performance.

The need for improved systems engineering processes, integrated models, including data analysis models, was recognized by NASA's Jet Propulsion Laboratory (JPL), with increasingly more complex missions and projects. It was recognized that their traditional processes did not adequately address system level interaction and specifications. In response to these problems, the JPL Integrated Model-Centric Engineering (IMCE) initiative was launched to transition the organization from document-centric engineering practices to integrated simulation-based models that support system trade studies, verification and validation [3].

The current study is inspired by this and other initiatives aimed at bringing PM and SE together.

7.3 Objectives and Related Research Questions

The aim of linking discipline-specific sub-models in the current study is to provide a practical approach to integrating these disciplines, where they can work together to identify and act on the consequences of potential design changes, within a system-of-systems (SoS) environment that is challenged by techno-socio-economic and cultural factors.

By the careful linking of key models, the objective is to provide the capability during the design cycle to advance the Knowledge curve and move up the Ease-of-Change curve so that product and project success can be better realized. As a minimum, this will reduce project cost overruns and schedule delays and better accommodate design changes and technology insertion throughout the design cycle.

The related research question in the current study is what this integrated model or simulator will look like and how can it be used to adapt to complexity and changes during the design cycle.

7.4 Background

The integration of program management and systems engineering has been defined as:

> *"a reflection of the organization's ability to continue program management and systems engineering practices, tools and techniques, experience and knowledge, in a collaborative and systematic approach, in the face of challenges, in order to be more effective in achieving common goals/objectives in complex program environments"* [5].

From this definition, it’s clear that the elements of tools, models, collaborative practices, and knowledge are important factors in developing the management flight simulator for product and project success.

In order to solve complex problems, it has been recognized that an integrated systems approach needs to include systems thinking, systems science and SE [7].

Systems thinking includes the discovery of patterns across systems, understanding interrelationships, how elements change over time and seeing the ‘big picture’. Systems science involves bringing together research into systems and understanding patterns of complexity that cross multi-disciplinary fields and areas of application. Systems engineering helps to integrate the different disciplines into a team for a structured development process across the product lifecycle [7].

In this approach, the focus is on bringing disciplines together to address complexity, with SE practices and cross-functional processes forming a foundation. As both complexity and change escalate throughout the design cycle, reducing risks is one of the primary goals of SE [7].

Collaborative practices include continuous improvement, use of external best practices, use of knowledge, mutual learning and social networking, and a structured support system [107].

With increasing system and program complexity and change, quick solutions may be sought in the form of off the shelf business tools and models. This approach has led to poor results as it is focused more at the component level and not at the holistic integrated system and organization level [108].

7.5 Integration Elements

The integration of selected models within a management flight simulator provides a shared platform for teams to game design change strategies in response to design risks and issues. This simulator includes the DSS with system normalized technical and quality measures, visualization of levels and trends in attributes for set-based design, and a system dynamics (SD) model. Other supporting models include the SRL, PMM and SNA models.

The taxonomy for multi-disciplinary tools and the criteria of simplicity, transparency, efficiency, accuracy, portability, automation and UX provides for broad integration requirements at the user level. From a systems, process and organizational perspective, other integration requirements are considered.

7.5.1 *Physical System Integration*

It was noted by NASA that physics-based models in the various engineering specialties are not connected to each other or to a system model and that analysis and trade studies require manual integration of results from the different domains. It was also noted that the different domains working in stovepipes can hide significant system level interactions that may only be discovered during final tests or after acceptance [3].

The DSS models include attribute management, a coupled SRM-DSM model and a dynamic component changeability chart. From a technical system perspective, integration of the DSS models and the supporting SRL model meets the requirements to describe the interaction of IPS components, their interfaces and design change propagation.

7.5.2 *Integration of Models and Information Systems*

In developing the DSS and simulator, features from IPPD information systems are relevant to the current study and include early knowledge, design analysis, simulation of tasks such as design changes, and an optimal decision process based on objective design attributes.

Success criteria for the integration of information include accessibility, usefulness, aids decision-making, and having a positive impact on the organization [109].

7.5.3 *Integration of Teams*

From an organizational and social sciences perspective, SNA can provide integration metrics. Effective knowledge transfer, communication and information flow are viewed as important requirements in development of the simulator. Moreover, use of the simulator in the gaming of change scenarios is viewed as an effective tool to help bring teams together.

7.5.4 *Integration of Management Curves Within the SD Model*

In describing management curves and their interaction with the DSS, the user requirements as well as other integration requirements are considered. These other requirements include addressing the techno-socio-economic and cultural factors in complex product and project management as well as the factors for project success.

7.6 Emergent Properties of the Simulator

The simulator models take on different forms and functions including tradeoff analysis, optimization of design attributes and simulation of management curves. Together, these models are used to manipulate and transform data within the simulator to provide useful information for decision-making. As the system, cross-functional processes and the organization mature so do the corresponding emergent properties.

The emergent behavior of the simulator can provide greater value than from the sum of its constituent models and elements, this concept is well-rooted in systems engineering theory.

7.7 Simulator and PM-SE Integration Requirements

The framework for the simulator is built on seven integration pillars, consisting of: systems thinking and system dynamics, integration factors and requirements, selection and integration of sub-models, a digital thread of linkages, set-based design approach for a robust design, action learning and agile principles for proactive risk and design change management, and inter-disciplinary informed decision-making.

7.7.1 *Systems Thinking and System Dynamics*

Systems thinking is used as a structured and logical approach to integrating elements of the simulator. Systems thinking may be thought of as transdisciplinary, drawing ideas from different disciplines in efforts to resolve problems [108]. The gaming of strategies using the simulator can provide a structured approach for bridging the gap between disciplines.

It has been widely accepted that systems thinking is critical in addressing social and economic challenges. As systems evolve, systems thinking can help in realizing options in decision-making and help to transcend disciplines and culture [110]. Systems thinking may also be described as a perspective, language and a set of tools [111].

In the current study, systems thinking is applied in bringing the different elements of the simulator together as a whole. These elements include data, models, cross-functional processes, and the techno-socio-economic and cultural factors affecting system, organizational and project performance.

While there does not appear to be a standard approach offered in applying systems thinking, it is applied in the current study using systems engineering tools such as causal loop diagrams (CLD's), system dynamics modeling and a N^2 component relationship diagram.

7.7.2 *Integration Factors and Common Themes for Integration Requirements*

7.7.2.1 *PM and SE Integration Factors*

While cost overruns and schedule delays are symptoms of project and product failure, the underlying factors, hidden influences and organizational dynamics can be ambiguous and often overlooked. These factors may be better understood through a literature review of project failures and successes.

Project failures have been linked to the lack of collaboration, poor design change management and technical and political risks [49] [64] [112]. These risks and an increasing abundance of information in complex projects can make it difficult to understand the impact of changes on system design and the project.

From a technical perspective, factors leading to cost overruns and schedule delays include numerous design changes, technical errors and challenges in technology advancement and system integration [12] [13] [52] [62].

From a program management perspective, success factors include a learning culture, competency, reliable procurement and material information, and relational subcontractor management [5] [9] [50] [62] [77] [88].

These factors and gaps support the need to improve collaboration and the management of information, knowledge, design changes, system integration, technology advancement, product quality and relational contracting. These factors, as well as integration requirements, are addressed in the simulator.

7.7.2.2 *PM and SE Integration Requirements and Common Themes*

There appears to be a positive correlation between project success factors and integration requirements for developing a simulator that integrates the system, processes, sub-models and organization. These requirements may be derived from the stated benefits of model-based systems, integration principles, practices, features and dimensions. From an extensive literature review, common integration requirements include communication and collaboration, social networking and recognizing team characteristics, early knowledge and a learning culture, early design analysis, mental models, understanding different perspectives, product quality and continuous improvement, and integration and simulation of information [5] [7] [98] [107] [113]. The integration requirements are listed in Table 7.1.

Table 7.1. Integration Requirements

Dimensions of PM-SE Integration [5]	Benefits of MBSE [7]	Integrated Product and Process Development Features [98]	Key Practices for an Integrated Management System [107]	Senge's Principles of a Learning Organization [113]
Processes, Practices and Tools (R2.1)	Communications (R1.2)	Team Collaboration (R1.3)	Infrastructure to Support Vision (R2.4)	Systems Thinking (E1.1)
Organization Environment: Executive Support, Knowledge and Culture (R6.1)	Knowledge (R6.1.1)	Early Knowledge (R6.1.1)	Cultivate Knowledge (6.1.2)	Personal Mastery (6.1.3)
People Competencies: Learning (R6.2), Communication and Leadership (R1.2)	Learning Systems Engineering (E1.2)	Optimization of Decisions (R4.1)	Learning (R6.2) and Social Networking (R1.4)	Team Learning (R6.2)
Contextual Factors: Program, Organization and Team Characteristics (R1.1)	Perspectives and Managing Complexity (R5.1)	Simulation of Information (R2.2)	Integration of Useful Information (R2.3)	Mental Models (R5.1)
Program Performance (R3.1)	Product Quality (R3.2)	Early Design Analysis (R4.2)	Continuous Improvement (R3.3)	Shared Vision (R1.5)

Of the five PM-SE integration principles listed, there is a sixth principle stated as effective integration [5]. This principle is considered an overarching principle that is inherent in the objectives of the current study. It includes the elements of information sharing, collaboration and rapid decision-making. Rapid decision-making is part of the agile management approach taken in use of the management flight simulator and forms part of the design change response strategy.

Under the principles of organization environment and people competencies, the element of leadership is considered outside the scope of the current study but is viewed as an important element in championing use of model-based systems and in bringing teams together.

The integration requirements are aggregated up into the common integration themes listed in Table 7.2.

Table 7.2. Common Integration Themes

Common Themes for Integration	Common Integration Requirements				
R1 Communication	R1.1 Contextual Factors: Program, Organization and Team Characteristics	R1.2 Communication	R1.3 Collaboration	R1.4 Social Networking	R1.5 Shared Vision
R2 Simulation	R2.1 Processes, Practices and Tools	R2.2 Simulation of Information	R2.3 Integration of Useful Information	R2.4 Infrastructure to Support Vision	
R3 Quality	R3.1 Program Performance	R3.2 Product Quality	R3.3 Continuous Improvement		
R4 Decisions	R4.1 Optimized Decisions	R4.2 Early Design Analysis			
R5 Mental Models	R5.1 Perspectives and Managing Complexity				
R6 Knowledge	R6.1 Environment: Leadership, Knowledge and Culture	R6.1.1 Early Knowledge	R6.1.2 Cultivate Knowledge	R6.1.3 Personal Mastery	R6.2 Team Learning

7.7.3 *Selection and Integration of Models*

7.7.3.1 *Selection of Models Through Reductionism*

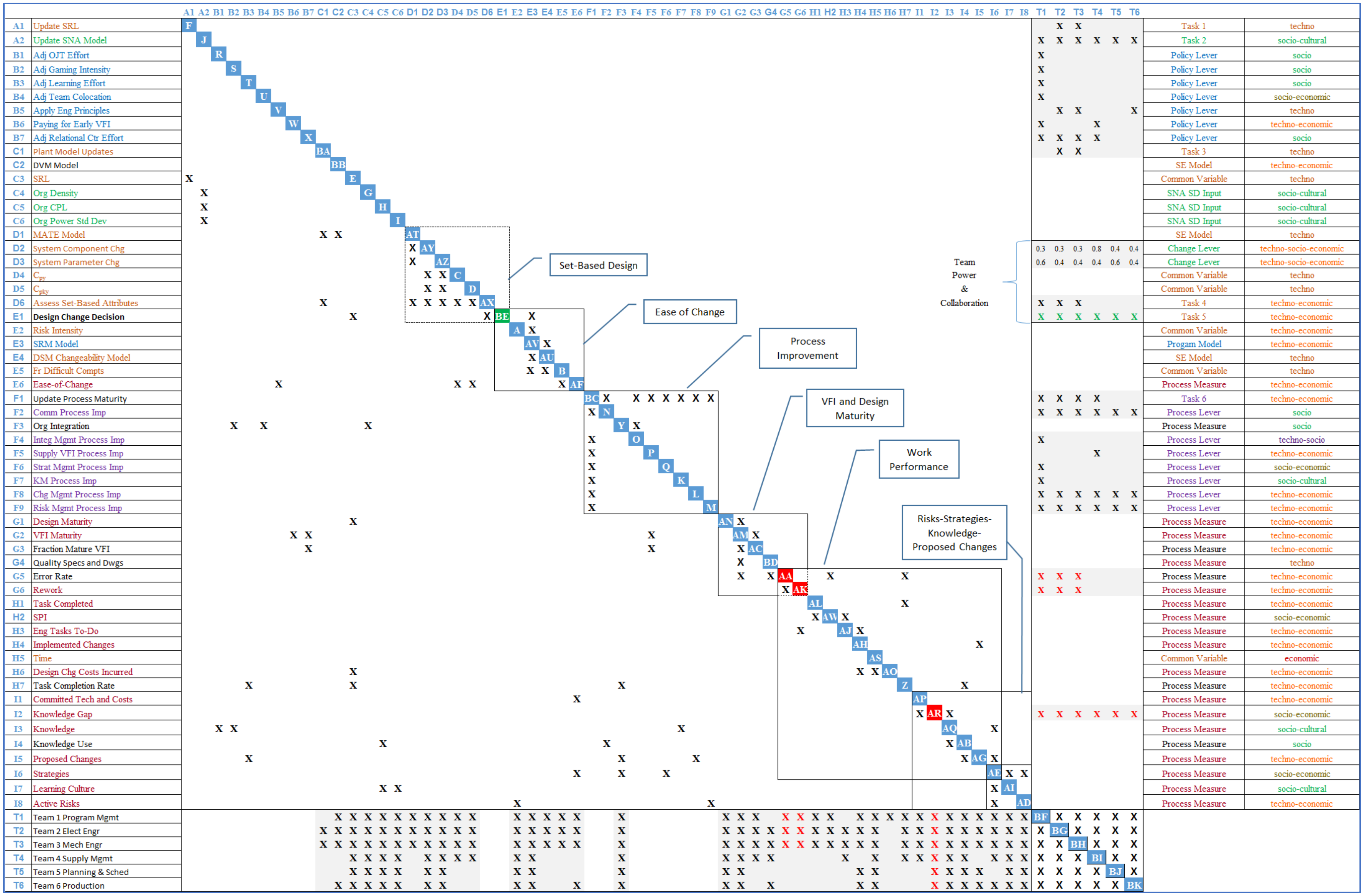
Models for the simulator were selected through a review of SE models and some PM tools stemming from concept design to those used throughout the design cycle. In this review, techno-socio-economic and cultural factors and interrelationships were analyzed. This includes the organizational environment and its disturbances, organizational contextual factors such as the social network, the effectiveness of program and systems engineering disciplines, competency through knowledge management, program performance, and the processes and tools that can be leveraged to enable integration. In this review, decomposing models and understanding their intrinsic characteristics for integration follows both the typical SE V-cycle and the scientific reductionist approach.

7.7.3.2 *N^2 Interface Matrix*

The relationships and integration points within the simulator may be represented through use of a DSM or diagramming of a N^2 matrix, as depicted in Figure 7.1. The input of top row elements on intersecting left column elements are assigned an '*X*'. The sequence of elements is rearranged to determine clusters around the matrix diagonal. These clusters help in developing entities and interrelationships within the simulator and its sub-models. Along with synthesizing integration requirements, N^2 diagramming can provide for a structured and formalized approach to developing the simulator framework.

Moreover, the feedback elements above the diagonal, feed forward elements below the diagonal and coupled relationships around the diagonal provide insight as well as validation on the inputs used for developing causal loop diagrams and the SD sub-model.

The goal in developing the N^2 diagram is to rearrange rows and columns through an iterative process so that most dependencies reside below the diagonal. From there, groups or clusters around the diagonal can be identified and visualized.



		T1	T2	T3	T4	T5	T6		
A1	Update SRL		X	X				Task 1	techno
A2	Update SNA Model	X	X	X	X	X	X	Task 2	socio-cultural
B1	Adj OJT Effort	X						Policy Lever	socio
B2	Adj Gaming Intensity	X						Policy Lever	socio
B3	Adj Learning Effort	X						Policy Lever	socio
B4	Adj Team Colocation	X						Policy Lever	socio-economic
B5	Apply Eng Principles		X	X			X	Policy Lever	techno
B6	Paying for Early VFI	X			X			Policy Lever	techno-economic
B7	Adj Relational Ctr Effort	X	X	X	X			Policy Lever	socio
C1	Plant Model Updates		X	X				Task 3	techno
C2	DVM Model							SE Model	techno-economic
C3	SRL							Common Variable	techno
C4	Org Density							SNA SD Input	socio-cultural
C5	Org CPL							SNA SD Input	socio-cultural
C6	Org Power Std Dev							SNA SD Input	socio-cultural
D1	MATE Model							SE Model	techno
D2	System Component Chg	0.3	0.3	0.3	0.8	0.4	0.4	Change Lever	techno-socio-economic
D3	System Parameter Chg	0.6	0.4	0.4	0.4	0.6	0.4	Change Lever	techno-socio-economic
D4	C_{py}							Common Variable	techno
D5	C_{pky}							Common Variable	techno
D6	Assess Set-Based Attributes	X	X	X				Task 4	techno-economic
E1	Design Change Decision	X	X	X	X	X	X	Task 5	techno-economic
E2	Risk Intensity							Common Variable	techno-economic
E3	SRM Model							Progam Model	techno-economic
E4	DSM Changeability Model							SE Model	techno
E5	Fr Difficult Compts							Common Variable	techno
E6	Ease-of-Change							Process Measure	techno-economic
F1	Update Process Maturity	X	X	X	X			Task 6	techno-economic
F2	Comm Process Imp	X	X	X	X	X	X	Process Lever	socio
F3	Org Integration							Process Measure	socio
F4	Integ Mgmt Process Imp	X						Process Lever	techno-socio
F5	Supply VFI Process Imp				X			Process Lever	techno-economic
F6	Strat Mgmt Process Imp	X						Process Lever	socio-economic
F7	KM Process Imp	X						Process Lever	socio-cultural
F8	Chg Mgmt Process Imp	X	X	X	X	X	X	Process Lever	techno-economic
F9	Risk Mgmt Process Imp	X	X	X	X	X	X	Process Lever	techno-economic
G1	Design Maturity							Process Measure	techno-economic
G2	VFI Maturity							Process Measure	techno-economic
G3	Fraction Mature VFI							Process Measure	techno-economic
G4	Quality Specs and Dwgs							Process Measure	techno
G5	Error Rate	X	X	X				Process Measure	techno-economic
G6	Rework	X	X	X				Process Measure	techno-economic
H1	Task Completed							Process Measure	techno-economic
H2	SPI							Process Measure	socio-economic
H3	Eng Tasks To-Do							Process Measure	techno-economic
H4	Implemented Changes							Process Measure	techno-economic
H5	Time							Common Variable	economic
H6	Design Chg Costs Incurred							Process Measure	techno-economic
H7	Task Completion Rate							Process Measure	techno-economic
I1	Committed Tech and Costs							Process Measure	techno-economic
I2	Knowledge Gap	X	X	X	X	X	X	Process Measure	socio-economic
I3	Knowledge							Process Measure	socio-cultural
I4	Knowledge Use							Process Measure	socio
I5	Proposed Changes							Process Measure	techno-economic
I6	Strategies							Process Measure	socio-economic
I7	Learning Culture							Process Measure	socio-cultural
I8	Active Risks							Process Measure	techno-economic
T1	Team 1 Program Mgmt	BF	X	X	X	X	X		
T2	Team 2 Elect Engr	X	BG	X	X	X	X		
T3	Team 3 Mech Engr	X	X	BH	X	X	X		
T4	Team 4 Supply Mgmt	X	X	X	BI	X	X		
T5	Team 5 Planning & Sched	X	X	X	X	BJ	X		
T6	Team 6 Production	X	X	X	X	X	BK		

Figure 7.1. N^2 Matrix of Simulator Elements

7.7.4 *Digital Thread of Linkages*

As depicted in Figure 7.2, elements of the simulator are connected by a digital thread of key transformational variables, referred to as a knowledge graph. The thread also connects technical measures to program and organizational measures. This includes a common ontology and hierarchical framework of design and program attribute measures as well a set of management curves.

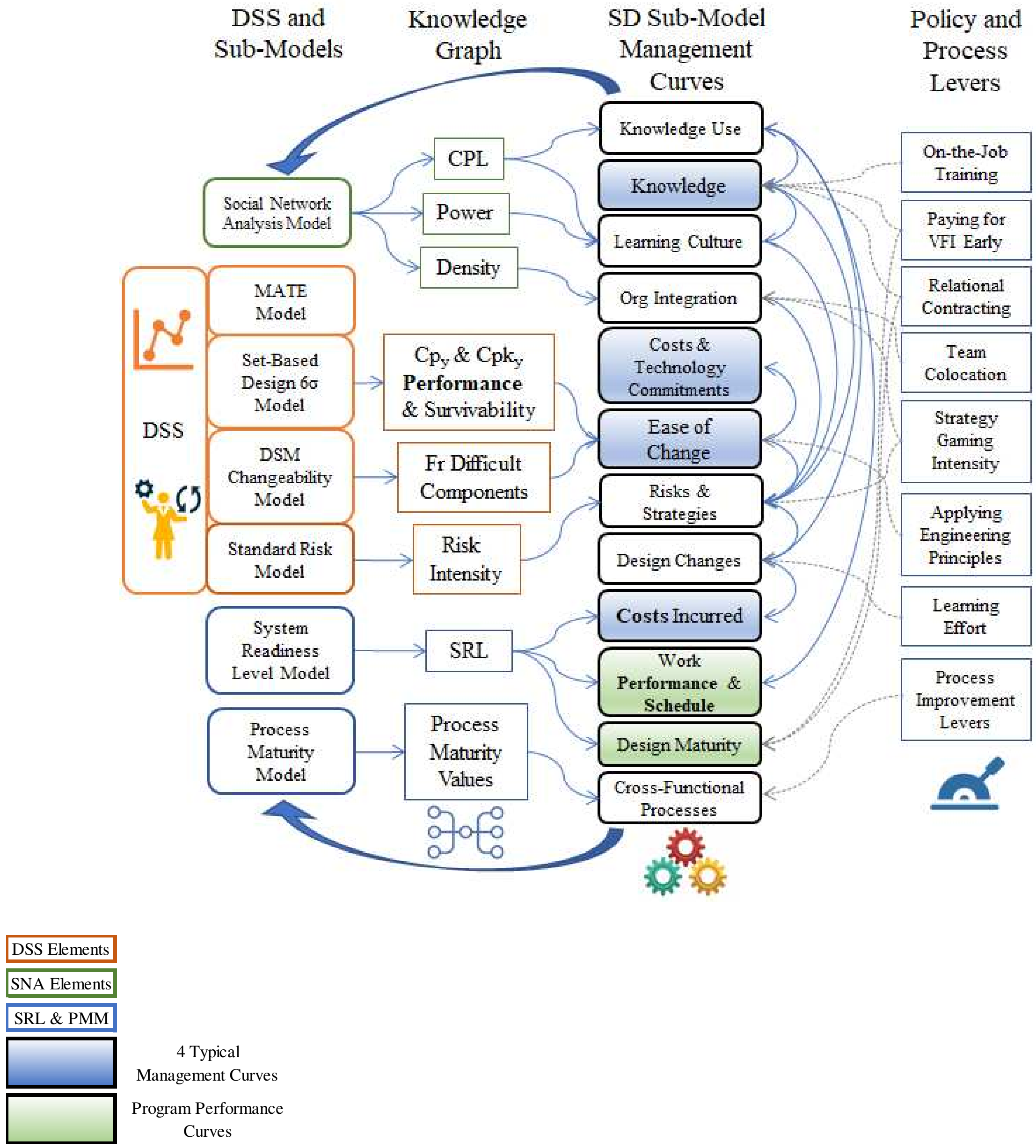


Figure 7.2. Simulator Digital Thread of Transformational Variables

7.7.5 *Set-Based Design for a Robust Design*

Set-based design was discussed in Chapter 5 and adopted as an approach to using the DSS for a robust design where the goal is to maintain design attributes above their lower threshold. When changes or new technology are introduced where their attribute level is low, the existing design can exhibit robustness in absorbing the change.

7.7.6 *Decision-Making*

Decision-making has been discussed in previous chapters in terms of design changes, SNA and the Power metric, decision rules and governance, game theory and convergence of strategy solutions, and early information and knowledge.

This chapter addresses decision-making at the macro level and describes how use of the simulator can help overcome project complexity and improve decision-making. Overcoming complexity includes aspects of agile management.

7.7.6.1 *Adaptability to Complexity*

Stage-gates for decision making were introduced in the 1980's as a disciplined approach for developing new products and getting them to market faster. Today's more turbulent environment calls for a more flexible and adaptive approach, one the incorporates aspects of agile management. Advances in this area have been made with incorporation of iterative build-test cycles and flexible decision structures. This adaptive approach includes the ability to respond to fluid information and changing customer requirements [50].

Organizations in situations of rapid change need to be flexible, adaptive, productive and able to tap into the organization's capacity to learn at all levels. Five disciplines required to achieve this include systems thinking, personal mastery, mental models, a shared vision, and team learning [113]. In the current study, these disciplines are achieved through use of the simulator. Gaming change scenarios can improve collective intelligence as well as adaptive intelligence in addressing project complexity.

With near-real time management of design attributes in the current study, a continuous design review regime can be implemented to augment the traditional stage-gate reviews.

7.7.6.2 *Ashby's Law of Requisite Variety in Decision-Making*

One of the concepts in managing complexity is the limitations of variety in responses to disturbances or risks. Ashby's Law of Requisite Variety requires a system to have a variety in responses to disturbances. In the current work, the relationship between disturbances (system risks or issues d_n) and team (T_n) responses as outcomes (design change strategies S_{ij}) may take the form depicted in Table 7.3.

Table 7.3. Risks and Design Change Strategies

		Response R (Design Change Strategies)					
		T_1	T_2	T_3	T_4	T_5	T_n
Disturbances D (Risks)	d_1	S_{11}	S_{12}	S_{13}	S_{14}	S_{15}	S_{1n}
	d_2	S_{21}	S_{22}	S_{23}	S_{24}	S_{25}	S_{2n}
	d_3	S_{31}	S_{32}	S_{33}	S_{34}	S_{35}	S_{3n}
	d_n	S_{n1}	S_{n2}	S_{n3}	S_{n4}	S_{n5}	S_{nn}

The outcome Sij may be further delineated into a set of system design attributes that are arrived at through teams gaming design change strategies.

In accordance with Ashby's Law of Requisite Variety, the variety in the outcomes, or strategies (*S*) in this case, cannot be less than the variety in disturbances (*D*) over the number of responses (*R*) [114].

$$var\ S \geq \frac{var\ D}{var\ R} \tag{7.1}$$

For example, for 10 disturbances and 2 team responses, the variety in strategies must be at least 8 bits and may consist of both good and bad responses.

$$2^8 = \frac{2^{10}}{2^2} \tag{7.2}$$

Matching variety in responses to disturbances is a condition for successful regulation and control in complex and social systems [115]. In the current study, the simulator provides for technical and project management perspectives in decision-making with adequate variety in responses to disturbances. The relationship between the number of strategies to risks is further exploited in SD model development.

In the gaming of solution strategies, the variety in strategies can help avoid shifting-the-burden and resorting to easy and quick solutions. Moreover, this can help in the sharing of different team perspectives in solving problems, as related to the Theory of Mind.

Ashby's law of Requisite Variety may not always apply to design change risks in the current study as well as in the real world. This law may be necessary but not enough for resolving problems. For instance, there may be only a few solutions to a change problem where these solutions are optimum given design and project constraints. At the same time, providing several cross-functional teams to address change problems can help assure optimal solutions can be achieved.

Achieving optimal solutions can be enhanced through a risk response strategy that includes not only a variety in responses but a framework for a set-based robust design.

7.7.6.3 *Cynefin Framework and Project Categories*

The Cynefin Framework provides four spaces for situating projects: complex, chaotic, ordered-simple, and ordered-complicated [116]. In the complex space, there can be unpredictable and emergent outcomes. In the chaotic space, a fire-fighting approach is often used. This space may be viewed as related to the NDM environment. In the ordered-simple space, there are known relationships where best practices can be applied. In the ordered-complicated space, there are fuzzy relationships where expertise is required to make sense of them. In the current study, the case study is viewed as residing between the complex and ordered-complicated spaces. In this region, teams can strategize solutions and leverage multi-disciplinary expertise. Use of the simulator is viewed as an enabler to help teams to probe, analyze, sense information and better respond to disturbances and problems.

7.7.6.4 *Ashby's Space*

The Ashby Space, as depicted in Figure 7.3, depicts a balance between variety in responses and variety in disturbances. The disturbances can be categorized in terms of chaotic, complex and ordered information [117].

In the chaotic region, disturbance information can be unclear, uncertain and difficult to extract. The response in this case can be varied including trial and error strategies. This situation can demand additional resources to sort and understand the disturbances. In the ordered region, disturbance information is linear, straight forward and can be easily resolved with few resources. In the complex region, disturbance information is a mix of the other two regions and requires additional resources.

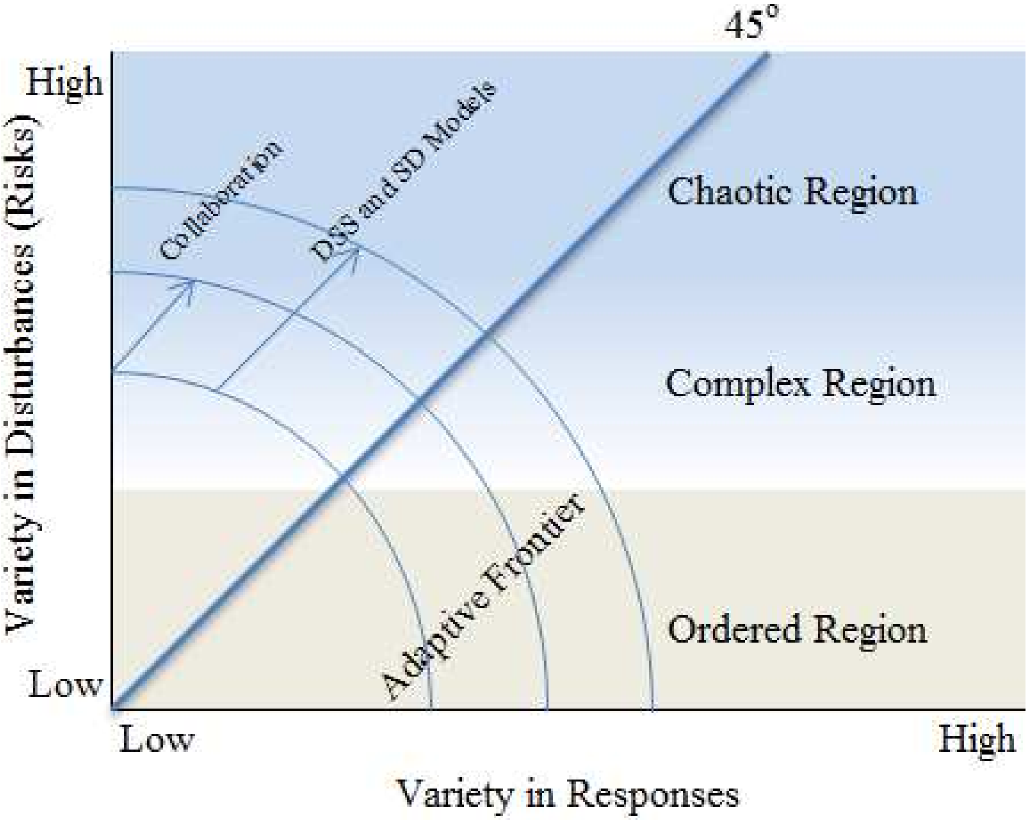


Figure 7.3. Categorization of Disturbances and Adaptive Frontiers for Decision-Making. Adapted [117]

The lower adaptive frontier is where resources and budgets may be at their limit in adapting and responding to a variety of disturbances. With increased capacity for social collaboration, the adaptive frontier may be expanded [117].

In the current study, it is proposed that this adaptive frontier can be further expanded using the simulator with increased collaboration, learning and knowledge.

7.7.6.5 *Jaque's Law of Requisite Cognitive Capacity*

There can be limitations in translating mental models from an individual on a higher cognitive stratum to an individual on a lower stratum. Jaque's Law of Requisite Cognitive Capacity states that additional effort and resources are required for this translation [118]. In accordance with this law, individual cognitive capacity varies and is dependent on the individual's lifetime, trajectory in cognitive development and timespan to think through problems and plan. Related to this is the absorptive capacity of an organization to exploit knowledge [70].

In the current study, it is proposed that use of the simulator can help to reduce this additional effort in translating mental models and can reduce the timespan to resolve problems. Furthermore, these models use a language that can be easily understood regardless of what cognitive stratum an individual is on.

7.7.6.6 *Agile Management and the Stacey Complexity Model*

While agile management typically involves rapid prototyping more suited to software projects, aspects of agile are relevant to the current study. Complex design projects such as the IPS can have high uncertainty, increased risks and complexity, and high rates of rework and change. These conditions can be addressed by an agile approach that involves incremental and interactive short cycles or sprints for exploring options, followed by feedback retrospective sessions.

The typical design project has defined requirements and a predictive product lifecycle; however, high technical uncertainty and how to design and build the system, may cause the project to become complicated. As depicted in Figure 7.4, the Stacey Complexity model suggests different management approaches to different types of projects [119].

In this model, complex projects can have high uncertainty around project requirements as well as high uncertainty around how to satisfy these requirements using knowledge and technology. As uncertainty increases, so does the risk of design changes and rework.

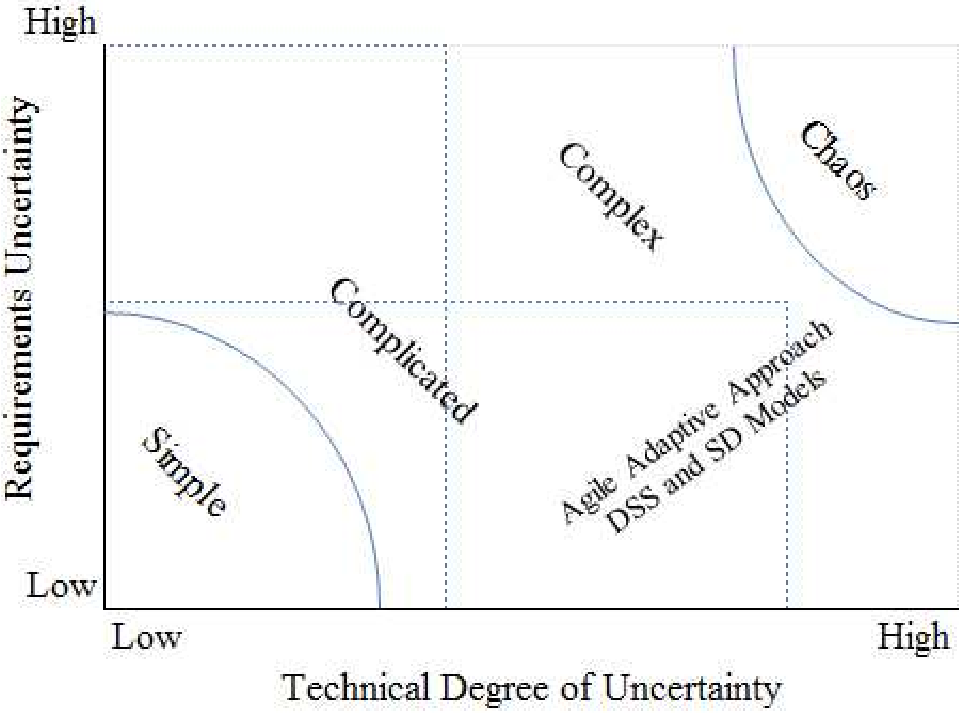


Figure 7.4 The Stacey Complexity Model and an Agile Adaptive Approach to Using the Management Flight Simulator. Adapted from [119]

To mitigate these risks, an agile approach consisting of small increments of work, feedback and adjustment is recommended in the current study through use of the management flight simulator.

As proposed for expanding the adaptive frontier in Ashby's Space, and for overcoming Jaque's limitation in cognitive capacity, the simulator is viewed as a tool to increase collaboration and adaptation to complex projects. The gaming of design change scenarios in response to risks and issues is viewed as an agile and adaptive approach that involves sprints and retrospective feedback sessions.

These scenarios are described within the DSS and form use cases that capture the team's different perspectives and decisions in resolving design problems.

7.8 Action Learning and Agile Management

Action learning was discussed in Chapter 4 where the quick cycling of what-if scenarios in response to risks can represent an iterative agile management approach. Agile management can also include an adaptive approach to problem solving and risk reduction.

New design projects of high uncertainty require teams to collaborate and solve problems with creative solutions [119]. These type of projects may benefit from the aspects of agile project management. In the traditional project management approach, requirements are determined upfront with changes made during the project. Conversely, agile project management explores feasibility of the product in short cycles and quickly adapts based on feedback and analysis [119]. The characteristics of the project environment where agile practices may apply include disruptive technology changes, high uncertainty in design requirements and a rate of design changes [119].

The IPS case study in the current study is a highly complex project that can be prone to high uncertainty. Applying agile management practices can be of value is addressing this complexity and uncertainty. The value may be seen in reducing the number of changes, rework, costs and schedule delays.

To mitigate the impact of design change risks, short design stages of incremental work and following the response strategy in the current study are proposed. The short design stages are reflected in monthly gaming of design changes using the management flight simulator and reduction of risks. These rapid and transparent feedback loops are common to the agile management approach. Other aligned practices using the management flight simulator include double-loop learning, adapting to design changes and adjusting the plan along the way.

Agile can be viewed as a blanket term that refers to any approach, technique, method or practice that fulfils the values and principles of the Agile Manifesto. The goal in agile is to deliver a continuous flow of value and achieve better business outcomes [119].

While this manifesto was formalized by leaders in the software industry in 2001, it can have relevance to other industry project management approaches including the practices adopted in the current study.

In assessing the alignment of the practices introduced using the simulator to agile management practices, the four values and 12 Agile Manifesto principles are compared as listed in Tables 7.4 and 7.5.

Table 7.4. Alignment of the Simulator Requirements to Agile Values

The Four Values of the Agile Manifesto [119]	Management Flight Simulator Values	Alignment
Working software over comprehensive documentation.	Working practical integrated model over excessive documentation.	Aligned
Customer collaboration over contract negotiation.	Collaboration by all stakeholders. Contract negotiation and amendments required in defense programs. **R1 – Communication, Collaboration, Social Networking and Stakeholder Perspectives.**	Partial
Individuals and interactions over processes and tools.	**E1 – Integration Strategy.** Focus of PM-SE integration using processes and combining models and tools.	Not Aligned
Responding to change over following the plan.	Follow plan in defense programs and adopt response strategy for changes. **E2 – Response Strategy** for responding to design change risks and new technology.	Not Aligned

Table 7.5. Alignment of the Simulator Requirements to Agile Principles

No.	The 12 Principles of The Agile Manifesto [119]	Management Flight Simulator Requirements	Alignment
A1	Our highest priority is to satisfy the customer through early and continuous delivery of valuable software.	**R6- Early knowledge, learning culture and early design analysis,** and continuous delivery in accordance with plan.	Partial
A2	Welcome changing requirements, even late in development. Agile processes harness change for the customer's competitive advantage.	**E2 - Response Strategy** for managing complexity and adapting to changes and new technology. Set-based goal-based attribute management for a robust design. Postponing commitments through Ease-of-Change allowing for just-in-time new technology for operational relevance and defense customer competitive advantage.	Aligned
A3	Deliver working software frequently, from a couple of weeks to a couple of months, with a preference to a shorter timescale.	**E2 - Response Strategy** for managing complexity including Action Learning, Team Learning, Double Loop Learning and frequent 'what-if' scenarios and solutions every week with end month reports. Demonstration reviews is an agile common practice. In software projects, prototyping is easy and less expensive compared to a complex warship design where prototypes would be costly.	Partial
A4	Business people and developers must work together daily throughout the project.	**R1 – Communication, Collaboration, Social Networking and Stakeholder Perspectives.** This includes business program management staff and engineers.	Aligned
A5	Build projects around motivated individuals. Give them the environment and the support they need and trust them to get the job done.	**S4 - Has a positive impact on the organization.** Motivate through use of simulator and, **R6- Early knowledge, learning culture and early design analysis.** Colocation of teams is viewed as an important policy lever. A supporting environment includes a safe environment where all teams can have an equal voice. This is also viewed as a success factor for agile management.	Aligned

A6	The most efficient and effective method of conveying information to and within a development team is face-to-face communication.	**R1 – Communication, Collaboration, Social Networking and Stakeholder Perspectives**	Aligned
A7	Working software is the primary measure of progress	Not applicable.	Not Aligned
A8	Agile processes promote sustainable development. The sponsors, developers, and users should be able to maintain a constant pace indefinitely	**E2 - Response Strategy** that includes proactive risk management and learning, adhering to schedule.	Aligned
A9	Continuous attention to technical excellence and good design enhances agility.	**R3 – Quality, continuous improvement and performance management**	Aligned
A10	Simplicity – the art of maximizing the amount of work not done – is essential.	**R3 – Quality, continuous improvement and performance management.** Efficiency in delivering minimum required and a focus on shared outcomes.	Aligned
A11	The best architectures, requirements, and designs emerge from self-organizing teams.	**R1 – Communication, Collaboration, Social Networking and Stakeholder Perspectives**	Aligned
A12	At regular intervals, the team reflects on how to become more effective, then tunes and adjusts its behavior accordingly.	**R1 – Communication, Collaboration, Social Networking and Stakeholder Perspectives.** Cross functional team meet and game design change solution and reduce active risks. Risk reduction includes addressing a backlog as an agile common practice. Retrospective sessions could also be held as an agile common practice.	Aligned

From this comparison, the management flight simulator requirements are mostly aligned with the principles of the Agile Manifesto. While not all simulator requirements are aligned, the goal of agile management is achieved through delivery of a continuous flow of value for achieving better business outcomes including reduced changes, costs and schedule delays. This continuous flow includes regular gaming of design change solutions, risk reduction, action and double loop learning through use of the simulator, demonstration reviews that can occur monthly, and the option for retrospective sessions.

7.9 Earned Value Management and The Management Flight Simulator

Earned Value Management (EVM) is a popular project management method used to monitor and control projects [109]. EVM dates to the 1960's in the management of government defense projects. This method considers the impact of time, cost and quality in the analysis of project status at any given time during the project.

In terms of time, it is the basis for determining how much work should have been completed against actual work. This also applies to planned and actual costs and schedule. Costs and schedule follow the typical S-curve behavior, like the knowledge and costs-incurred management curves discussed in the current study. EVM links the metrics of costs and schedule against a time-phased plan so that variances may be calculated.

EVM terms for calculating variances include planned value (PV), earned value (EV) of physical work completed, and actual cost (AC) or realized cost of work. From these terms, cost and schedule performance indices, CPI and SPI respectively, may be calculated.

As discussed in Chapter 6, EVM is limited to providing project performance that is based on past performance. One of the few EVM forecasted measures is estimate at completion (EAC) which is based on actual costs and an estimate of remaining costs.

The EVM metrics are depicted in Figure 7.5. The AC curve may be viewed as the Costs-Incurred management curve, and the earned value curve may be viewed as completed tasks within the SD model.

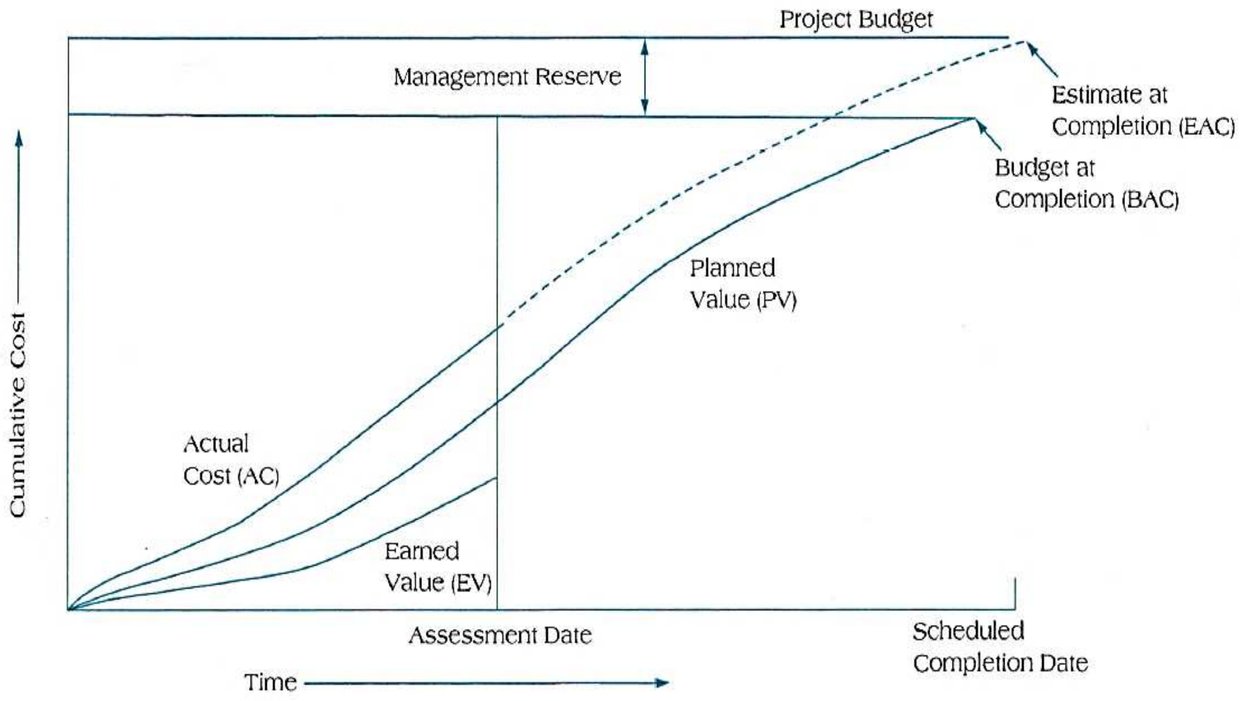


Figure 7.5 Typical EVM Curves [109]

EV updates may be compared to the predicted trend of completed engineering tasks within the SD model. Furthermore, the EVM schedule performance index (SPI) may be compared to that predicted in the SD model.

These comparisons between EVM and associated management curves provides for a different perspective on EVM where management curves are based on several influencing factors not considered in the EVM approach. At the same time, updated EVM metrics may help in calibrating associated project management curves with the SD model.

The EVM measures and the project management costs-incurred (AC) and completed tasks (EV) within the SD model are considered complimentary and provide for a larger picture of project performance. The alignment between EVM principles and the management flight simulator requirements and features are listed in Table 7.6.

Table 7.6. Alignment of EVM Principles and Management Flight Simulator Practices

EVM Principles	Management Flight Simulator Practice	Management Flight Simulator Element	Alignment of Simulator to EVM Principles
Monitor PV [99]	PV for estimated tasks within the SD sub-model	SD sub-model engineering tasks	Partial
Monitor EV [99]	Predict completed engineering tasks based on organizational, cultural, social and human factors	SD sub-model Tasks Completed	Partial
Monitor AC [99]	Limited to design change predicted costs-incurred	SD sub-model Costs-Incurred management curve	Partial
Tools to objectively measure work performance [109]	Engineering task plan and additional rework predicted	Work Performance	Partial
Produce decision-making information in ascending levels of management [109]	Design Attribute technical measures, predicted rework and management curves	DSS, SRL, PMM, SNA, SD sub-model	Aligned
Analyzes and forecasts impact of variances from plan [109]	Variance and trends in design attribute levels, predicted management curves	DSS and SD sub-models	Aligned
Schedule performance [99] [109]	Estimates SPI based on human and organizational factors	Work Performance SD sub-model	Partial
Cost performance [99] [109]	Commitment and Costs-Incurred predicted management curves	SD sub-model	Partial
Quality performance [99] [109]	Design Attribute technical measures, SRL and SRM-DSM	DSS, SRL and SRM-DSM	Aligned

While the SD model project management curves are based on engineering tasks associated with the IPS case study, the associated project performance measures may be aggregated up to the larger set of engineering systems and tasks required for the ship design and build. Similarly, EVM IPS metrics may be aggregated up as part of all engineering system tasks.

As may be the case with other performance metrics, it is important that the information used for metrics is accurate and objective. Updated information as input into EVM is only as accurate as team members and managers allow it to be through an honest reporting system [109]. On the other hand, information by way of objective design attributes within the DSS sub-model can help with data integrity. At the same time, other management flight simulator measures are subject to team member estimation. These estimated measures reside within the SRM, DSM, SRL, PMM, and SNA.

For both EVM and the management flight simulator, it is important to establish system and project performance standards for honest and unbiased reporting. While both approaches offer different perspectives and insight into project performance, their accuracy should always be questioned.

Another problem with establishing accurate and meaningful EVM results is related to the need to recognize human factors in all project completion estimations [109]. For instance, there can be a strong incentive for team members to report stronger results than actuals in order to promote a favorable project status considering political and organizational pressures.

Key components and indicators of project performance not captured by EVM include technical skills, management, communication, motivation, and leadership [109]. While EVM answers the ‘what’ questions through its metrics, the management flight simulator can help to answer the ‘why’ questions with its underlying organizational, social and culture interrelationships.

The key to developing useful project control processes is in recognizing the strengths and weaknesses of alternative methods and developing an approach that best suits the project [109]. The management flight simulator in the current study and the response strategy for using it provides a complimentary approach for better estimating project performance.

7.10 The Management Flight System and Control Systems Theory

Feedback control systems are pervasive in both industry and in everyday life. In the broadest sense, it is any interconnection of components to provide a desired function [120]. The feedback feature can help to stabilize unstable systems that have sensitivity in existing characteristics and that experience disturbances.

The simulator in the current study predicts the state of the physical system and its impact on management curves where teams can respond with design change strategies using interactive controls. The management of attributes and management curves in the current study may be thought of as a control system, as depicted in Figure 7.6. Design changes and new technology insertion are represented as disturbances to the system. The system attributes and management curves can represent the plant or process in control system theory. The interactive parameter, process and policy levers in the simulator may be thought of as controllers that produce desired plant behavior.

Some of these levers will have more of an influence than others, the level of influence is determined in the current study through a sensitivity analysis using Vensim® software. The range of the lever values were validated for SD model stability using the same software. Use of key levers within the simulator are based on observed outputs. Using the appropriate levers can provide for optimization as well as stability in the system.

To improve ability of the system to respond to disturbances, a feed forward feature is incorporated where the impact of changes can be played out through what-if scenarios early in the design cycle. Stability can be improved by both the feed forward feature and the controllers or levers used within the simulator.

In many control systems, there is a need to calibrate the system to reestablish knowledge of the input-output relationship often enough to obtain desired accuracy [120]. In the current study, the simulator also requires calibration. This can be done through comparing actual results in the performance of attributes and management curves against those predicted. In the calibration process, causal loop gains within the SD model may be adjusted accordingly.

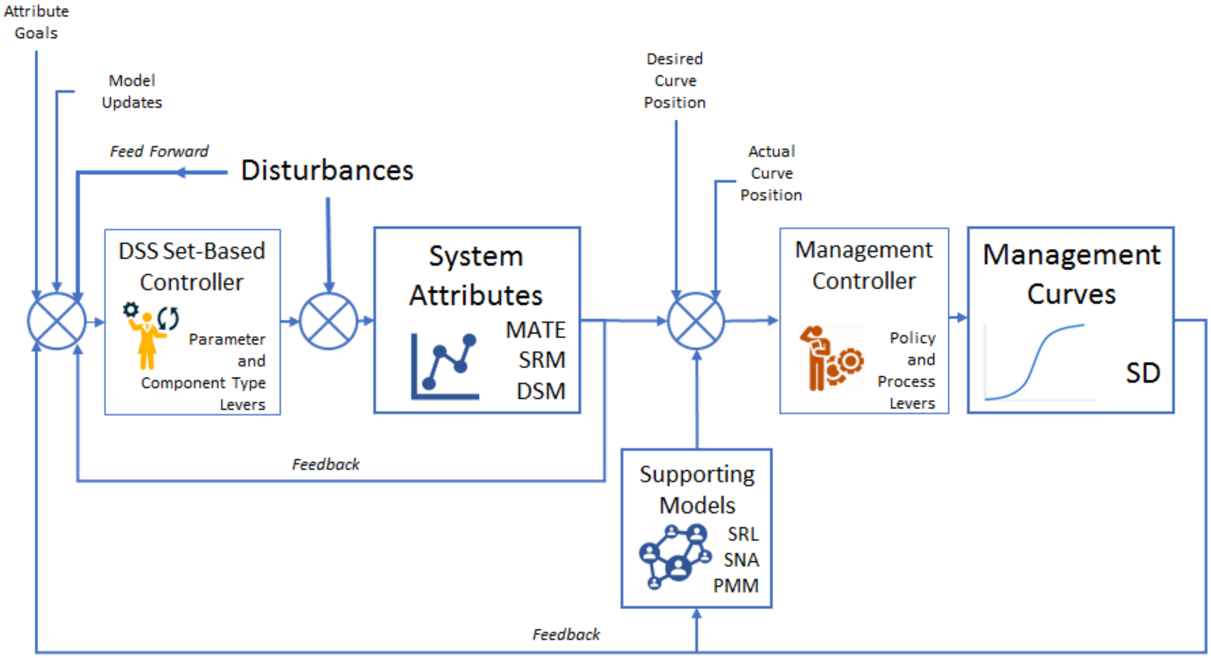


Figure 7.6. Management Flight Simulator as a High-Level Control System

In applying levers, the timing for them to take hold within the system may be a matter of trial and error. If not conscious about the delay system response, more corrective action may be applied than needed. One of Senge's management principles states that in a sluggish system, aggressiveness produces instability and that one can either be patient or make the system more responsive [113].

While the way levers are applied in the simulator can affect stability of the system attributes and management curves, the relationship between the number of strategies and risks may also affect stability. This relationship is further exploited in the current study through SD model development.

When systems work well, there can be harmony and resiliency in their functioning [110]. Resilience is the ability of the system to bounce back after a disturbance. In terms of the SD model, this property may be achieved through a rich structure of feedback loops that work in different ways to restore and stabilize system behavior [110].

This rich structure is achieved in the current study with elements related to cross-functional processes, stocks, causal relationships through feedback loops, techno-socio-economic factors, and levers that can help to restore and stabilize system behavior.

7.11 Conclusion

The integration strategy discussed in this chapter includes the seven pillars for integration consisting of: systems thinking and system dynamics, integration factors and requirements, selection and integration of sub-models, a digital thread of linkages, set-based design approach for a robust design, action learning and agile principles for proactive risk and design change management, and inter-disciplinary informed decision-making. Design change and project management using the simulator can be complementary to traditional EVM practices.

In delineating these pillars and elements for simulator development, systems thinking, social sciences, SE and Control Theory were leveraged. With key PM-SE cross-functional processes, integration factors and requirements investigated and described, a foundation is established to move forward with CLD and SD model development as final steps in building a functional flight management simulator prototype.

The simulator may be viewed as an adaptive control system that addresses complexity in the design, project and within the organization.

Chapter 8 – Casual Loop Diagrams and SD Model Development

8.1 Introduction

From the PM and SE processes, elements, levers and common integration requirements discussed in previous chapters, the aim in the current chapter is to use this information in developing an integrated model, known as the management flight simulator. This simulator includes the necessary linkages for integrating the decision support system (DSS) with a system dynamics (SD) model. The integrated DSS, SD and supporting models form a management flight simulator for teams to game design change strategies in response to design risks and issues.

8.2 Motivation

It has been stated that several design models fail to represent the interaction across domains and do not capture the aspects of time and the social sciences [92]. The management flight simulator in the current study provides a practical approach for integrating PM and SE and captures the aspects of time and the techno-socio-economic and cultural factors in decision-making.

Within the simulator, underlying models are linked in a unique way with common variables of interest. Knowledge management, design change and risk management processes are exploited in a way that provides structure and meaning to communication and collaboration of multiple disciplines within a complex project management environment.

8.3 Objectives and Related Research Questions

The objective in the current chapter is to develop the necessary linkages and relationships to assemble the complete management flight simulator as a functional prototype. The focus is on the final SD model with its process and policy levers.

Related research questions are addressed including what the prototype should look like and how it can address complexity and design changes.

8.4 Background

With committed costs and technology increasing throughout the design, there can be detrimental consequences from early decisions made with inadequate knowledge. These consequences include increased effort and costs along the way to make changes or introduce new technology. Moreover, the costs to extract errors can become exponential, as depicted in Figure 8.1.

Both the Knowledge and Ease-of-Change curves discussed in the current study can have a positive effect on this problem. The management curves, influencing factors, related entities and interrelationships may be described and understood through causal loop diagrams.

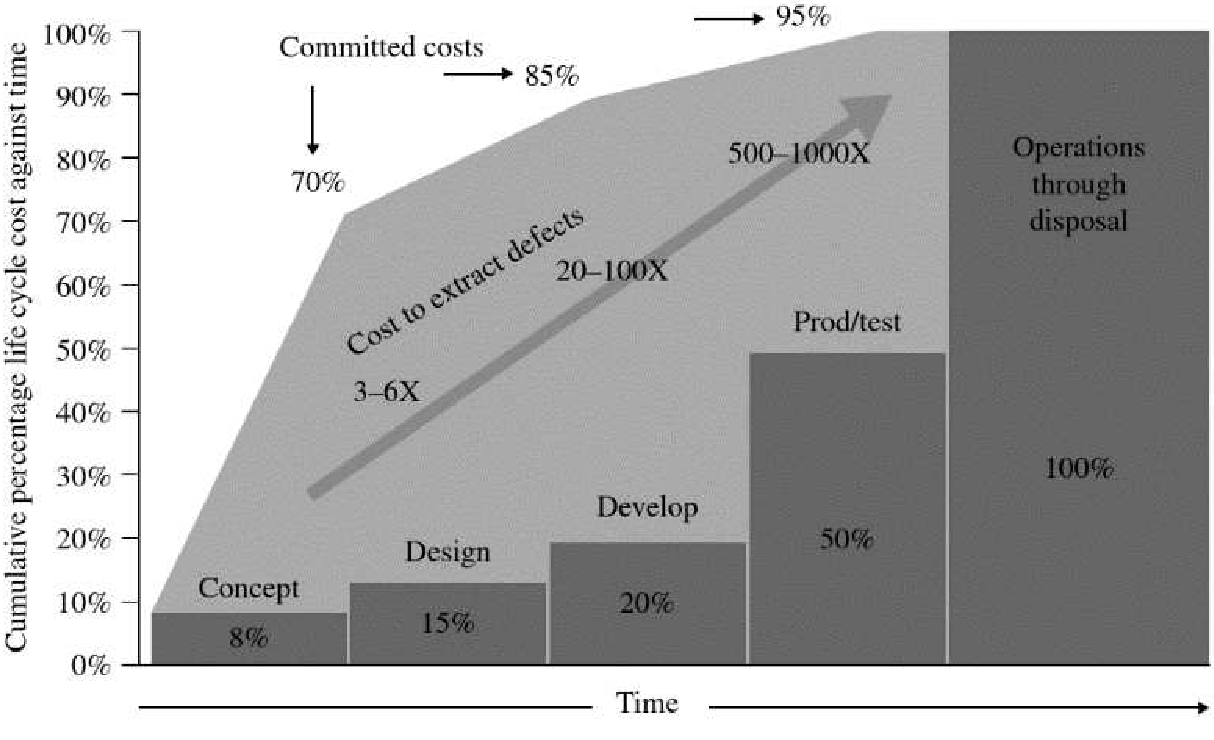


Figure 8.1. Committed Life Cycle Costs Against Time [7], Credited to DAU

8.4.1 *Causal Loop Diagrams*

The influence of both project and engineering system information on design changes, work performance, design maturity, and risk management are addressed in development of CLD's. In SD model development, CLD's consisting of influencing factors, flows and stocks are defined. Feedback loops can be either positive reinforcing (R) loops or negative balancing (B) loops.

The polarity of links between variables describe the effect of one variable on another. If the polarity is positive, then if the cause is positive or negative, the effect will be positive or negative respectively. On the other hand, if the polarity is negative, then if the cause is positive or negative, the effect will be the opposite.

In the current study, CLD's can help in identifying the relationships and action mechanisms for the integration of entities within the SD model.

8.4.2 *SD Model Development*

SD models have not been prevalent in the last few decades; however, SD models are of value in capturing the techno-socio-economic and cultural factors involved in project management and systems engineering. In the current study, SD modeling is viewed as complimentary to the DSS, forming an overall management flight simulator.

SD modeling can be useful to describe the behavior of complex projects from a 'big picture' systems thinking perspective. SD captures higher order system emergent behavior not captured in sub-systems and components. In the current study, it can help teams simulate the performance of project management and systems engineering where proactive steps can be taken to improve performance. The SD model can support team reasoning, learning and encourage systems thinking and scenario planning [121].

Management curve dynamics and influencing factors are captured within the SD model using Vensim® software. Influencing the behavior of the management curves may be achieved through process, policy levers and constants within the SD model. The SD model consists of stock levels, flows, and feedback loops that describe the system under investigation. The stock is the foundation of a system, it can be counted and measured at any given time.

Feedback loops can reinforce or balance the growth and decay behavior of stock levels. Complex behavior of systems occurs as relative strengths of feedback loops shift. Unsustainable patterns in systems dynamics can cause problems across the organization if left unchecked. In the current study, this could translate into unlimited growth in risks, rework, design changes, and costs. Of note, the balancing loop has its breakpoint where it can pull the stock level away from its goal more strongly than the reinforcing loop [110]. This requires careful planning in developing the appropriate levers and constants in development of the SD model.

In the development of a SD model, five interrelated principles of a learning organization are considered. These include systems thinking, personal mastery, mental models, shared vision, and organization learning [113]. Of interest are the principles of systems thinking, mental models and learning. Systems thinking involves reinforcing and balancing loops, mental models address the potential consequences of action, and learning entails the aspects of complex problems, knowledge, and the interaction of teams.

The steps in SD model development follow problem definition, identification of key variables, reference modes, observing qualitative and behavioral trends, and testing [98], these steps are followed in the current study.

In the current study, causal loops, flows and stocks have been defined from both a project management and systems engineering perspective. The behavior of a stock level (S) may be described by the integral of inflows minus the outflows, and an initial stock level (S_{to}).

$$S = \int_{t_0}^{t} (Inflows - Outflows)\, dt + S_{t_0} \tag{8.1}$$

Stock growth and decay may be described through S-curve behavior, as depicted in Figure 8.2. Initially, positive feedback generates exponential growth, this is counteracted by negative feedback that stabilizes growth.

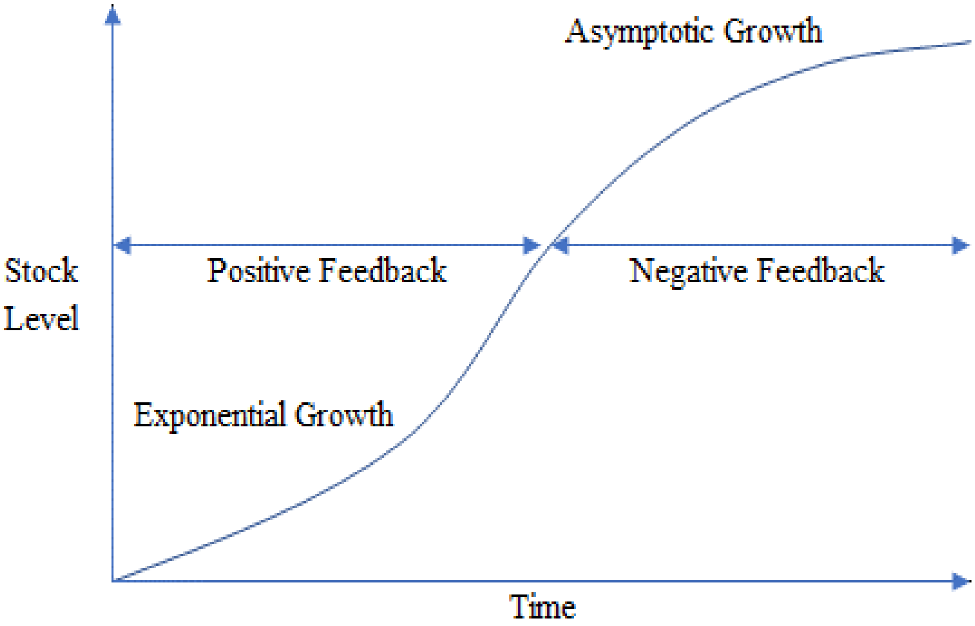


Figure 8.2. S-Curve Behavior. Adapted from [75]

As depicted in Figure 8.3, the reinforcing (R) loop regulates growth while two balancing (B) feedback loops regulate stock decay. One balancing loop connects stock to the outflow; the other provides a loss fraction that causes the shift of dominance in the S-curve. Equilibrium is achieved when the loss fraction (L_F) equals the gain fraction (G_F).

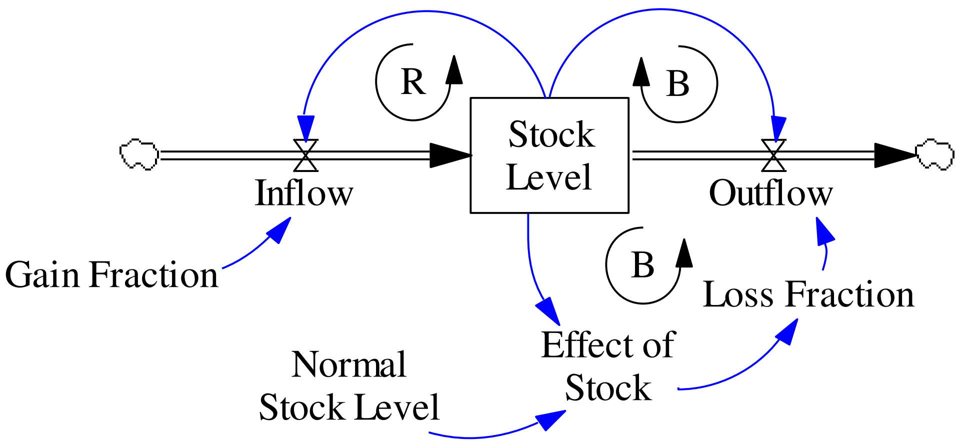


Figure 8.3. S-Curve Behavior. Adapted from [75]

The S-curve behavior may be described as follows:

$$S = \int_{t_0}^{t} (G_F - L_F)\, dt + S_{t_0} \tag{8.2}$$

The stocks that follow S-curve behavior in the current study include knowledge, culture, design changes, tasks, VFI maturity and design maturity. In describing development of these S-curves, the Knowledge curve serves as a good example.

In developing the knowledge management model, it was assumed that as knowledge grows, it will lead to the generation of more knowledge at some determined rate. At the same time, stabilizing effects can erode knowledge such as human resource attrition and the obsolescence of knowledge [75]. The exponential growth of knowledge is limited as these stabilizing processes provide a shift from exponential to asymptotic growth. The shift from positive to negative growth provides the S-shaped sigmoidal curve.

The knowledge level increases only if the gain fraction is greater than the loss fraction. The strength of the negative knowledge erosion loop becomes stronger with the knowledge stock level. In the current study, the effect of knowledge capacity is governed by a normal knowledge level goal of 100 percent.

The development of the uniquely coupled risk-strategy SD model in the current study is based on the typical Lotka-Volterra predator-prey relationship [122]. In the current study, the underlying assumptions for predator-prey relationships remain, they include a rate of change in population that is proportional to its size and the fact that predators will never stop hunting prey.

As depicted in Figure 8.4, predators are viewed as strategies; prey are viewed as design risks.

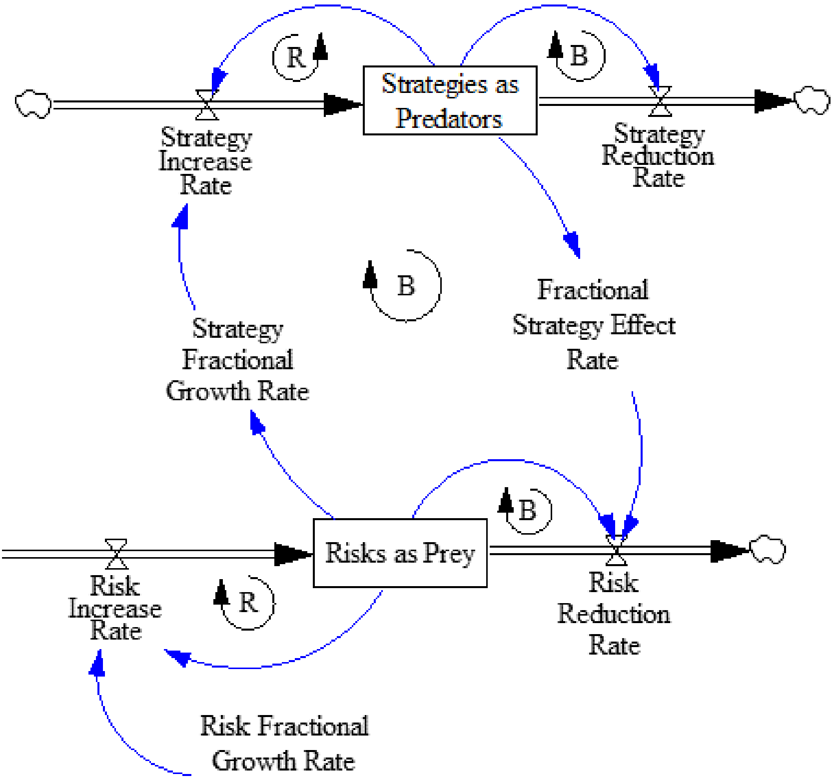


Figure 8.4. Strategy-Risk Management Curve Behavior. Adapted from [122]

The Lotka-Volterra differential equations take the form:

$$\frac{ds}{dt} = \alpha s - \beta sr \tag{8.3}$$

$$\frac{dr}{dt} = \delta sr - \gamma r \tag{8.4}$$

where *ds/dt* and *dr/dt* are rates for strategies (*s*) and risks (*r*) respectively, t is time, and *α, β, δ, γ* are positive real constants.

Since the underlying equations are differential, the solutions are deterministic, and the time is continuous with overlapping generations of predators and prey [122]. In the current study, the overlapping behavior of strategies with risks is present.

SD factors include the SD variables of gain, decay, loss fraction and ratios between variables. These factors are associated with project management and systems engineering factors and levers of influence, as discussed in previous chapters.

8.4.3 *Reference Modes*

Reference modes provide data on system, organizational and project performance over time and can be based on both literature results and real-world problems. These reference modes provide a baseline from which to analyze patterns in behavior within the SD model. In the current study, reference modes from literature includes the relative position and contribution to the four management curves. Real data from shipyards include VFI maturity and number of design changes for a similar IPS design. These reference modes are incorporated within the SD model over a ship design cycle of 65 months and a time horizon of 100 months, as described in Table 8.1.

Table 8.1. Ship Design Cycle Milestones

Design Stage	Milestone (Months)
Pre-Concept Design	8
Concept Design	18
Preliminary Design Review (PDR)	26
Critical Design Review (CDR)	36
Build	55
In-Service	65

The reference modes and goals for their position across the design cycle are listed in Table 8.2. The position of predicted management curves within the simulator can be compared to these goals and improved upon through policy and process improvement levers.

Table 8.2. Management Curve Reference Modes and Goals

Management Curve	Reference Mode	Goal
Knowledge	The simulator incorporates the phased reference mode from literature as a starting point [11].	To advance the knowledge curve enough to reduce the Knowledge Gap.
Ease-of-Change	The simulator incorporates the phased reference mode from literature as a starting point [11].	To move the Ease-of-Change curve up so that it does not hit zero at In-Service.
Costs-Incurred	There is no real reference mode for this other than perhaps a previous similar system design. This cost information was difficult to obtain during the current study and considered confidential.	To improve upon the previous month's prediction.
Commitments	The simulator incorporates the phased reference mode from literature as a starting point [11]. Commitments may be measures by number of purchase order but other inputs include relational contracting and service level agreements.	To maintain no more than 85 percent prior to detailed design [4] [7]. For future consideration, to achieve commitments in accordance with the purchase order schedule.
Proposed Design Changes	The reference mode used within the simulator is based on a similar IPS design as described in Chapter 5.	To reduce as much as possible after preliminary design.
Implemented Design Changes	The reference mode used within the simulator is based on a similar IPS design as described in Chapter 5.	To reduce as much as possible after preliminary design.
VFI Maturity	The reference mode used within the simulator is based on a similar IPS design as described in Chapter 5.	To achieve VFI Maturity in accordance with the VFI acquisition schedule.
Design Maturity	There is no real reference mode for design maturity. The current study proposes a way to measure this. It is also related to VFI maturity.	To attain at least 85 percent prior to production [10].

8.5 Results

8.5.1 *Causal Loop Diagrams*

The outputs from the DSS model are used as inputs into the SD model. These outputs include C_{py}, C_{pky}, fraction of components difficult to change, risk intensity, SRL, and the SNA measures of organization density, CPL, and team Power standard deviation.

Integration points between the DSS and SD models, by way of a high-level CLD, is depicted in Figure 8.5. The top four entities of knowledge, ease-of-change, commitments and incurred costs are the primary management curves discussed in the current study.

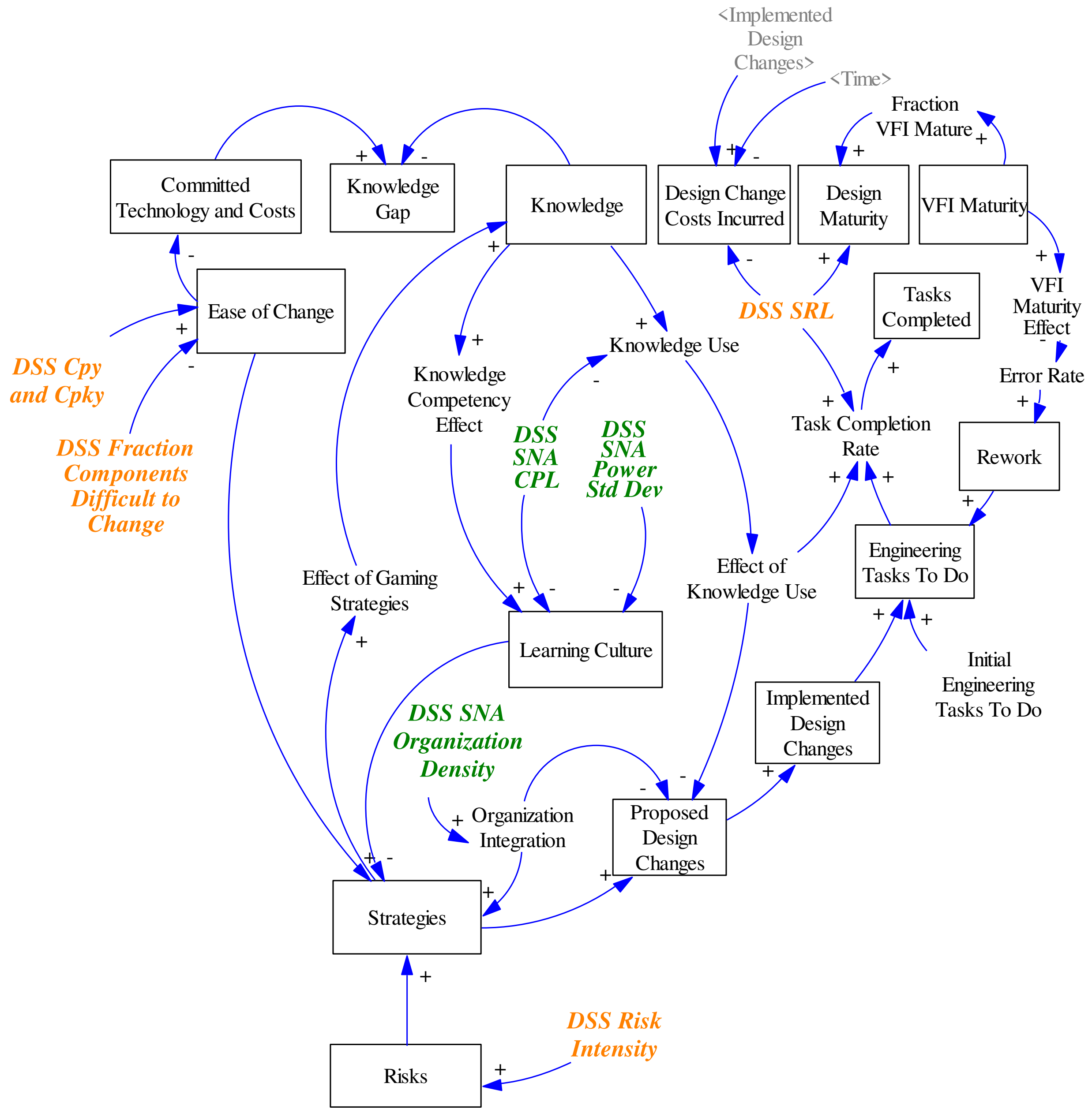


Figure 8.5. Management Flight Simulator High-Level CLD

Other related management curves are included in the current study as part of developing a comprehensive and holistic SD model.

8.5.1.1 *Knowledge CLD*

The knowledge management integration points within the SD model include the knowledge management inputs of strategies, paying for VFI and relational contracting, SNA CPL, human attrition, and on-the-job training. The knowledge management outputs include the entities of learning culture, task execution, and the rationalization of design changes.

The CLD for the knowledge management model in the current study is depicted in Figure 8.6. It consists of one reinforcing (R4) feedback loop and four balancing (B9, B10, B11 and B12) feedback loops. The reinforcing (R4) feedback generates knowledge and is affected by strategies and gaming as well as on-the-job training. The two balancing (B9 and B10) feedback loops act to reduce knowledge and cause typical S-shaped behavior. Similarly, the two balancing (B11 and B12) feedback loops act to transfer knowledge and cause typical S-shaped behavior.

Policy and process levers for knowledge gain include on-the-job-training (OJT) and improvement to the knowledge management process. Knowledge Use is positively affected by maturity of the communication management process and by the SNA CPL. In the current study, the knowledge gap is represented as the difference between the knowledge level and contribution of committed costs and technology.

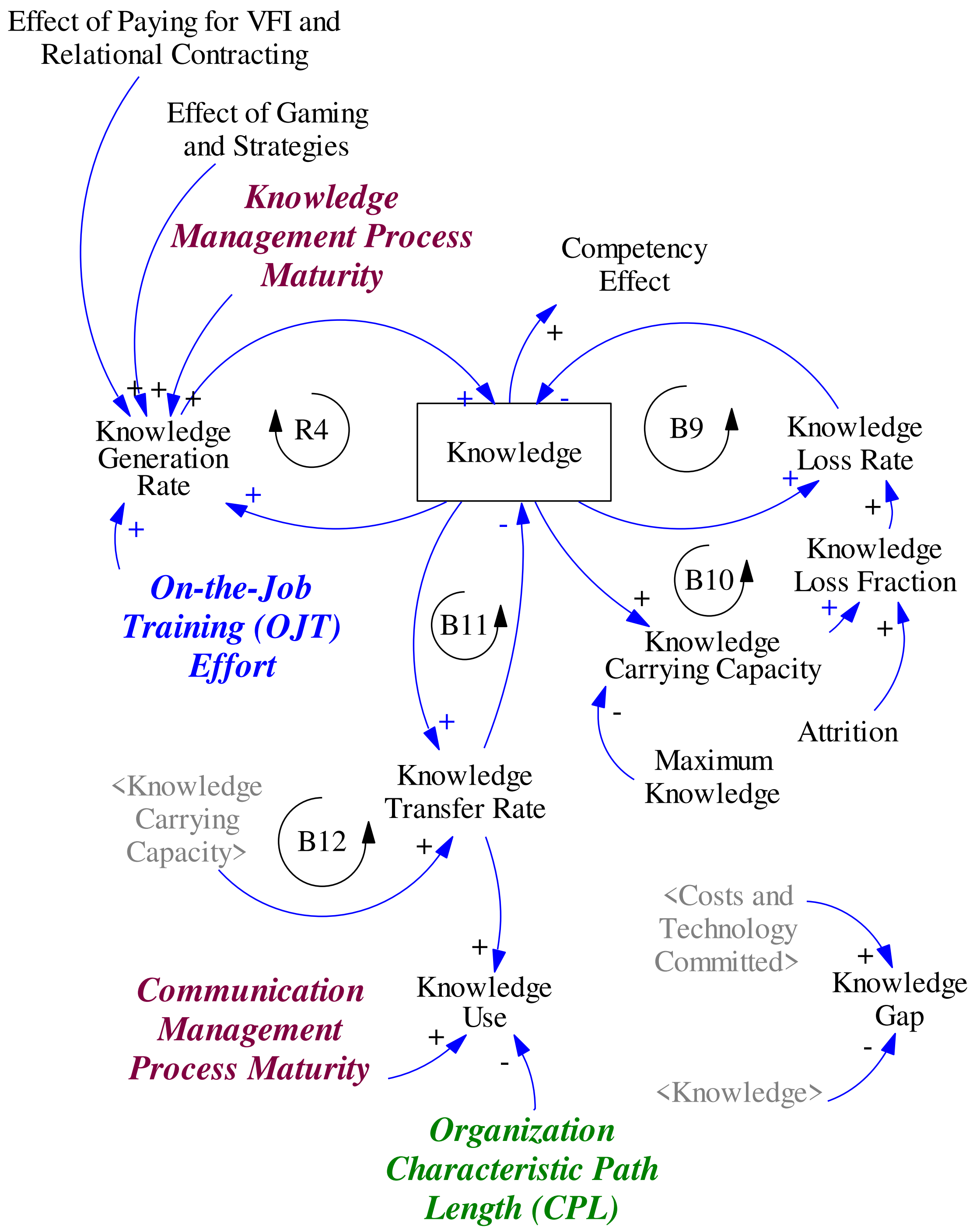


Figure 8.6. Knowledge CLD

8.5.1.2 *Ease-of-Change CLD*

The ease-of-change CLD depicted in Figure 8.7 includes a balancing (B13) feedback loop that reduces the level of ease-of-change. Influencing factors include system attribute variance, the fraction of components difficult to change, and the application of engineering principles. An increase in the attribute variance measures of C_{py} and C_{pky} lead to an increase in design flexibility and a decrease in rate of reduction for ease-of-change. Similarly, an increase in the application of engineering principles acts to decrease the reduction rate. An increase in the fraction of components difficult to change acts to increase the ease-of-change reduction rate.

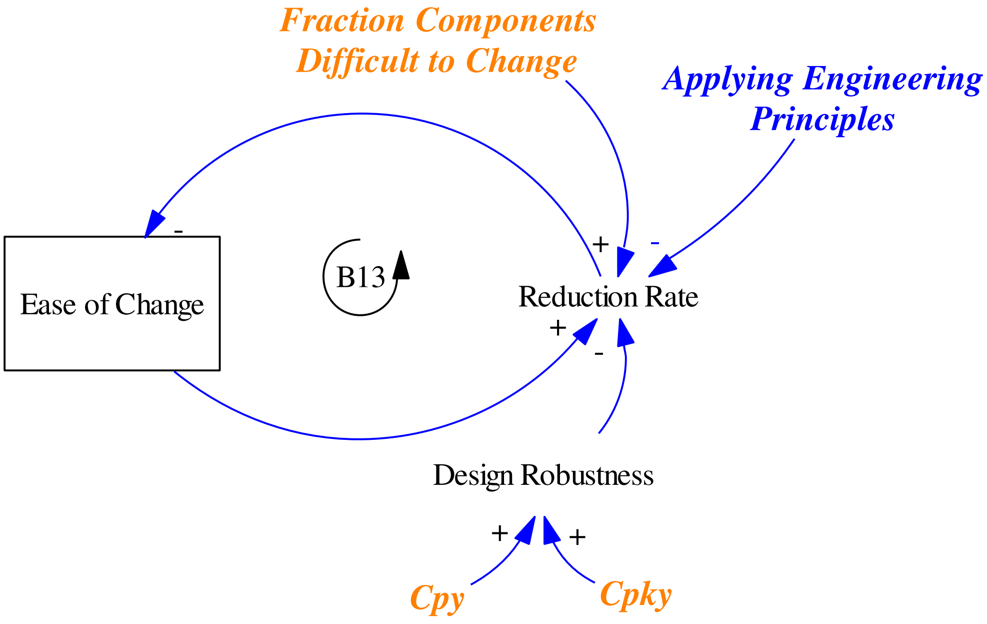


Figure 8.7. Ease-of-Change CLD

8.5.1.3 *Commitments CLD*

While most commitments are made prior to detailed design, there is little knowledge of the design and the impact from potential changes. The effect of increasing the commitment fraction is to positively influence the rate of costs and technology committed within the reinforcing (R7) feedback loop, as depicted in Figure 8.8.

This commitment fraction may be increased through several influencing factors including the state of knowledge level. On the other hand, commitments may be driven by schedule constraints, milestone payments and sub-contract awards. This can often be the case for warship defense projects. There can competition between advancing the Commitments curve and postponing it.

There can be unknowns and just-in-time technology insertion years into the design cycle where reserving commitments may make sense. In the current study, the focus is on postponing the Commitments curve enough to allow for some unknowns and just-in-time technology insertion, the mechanism for doing this is through the ease-of-change lever.

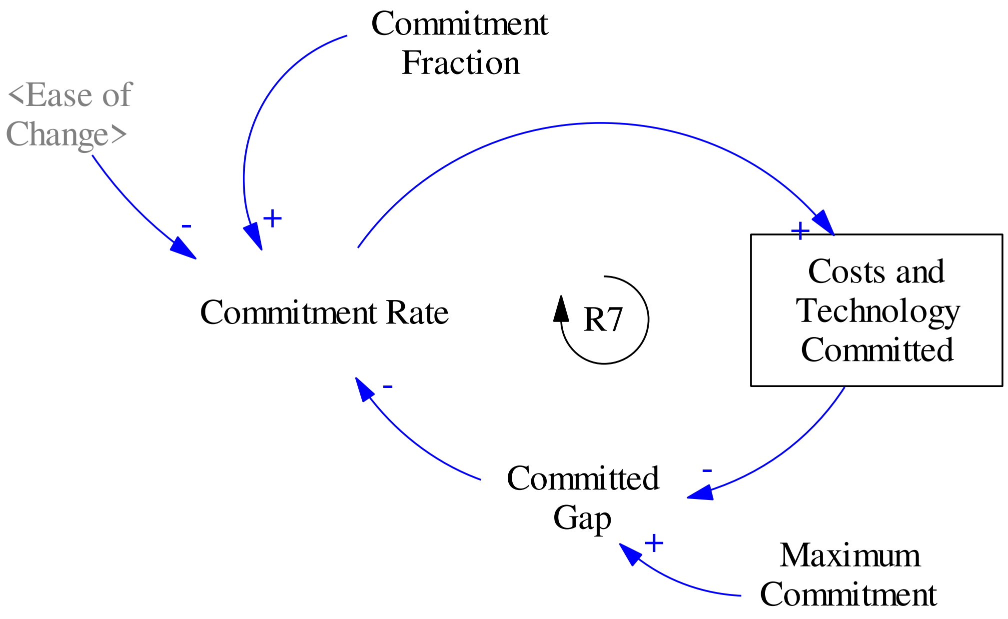


Figure 8.8. Costs and Technology Commitments CLD

8.5.1.4 *Incurred Design Change Costs CLD*

As design changes are delayed to later in the design, increased costs can be expected. The average cost per change is adjusted to reflect the effect of time in the design cycle. In addition to this adjustment, a CCF is applied to account for the influence of SRL.

The design change costs and influencing factors are depicted in Figure 8.9. Adjusting design change costs in this way is viewed as a positive step toward improving cost estimates.

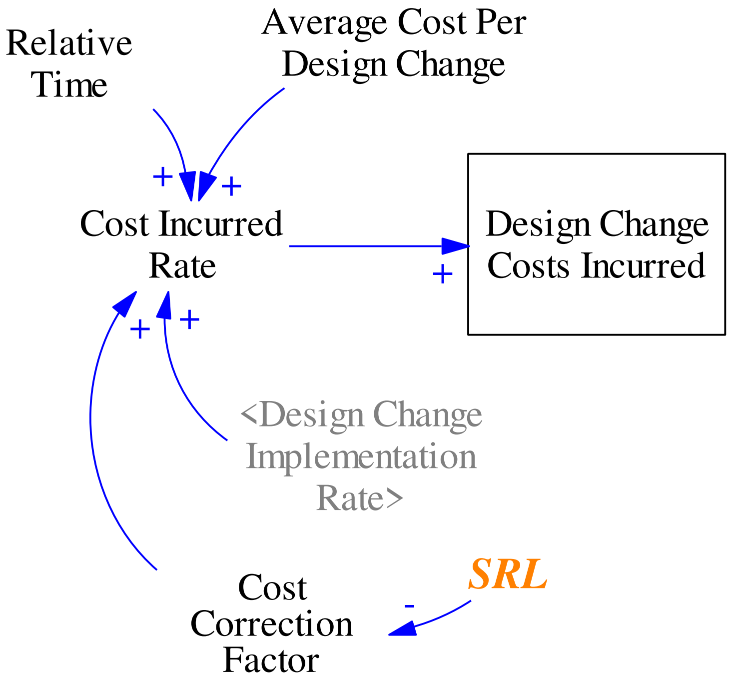


Figure 8.9. Design Change Costs Incurred CLD

8.5.1.5 *Design Changes CLD*

The design change CLD depicted in Figure 8.10 consists of a reinforcing (R3) feedback loop and two balancing (B7 and B8) feedback loops. The reinforcing loop acts to increase proposed design changes as influenced by the time to convert strategies to proposed changes and by an adjustment based on the ratio of strategies to changes. This ratio acts to balance the rate of proposed changes through the balancing (B7) feedback loop. The number of proposed changes is restricted through the balancing (B8) feedback loop where the factors of learning effort, knowledge use and organization integration work to rationalize and reduce the number of proposed changes. The number of proposed design changes is subjected to an approval rate and implementation rate.

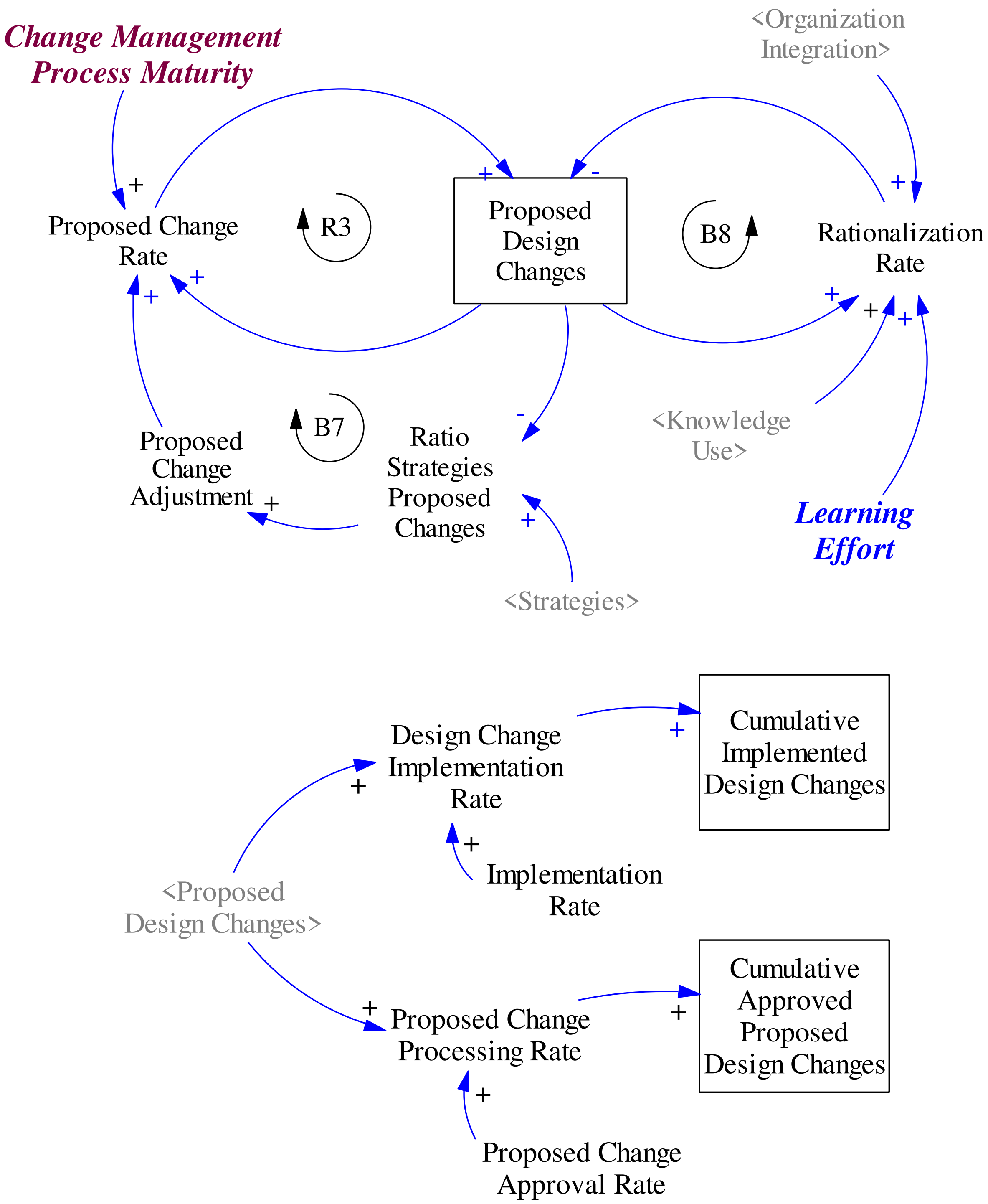


Figure 8.10. Design Changes CLD

8.5.1.6 *Risks-Strategies CLD*

In the current study, the register of active risks is considered the initial input and driver for the overall management flight simulator. These risks are mapped to primary system components where there is a potential design change. In advancing knowledge in the design cycle, a proactive approach may be taken in formulating strategies to deal with the risks. The gaming of strategies and potential solutions is viewed as generating tacit knowledge. The variety in these solutions provides for increased options and flexibility in design.

The reference flow of risks over time may represented by generic curves found in literature [123]. As late decisions on design changes can significantly increase costs, greater effort early in the design is recommended. Increased front end design can change risk patterns and reduce latent design and program risks [123] [124].

In the current study, risks can be reduced through increased front end design and by acting on risks early in design, this desired behavior is depicted in Figure 8.11.

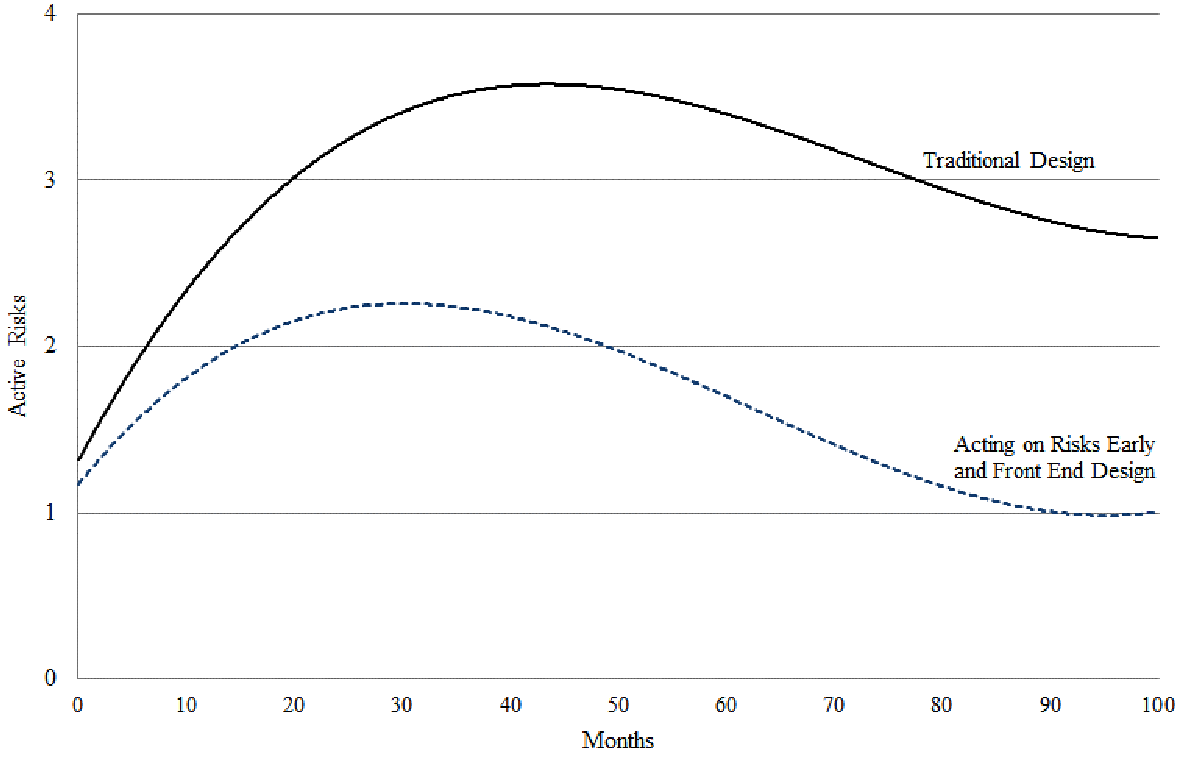


Figure 8.11. Reducing Risks Through Front End Design and Acting on Risks Early [123]

The coupled risks-strategies CLD depicted in Figure 8.12 is based on the Lotka–Volterra equations. The intensity of active risks is based on average probabilities and impacts from the DSS SRM. This positively influences the rate of risk generation as described through the reinforcing (R1) feedback loop. Balancing (B1 and B2) feedback loops act to reduce the number of risks through design change strategies. As strategies increase, risks are reduced to a point where fewer strategies are required. This is achieved through the balancing (B3 and B4) feedback loops. The factors of organization integration and ease-of-change in design positively influence the generation of strategies through the reinforcing (R2) feedback loop.

The organization integration factor is affected by the gaming intensity, level of team colocation, organization density, and maturity of the integration management process. The number of strategies is reduced by non-converging strategies where system attribute thresholds are not respected. Both balancing (B5 and B6) feedback loops act to reduce the number of strategies. The ratio of risks to strategies acts as a mechanism to maintain the balance between strategies and risks, like the predator-prey balance in nature. An increase in the state of the strategic management process and learning culture acts to decrease the strategy reduction rate. An increase in maturity of the integration management process leads to an increase in strategies, and an increase in maturity of the risk management process leads to an increase in the mitigation of risks.

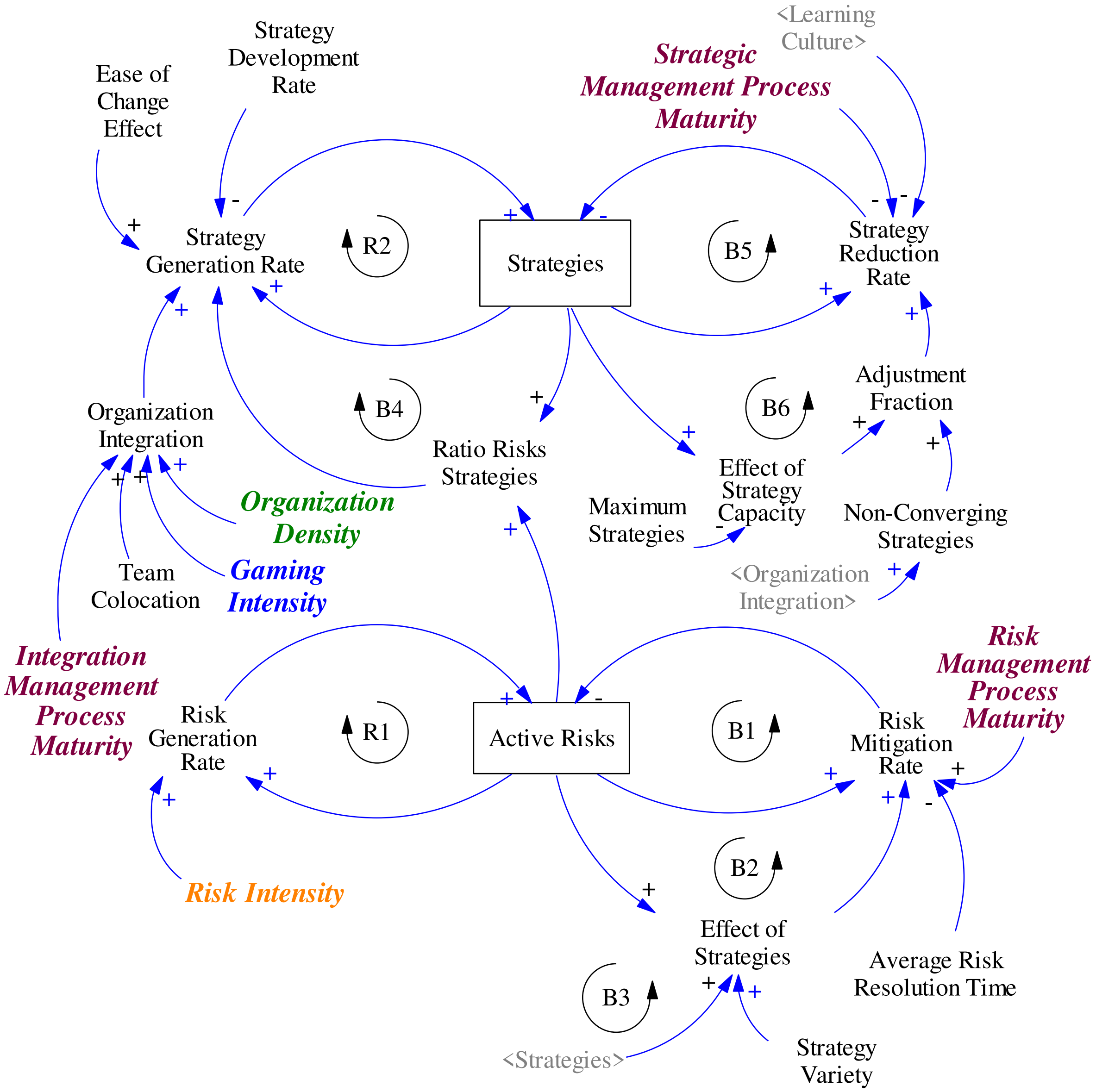


Figure 8.12. Risks-Strategies CLD

8.5.1.7 *VFI Maturity*

Vendor furnished information (VFI) contributes to explicit knowledge and design maturity. The VFI required is typically known early in the design but acquiring VFI from vendors or from past similar projects is one of the major challenges in ship design. The SD model policy levers considered in the current study to advance VFI are relational contracting with the vendor, paying for VFI, and improvement to the supply and VFI management process.

As depicted in Figure 8.13, the reinforcing loop (R5) represents the positive influence of learning from vendors on the VFI acquisition rate, leading to increased VFI maturity. The two balancing loops (B14 and B15) act to reduce the number of total VFI required.

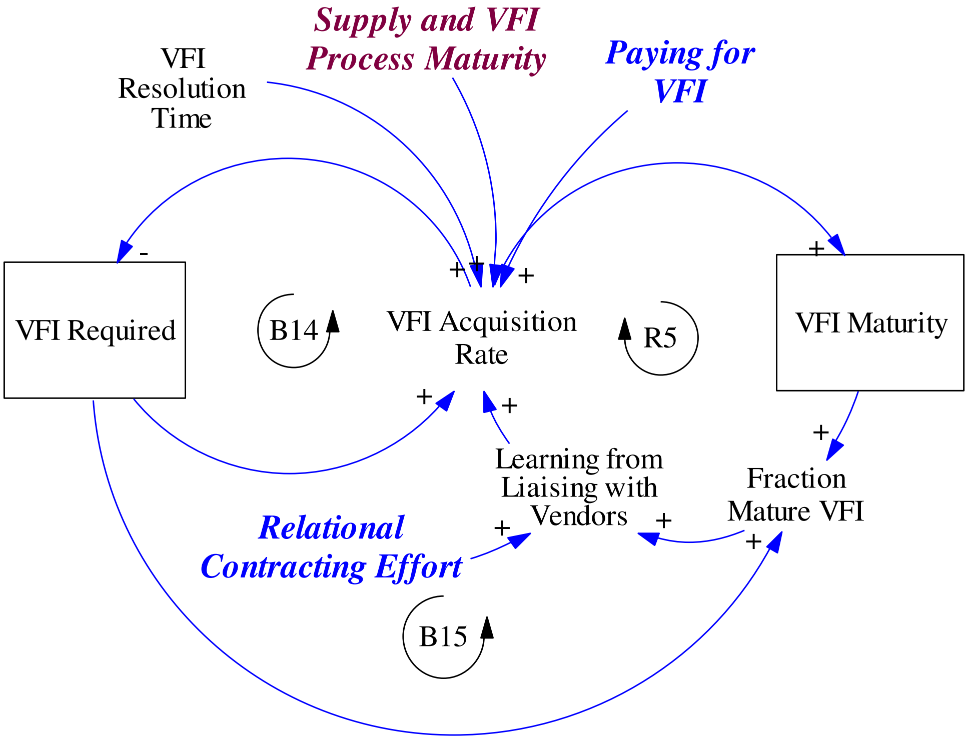


Figure 8.13. VFI Maturity CLD

8.5.1.8 *Design Maturity*

In the current study, assessing design maturity includes several project management and systems engineering measures. One of the goals in exercising the SD model is to achieve a design maturity of 85 percent prior to the build stage.

The design maturity CLD in Figure 8.14 consists of a reinforcing (R6) feedback loop and two balancing (B16 and B17) feedback loops. The design maturity rate is influenced by VFI maturity, schedule performance index (SPI), SRL, and level of the proven design used in the project. These factors represent an integrated set of project management and systems engineering measures that define design maturity.

The effect of rework is incorporated within the balancing (B17) feedback loop and acts to reduce the level of design maturity.

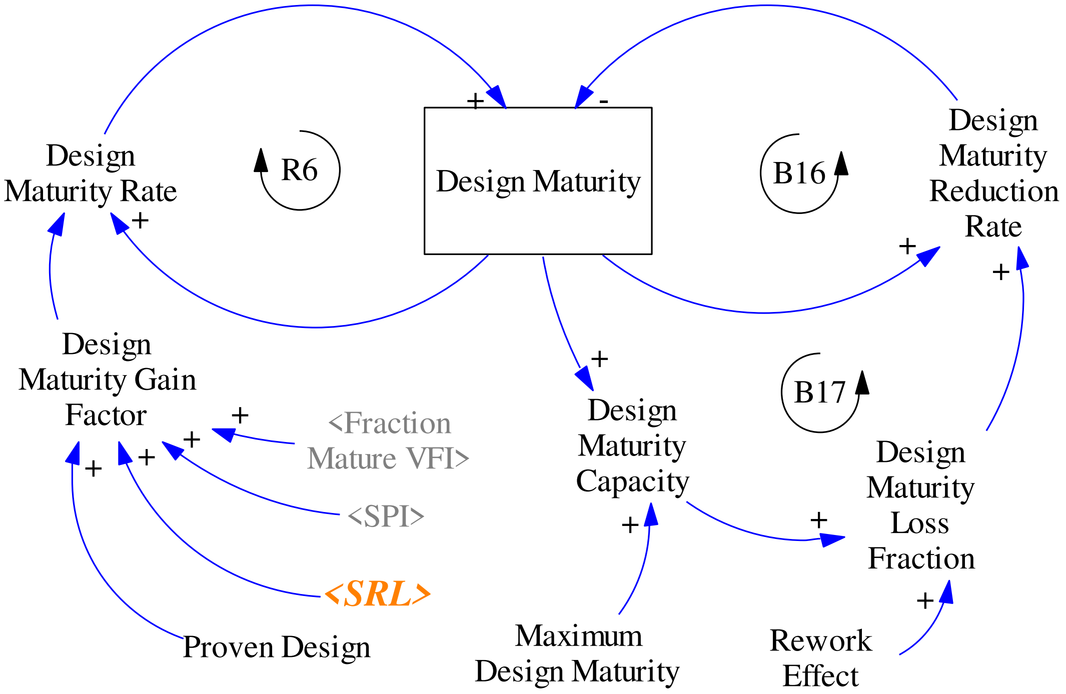


Figure 8.14. Design Maturity CLD

8.5.1.9 *Engineering Tasks and Work Performance*

External conditions such as risks, procurement challenges, and resource availability can negatively affect budget and schedule, leading to rework [125]. Schedule delays can create pressure to work harder but this can also lead to errors and rework. The relationship between work performance and rework is depicted in Figure 8.15. In the current study, the number of initial tasks, rework and design changes form the number of tasks to do. These tasks are executed in accordance with the balancing (B18) feedback loop. The error rate causes rework through the reinforcing (R8) feedback loop. As the work to do and error discovery rate increases, a reinforcing loop (R10) is enabled. The increased planned work and pressure to work harder act to increase the error rate and work to do through the reinforcing (R9) feedback loop. As the work done is increased, the balancing (B19) feedback loop acts to reduce pressure to work harder and the error rate, leading to less work to do. Similarly, as planned work is achieved, balancing (B20) feedback loop acts to reduce the planned work.

The policy lever of Learning Effort in the SD model acts to increase the task completion rate. The SRL factor is an output from the DSS model, the higher the SRL; the higher the task completion rate.

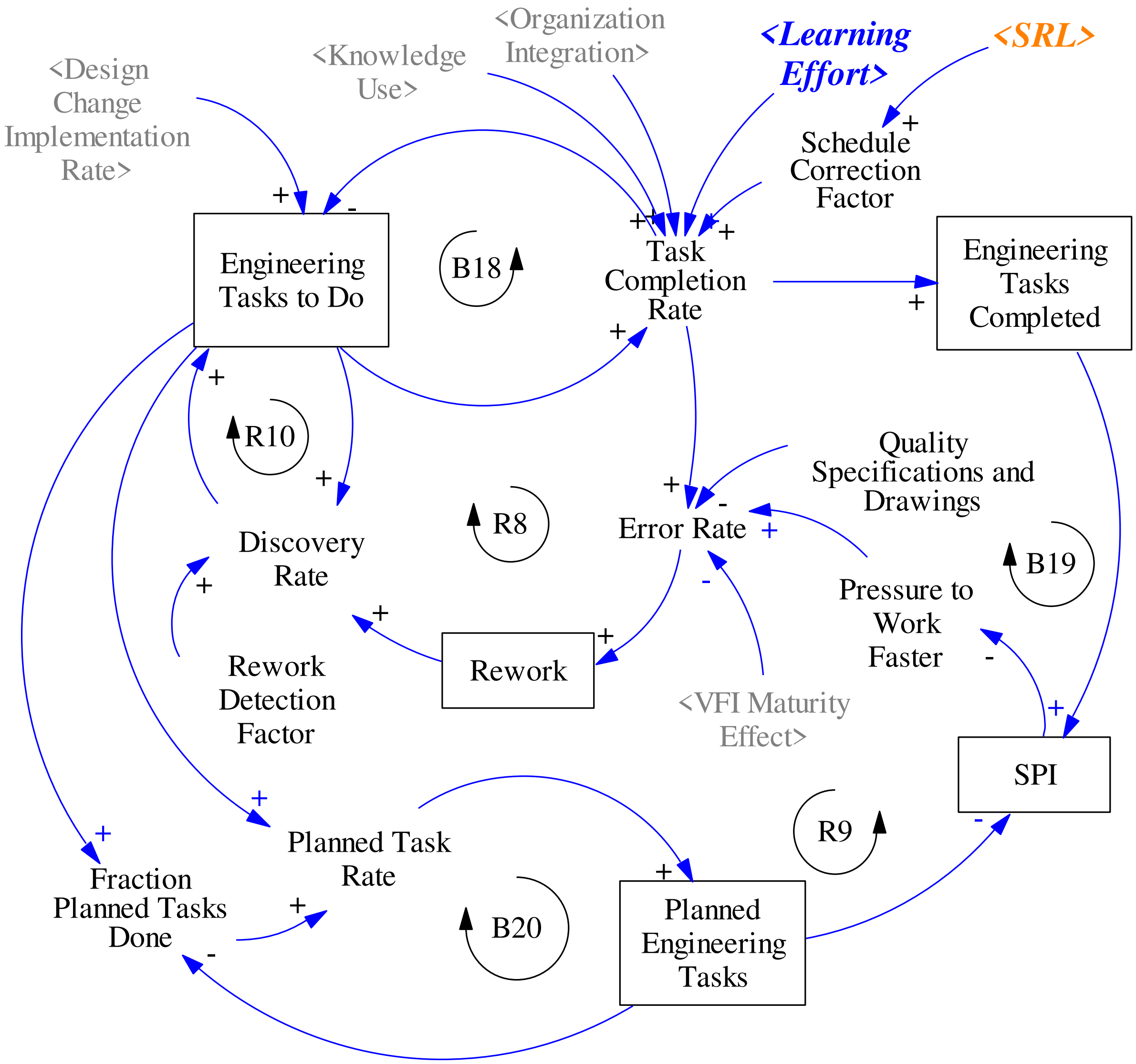


Figure 8.15. Work Performance and Rework CLD

8.5.1.10 *Learning Culture CLD*

In the current study, culture in measured through several factors, as depicted in Figure 8.16. In moving toward a learning culture, the factors of knowledge level or competency, communication, and the ability for team members to question and have an equal voice are captured as they affect the reinforcing (R11) feedback loop. The SNA characteristic path length (CPL) represents the cultural factor of communication where the shorter the CPL; the better the communication. Both measures of Power standard deviation and CPL are outputs from the SNA where specific values are associated with different types of design changes, namely a system parameter change or a component type change.

The Knowledge Program (P) and ability to Question (Q) contribute to what has been termed Revan's action learning, as described in the previous chapter.

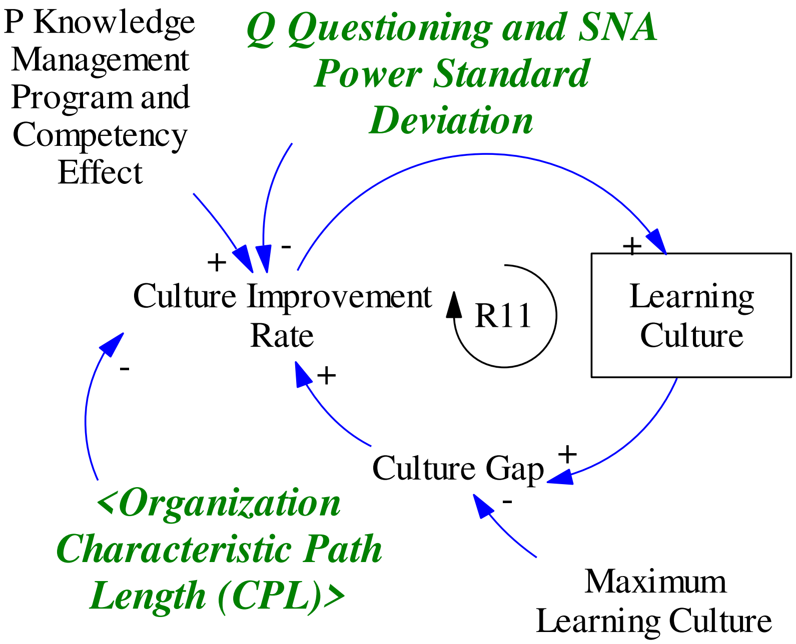


Figure 8.16. Learning Culture CLD

8.5.2 *SD Models*

The SD model includes the four primary management curves and others that are aligned with the common PM-SE integration themes and the techno-socio-economic and cultural factors affecting them. These SD sub-models follow the interrelationships described in their respective CLD's. The SD models are required for input into Vensim® software

8.5.2.1 *Knowledge SD Sub-Model*

The Knowledge SD sub-model in Figure 8.17 reflects its CLD where it includes knowledge generation, loss and transfer. The effect of Knowledge transferred is translated into Knowledge Use and used in other SD sub-models.

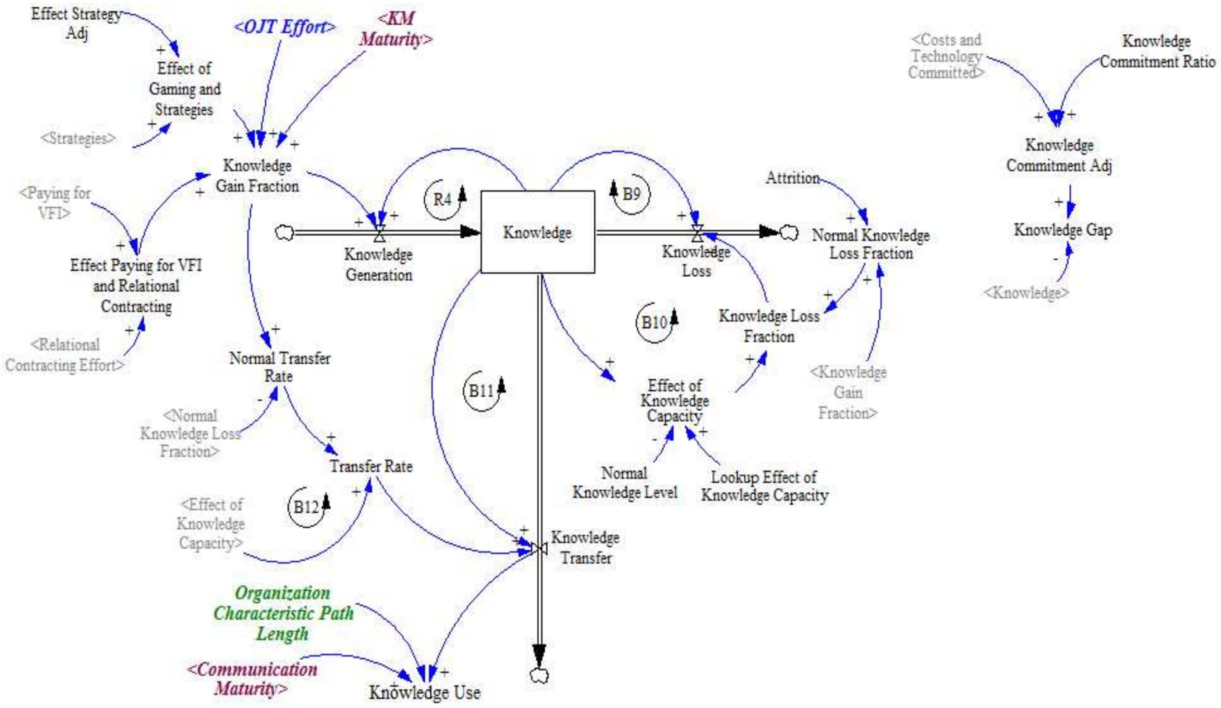


Figure 8.17. Knowledge SD Sub-Model

8.5.2.2 *Ease-of-Change SD Sub-Model*

As depicted in Figure 8.18, the SD sub-model Ease-of-Change receives inputs from the DSS model in terms of variance across performance and survivability attributes and fraction of components difficult to change.

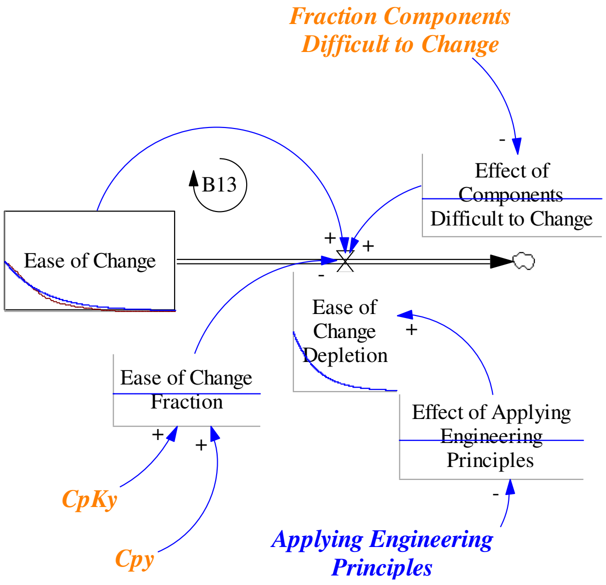


Figure 8.18. Ease-of-Change SD Sub-Model

8.5.2.3 *Commitments SD Sub-Model*

The committed costs and technology view provide a reference for calculating the knowledge gap, the SD sub-model is depicted in Figure 8.19.

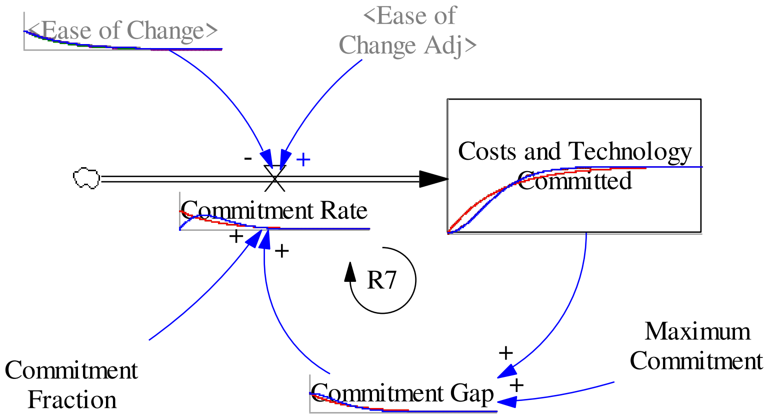


Figure 8.19. Commitments SD Sub-Model

8.5.2.4 *Costs Incurred SD Sub-Model*

The effect from advancing knowledge and design changes in the design cycle can be translated into design change costs incurred, the SD sub-model is depicted in Figure 8.20.

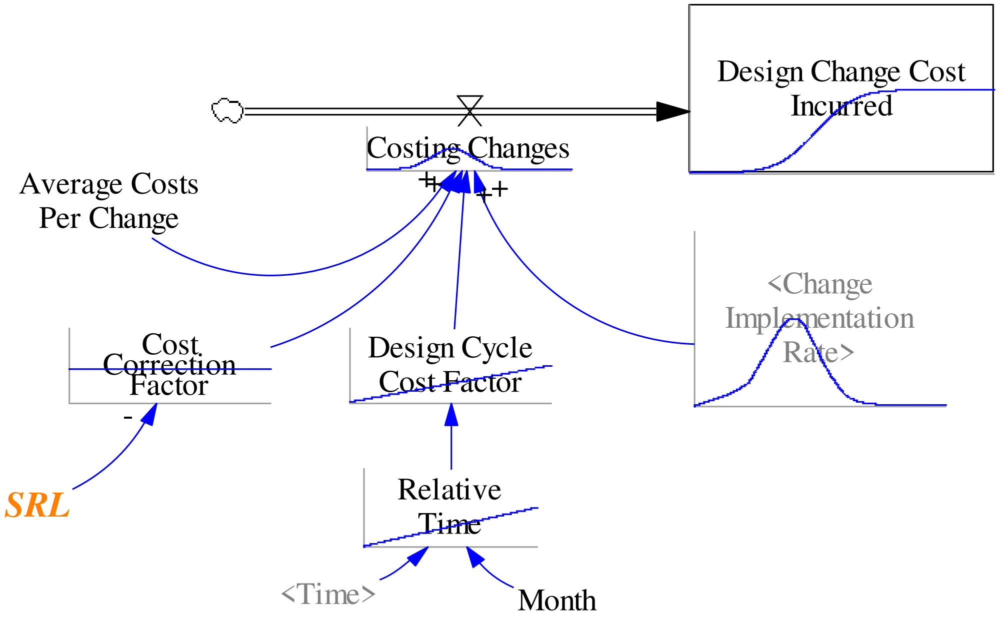


Figure 8.20. Design Change Costs Incurred SD Sub-Model

8.5.2.5 *Risks-Strategies and Design Changes SD Sub-Model*

In SD model development, there were logical flows recognized between risks, strategies to mitigate risks, strategies that affect knowledge gain, and proposed and implemented design changes.

As depicted in Figure 8.21, the uniquely coupled risk-strategy, Lotka-Volterra, relationship balances the economy of risks and strategies for resolving design change problems. At the same time the strategizing of solutions has a positive effect on knowledge gain.

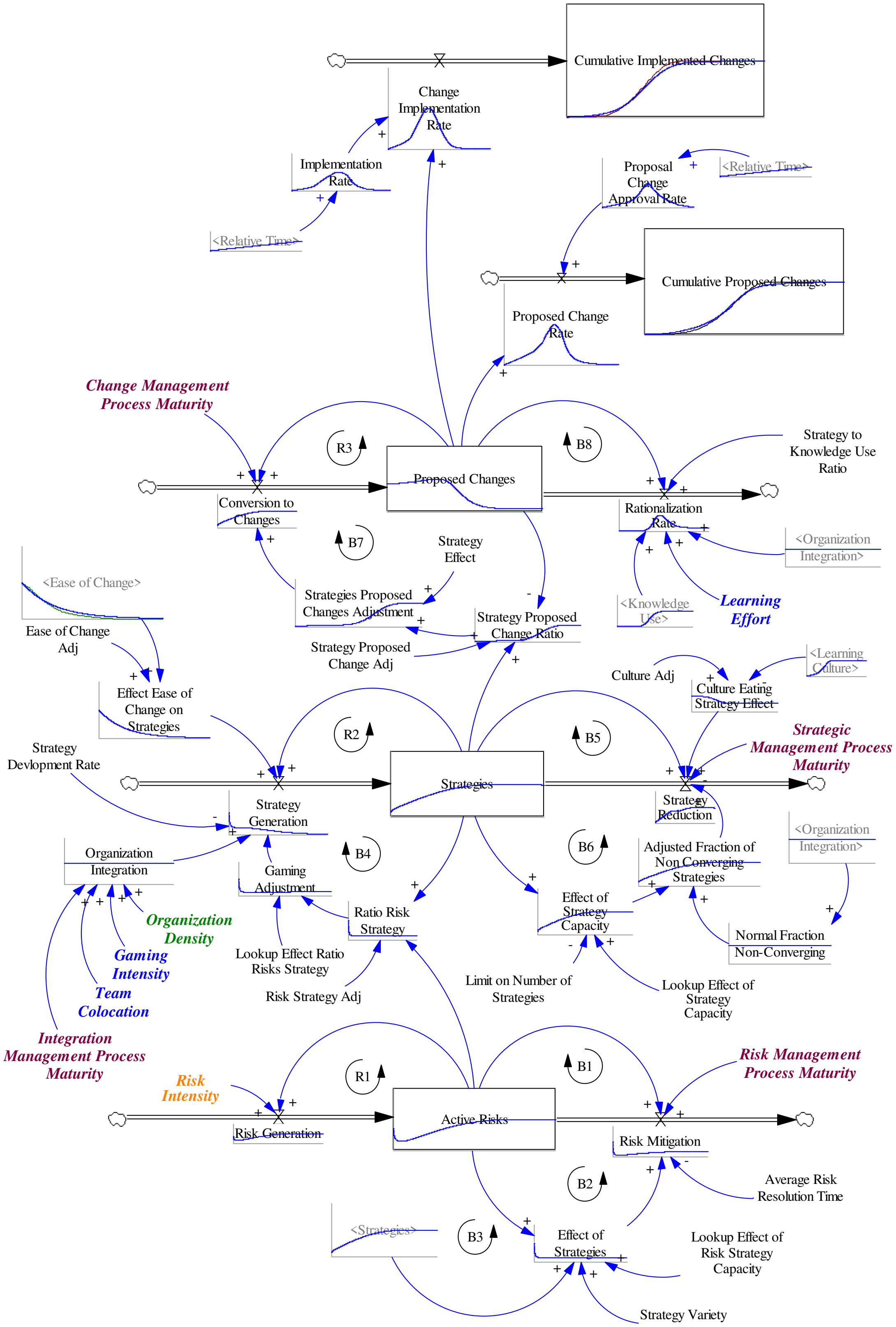


Figure 8.21. Risks-Strategies and Design Changes SD Sub-Model

8.5.2.6 *VFI Maturity and Design Maturity SD Sub-Models*

The Design and VFI Maturity SD sub-model is depicted in Figure 8.22 and includes the DSS input of SRL as well as internal SD model linkages such as the effect of rework on reducing Design Maturity.

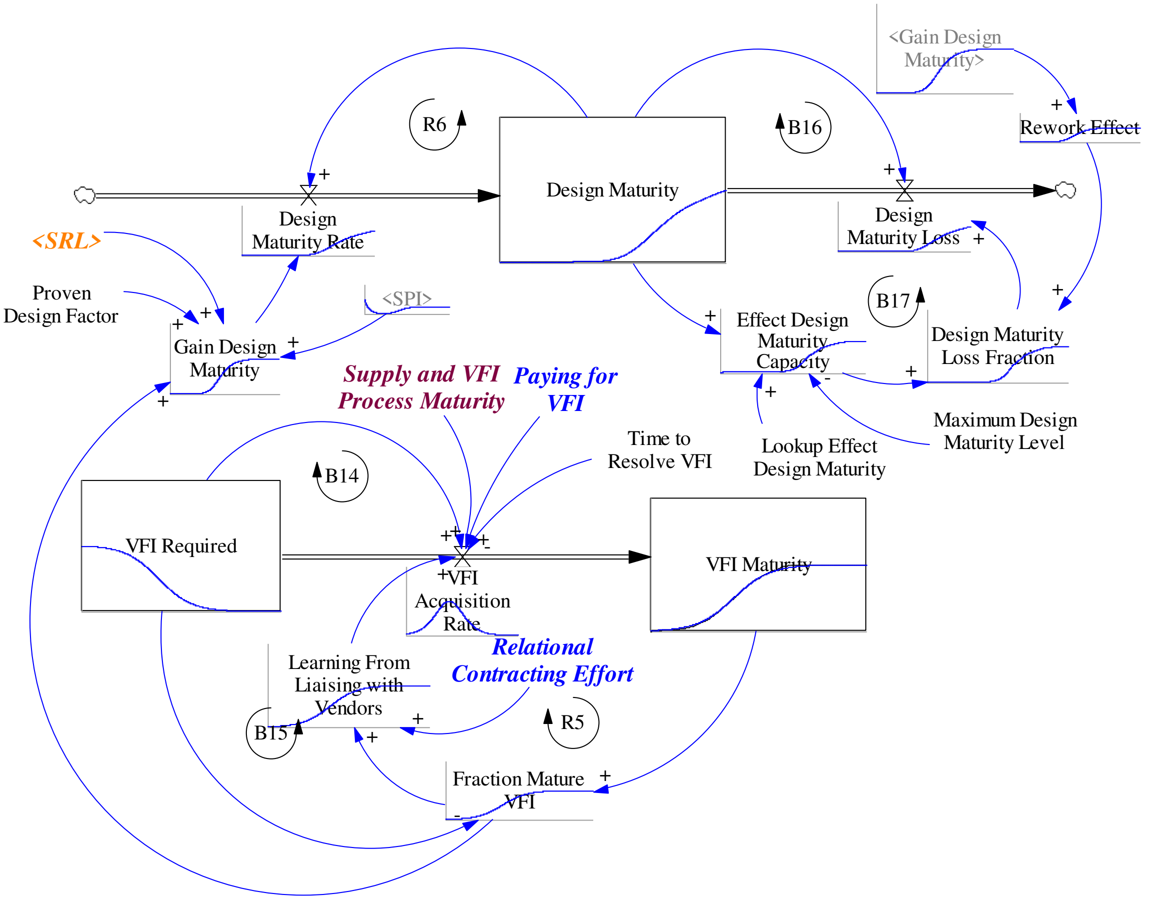


Figure 8.22. VFI Maturity and Design Maturity SD Sub-Model

8.5.2.7 *Engineering Task and Work Performance SD Sub-Model*

As depicted in Figure 8.23, this view provides project management measures and behavior that can enhance the traditional project management EVM approach. As traditional project management earned value management techniques are deficient in capturing the ‘big picture' of system, organizational and project performance, the current management flight simulator offers a different perspective and tool that may be used in parallel.

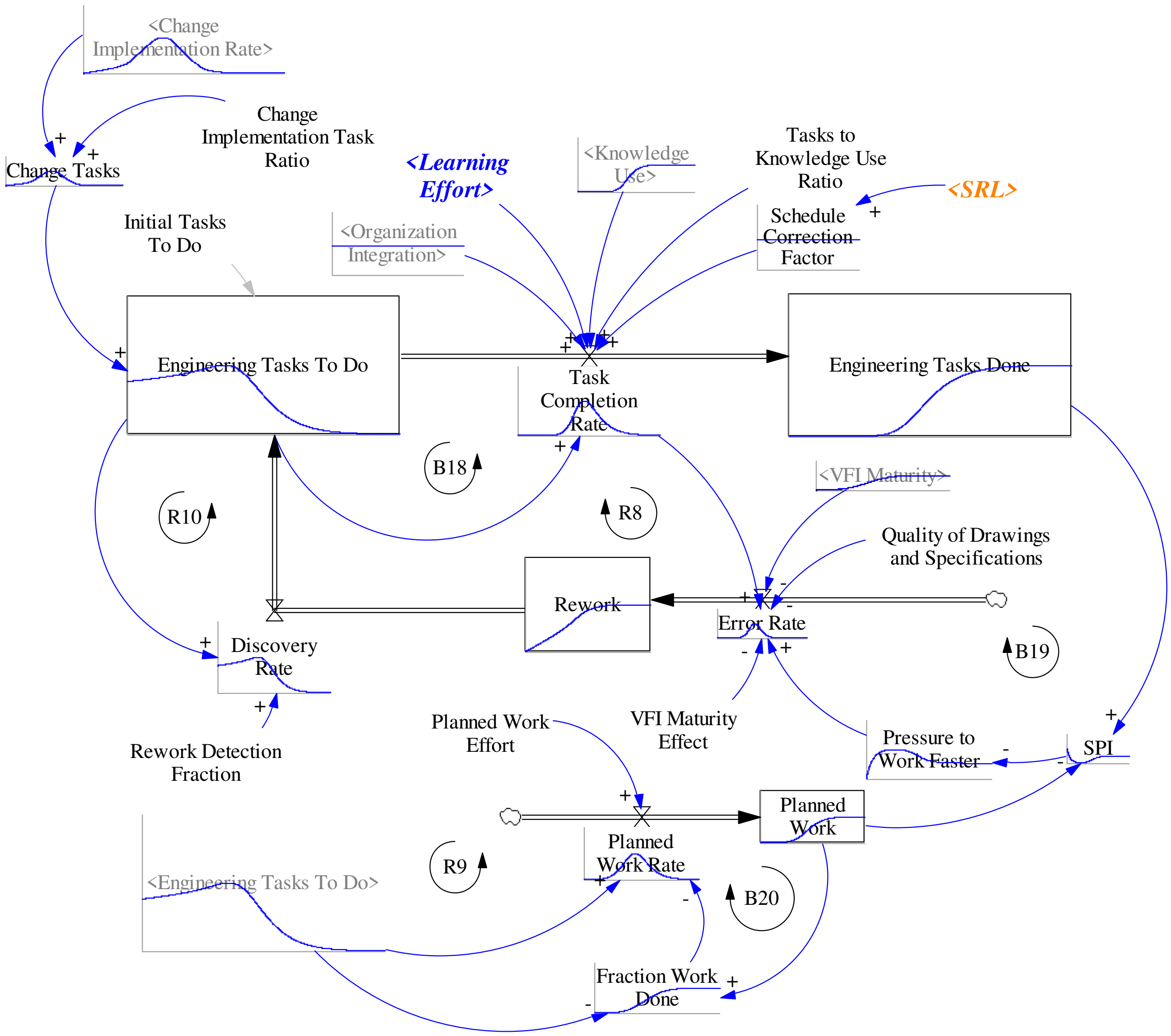


Figure 8.23. Engineering Tasks and Work Performance SD Sub-Model

8.5.2.8 *Learning Culture SD Sub-Model*

The SD sub-model for level of Learning Culture is depicted in Figure 8.24, with the inputs of action learning (knowledge program 'P' and ability to question 'Q'), and CPL.

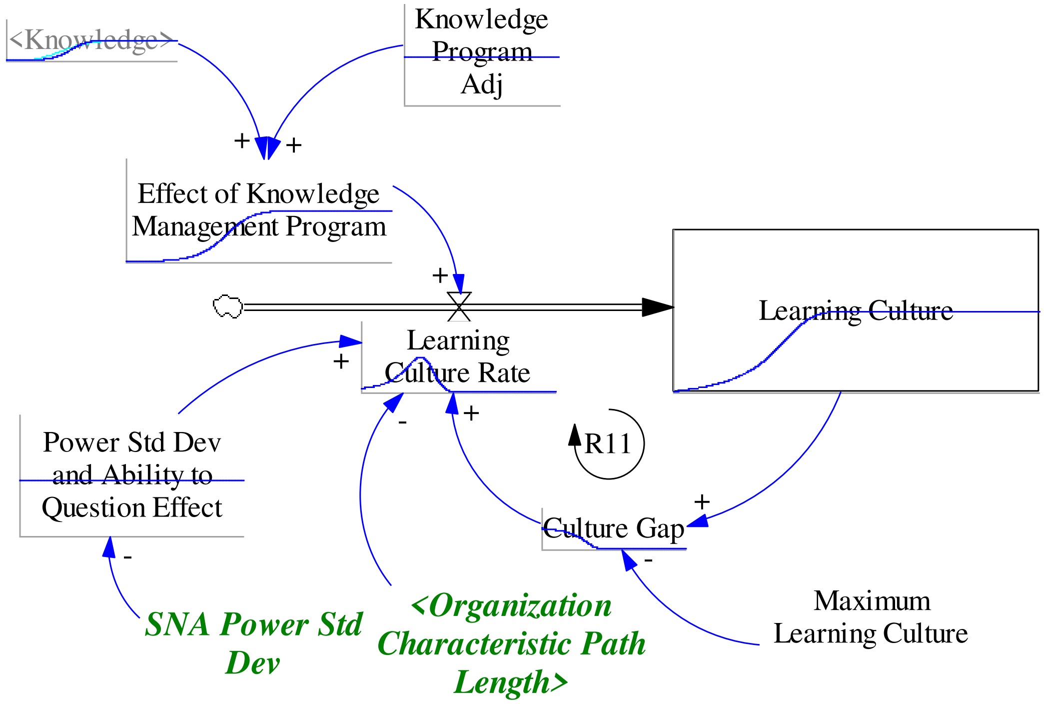


Figure 8.24. Learning Culture SD Sub-Model

8.5.3 *SD Model Feedback*

The SD model is based on a continuous predictive system that consists of stocks, flows and differential equations. The position of SD management curves is monitored where corrective action may be taken by HIL adjustment to policy and process levers.

This adjustment represents a discrete event that takes time to take hold in influencing the position of management curves and state of the physical system and entities within other sub-models. In this way, the integrated model represents a feedback control system where there is monitoring of variables against target values and HIL adjustments are made as required. Against the backdrop of this control system is double-loop learning where what-if scenarios can challenge, reinforce and build on the mental models and intuition for informed decision-making.

8.5.4 *SD Model Policy Levers*

In the current study, seven key policy levers were considered in the development of the SD model. These policies are listed in Table 8.2 with reasonable baseline values assigned, leaving room for the application of policy improvement levers. The range of values that may be used in the application of these levers is also provided in Table 8.3. Each policy lever is assessed and calibrated independently, without the adjustment to other levers and their baseline values.

Table 8.3. SD Model Policy Levers

SD Model ID	Policy Lever	Current SD Model Calibration Value	Minimum	Maximum
1	OJT Effort	1.25	1.1	1.6
2	Gaming Intensity	0.9	0.8	1.3
3	Learning Effort	4	3	8
4	Team Colocation	0.8	0.7	1.2
5	Applying Engineering Principles	0.1	0	0.5
6	Paying for VFI	0.4	0.3	0.8
7	Relational Contracting Effort	0.3	0.2	0.7

8.5.5 *SD Model Process Improvement Initiative Effort Levers*

In the current study, seven key cross-functional processes were considered in the development of the SD model. These processes are listed in Table 8.3 with reasonable baseline values assigned, leaving room for the application of process improvement levers. The range of values that may be used in the application of these levers is also provided in Table 8.4. Each process improvement lever is assessed and calibrated independently, without the adjustment to other levers and their baseline values.

Table 8.4. SD Model Process Improvement Levers

SD Model ID	Process Improvement Lever	SD Model Calibration Value	Minimum	Maximum
8	Knowledge Management	0.6	0.5	1
9	Design Change Management	0.8	0.5	1
10	Risk Management	0.8	0.5	1
11	Communication Management	0.8	0.5	1
12	Integration Management	0.8	0.5	1
13	Supply and VFI Management	0.8	0.5	1
14	Strategic Management	0.8	0.5	1

8.5.6 *Organization Investment in Applying Levers*

The return on investment from applying systems engineering efforts has been investigated in other research where 14.4 percent of program costs invested in systems engineering were assessed as optimal for project success [123]. The effort expended in using the management flight simulator in the current study and in gaming design change scenarios is estimated at well below 14.4 percent. Through the adjustment of key SD model policy and process levers, the return on investment may be realized in reduced design change costs and schedule delays, as well as in other benefits.

8.5.7 *SD Model User Interface*

The interactive SD Model consists of project management and systems engineering views that capture the socio-techno-economic, cultural aspects and behavior based on both DSS model inputs and adjustments made to policy and process improvement levers.

As depicted in Figure 8.25, the main page of the SD model consists of seven policy levers and seven process improvement levers that may be adjusted in response to the state of program management curves. The SD model receives inputs from the DSS, SNA, PMM and SRL sub-models where the system state impacts the position of the management curves.

Another SD model page provides a more comprehensive set of a management curves, as depicted in Figure 8.26.

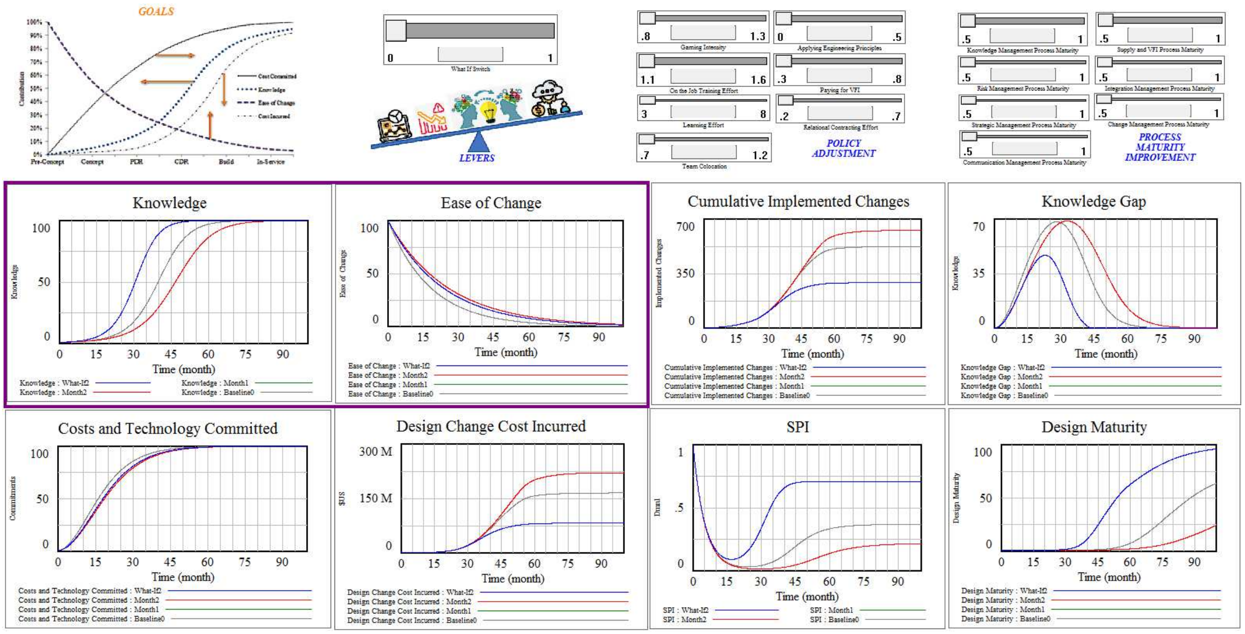


Figure 8.25. SD Model Main Page

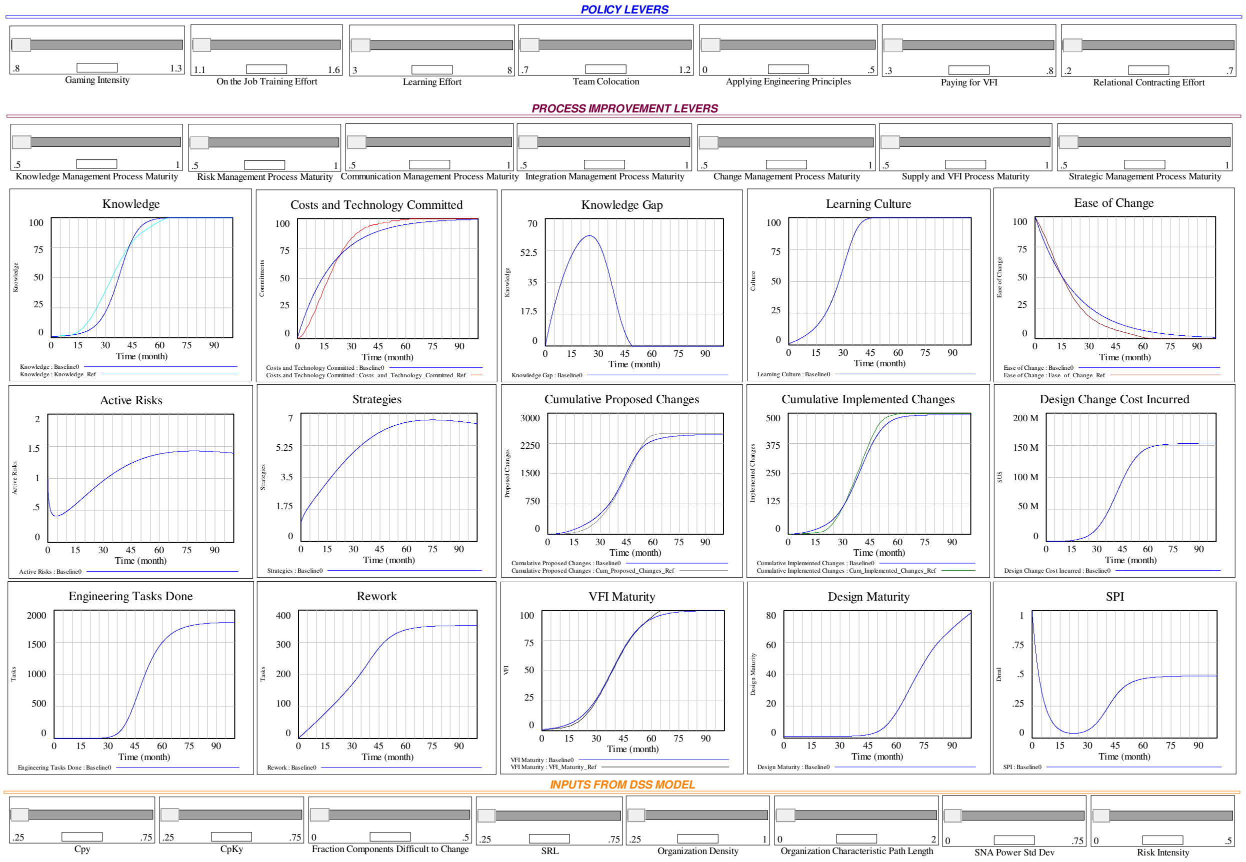


Figure 8.26. SD Model Extended Management Curves

8.6 Comparing Predicted Management Curve Behavior to Actuals

The predicted behavior of a select number of management curves may be compared to actual values as depicted in Figure 8.27. These are readily available measures captured within traditional program performance tools. Any differences between predicted and actual values and trends may be used to calibrate levers and constants within the SD model.

While validating structure and behavior of predicted curves within the SD sub-model can provide a level of confidence, comparison of predicted management curves against the trend of actual curves can help to calibrate the simulator and reinforce this confidence.

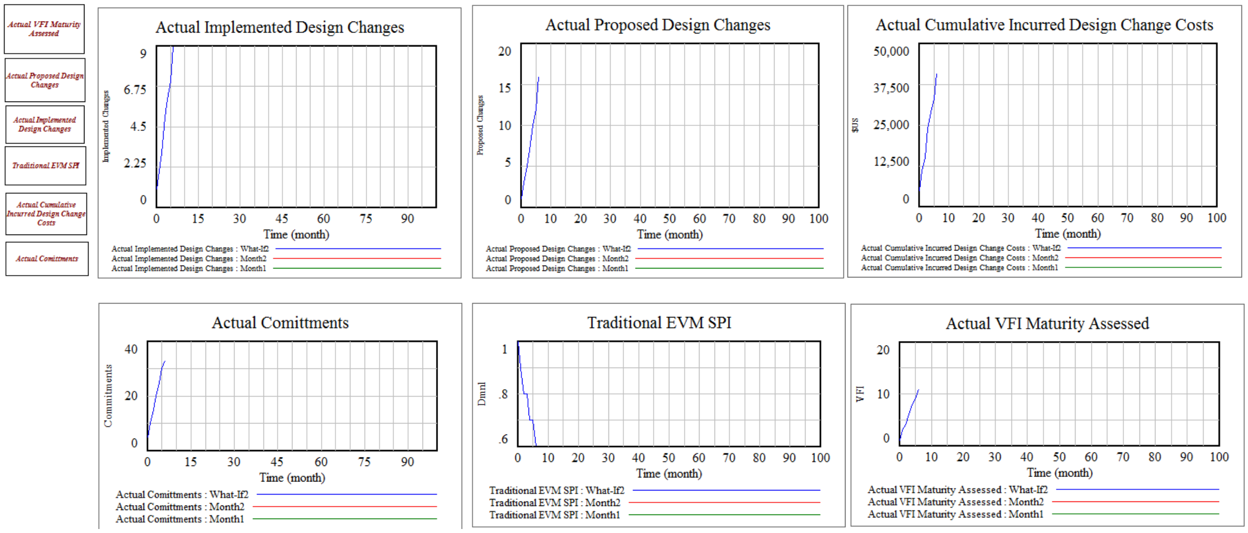


Figure 8.27. SD Model Actual Update Page

8.7 Conclusions

The world of complex project management and systems engineering is dynamic, consisting of several interacting components. The simulator captures key components that are relevant to the integration of these two disciplines and the management of knowledge, risks, design changes, and work performance throughout the design cycle.

This simulator provides interactive controls and policy and process levers whereby teams can game design change strategies in response to risks and issues. Use of the simulator can reduce design change costs normally incurred later in the design cycle by advancing the Knowledge curve and by moving up the Ease-of-Change curve early in the design. This can provide for a robust design and flexibility in developing design change strategies and procurement options.

In the current study, the management flight simulator can help an organization more easily find optimal solutions, saving time and increasing confidence in the decision. The simulator can also help decision-makers better understand systems and the impact of changes to them.

Validation of the management flight simulator follows in the next chapter with application of typical design change scenarios to the IPS case study.

Chapter 9 – Validation of the Management Flight Simulator

9.1 Introduction

The management flight simulator developed in the previous chapter provides a practical approach and model to help integrate the disciplines of project management and systems engineering. This model provides system performance attributes and predicts the impact of the system state and its associated risks on several design life-cycle management curves.

The focus in the current study is on the four typical management curves described in the previous chapters. The hypothesis proposed in the current study whereby, if both the Knowledge and Ease-of-Change curves can be positively influenced, then the Commitments and Costs-Incurred curves will in turn be improved. Other positively management curves that are natural extensions of these curves include number of design changes, risks-strategies, VFI maturity, design maturity, work performance, and the learning culture.

Simulation models are approximate imitations of real-world systems and they never exactly imitate the real-world system. Due to this, a model should be verified and validated to the degree needed for the models intended purpose or application [126].

In the current study, verification and validation is carried out to a reasonable degree to provide a level of confidence for decision-makers using the management flight simulator. With continued use of the model and validation, confidence in the model is expected to increase.

This chapter provides verification and validation of the simulator through a structured methodology, including the application of three design change scenarios and surveys with industry experts.

The PM-SE integration themes, requirements and potential benefits from using the simulator were translated into eleven questions forming a survey that was conducted with 28 SE and PM participants at the International Council on Systems Engineering (INCOSE) International Workshop (IW) 2020 on MBSE. The results of this survey are presented in the current chapter and are viewed as a significant contribution to validation of the simulator benefits and associated integration requirements.

9.2 Motivation

The simulator provides a practical and novel approach to linking cross-functional processes and models using a digital thread known as a knowledge graph. The value in doing this is in connecting physical system information to design life cycle management curves, relating and communicating information, and understanding the 'why' through causal relationships of system changes and their impact on the overall systems engineering and project management system. The benefits include reduced costs, delays and identifying problems early in the design cycle.

9.3 Objectives and Related Research Questions

The goal of verification and validation in the current study is to confirm the accuracy and ability of the model in predicting the real-world system, including the behavior of several management curves. This goal includes comparing the state of a baseline model to a modified model as a result of changes to system, policy and process improvement levers. Actual real time data for a limited number of curves may also be compared to baseline reference modes and to predicted optimal curves using observed behavior and comparison measures.

This chapter also covers the benefits from using the management flight simulator and the return on investment as seen through reduced costs and schedule delays.

9.4 Background

It has been noted that it is difficult to validate system dynamic models when several subjective components exist, however; the structure and behavior of such models can provide validation against real world scenarios [121]. System dynamic models typically incorporate several relationships, behaviors and effects that are viewed as ‘white box’ models, while the data-driven equation-type components are viewed as ‘black box’ models. Both the DSS and SD model in the current study incorporate the aspects of both ‘white box’ and ‘black box’ models.

While validation of simulation models is viewed as important, there does not appear to be a standard approach for doing this. There have been validation concepts discussed in literature some ten to thirty years ago. Nevertheless, these concepts are viewed as relevant to the current study in working toward a structured approach to verification and validation of the management flight simulator.

Verification is concerned with developing the simulator in accordance with stated requirements using a structured approach. In the current study, this approach includes the seven pillars for integration. It also includes systems thinking and a systems engineering perspective with use of SE models and integration tools such as the N^2 DSM diagram and knowledge graph. These techniques are used to ensure the right inputs, outputs and logic are represented in the management flight simulator.

Validation is concerned with developing the model so that it accurately represents the real world or system. As part of verification and validation, testing of the model during its development was ongoing where errors were fixed to ensure correct functionality and that the requirements were satisfied. This also included calibrating the SD model management curves to better match reference modes.

There can be several validation techniques including face validity through industry consultation, extreme condition testing, parameter variability or sensitivity analysis, and predictive validation where the model predicts behavior [126].

These techniques can involve qualitative as well as quantitative analysis, however; qualitative analysis appears to be the focus in the validation of SD models. The validation of SD models has been criticized for relying on informal subjective and qualitative approaches [120].

Nevertheless, in the current study both a qualitative and quantitative objective approach are taken toward model validation.

9.5 Verification and Validation Methodology

The requirements and specifications for developing the model forms the foundation for verification and validation [127]. The requirements for the integration of information management systems, PM-SE disciplines and models were presented in previous chapters.

In assessing model validity, three design change scenarios are applied to the management flight simulator. In response to these changes, the user has the option to adjust system parameter and component type settings within the DSS model where system attributes can be affected. With a change in system state, management curves within the SD sub-model can be affected. Likewise, adjustments to policy and process levers can affect the position, level and direction of the management curves.

The underlying equations of the SD model can be validated through consistency checking and the balancing of equations. With changes to the system, the behavior may be validated through observing attribute and management curve levels and patterns as being intuitively correct.

The validation techniques adopted in the current study fall into the categories of model structural tests and behavioral tests. Within these categories, qualitative and quantitative techniques and analysis can be conducted. The verification and validation methodology followed in the current study is depicted in Figure 9.1.

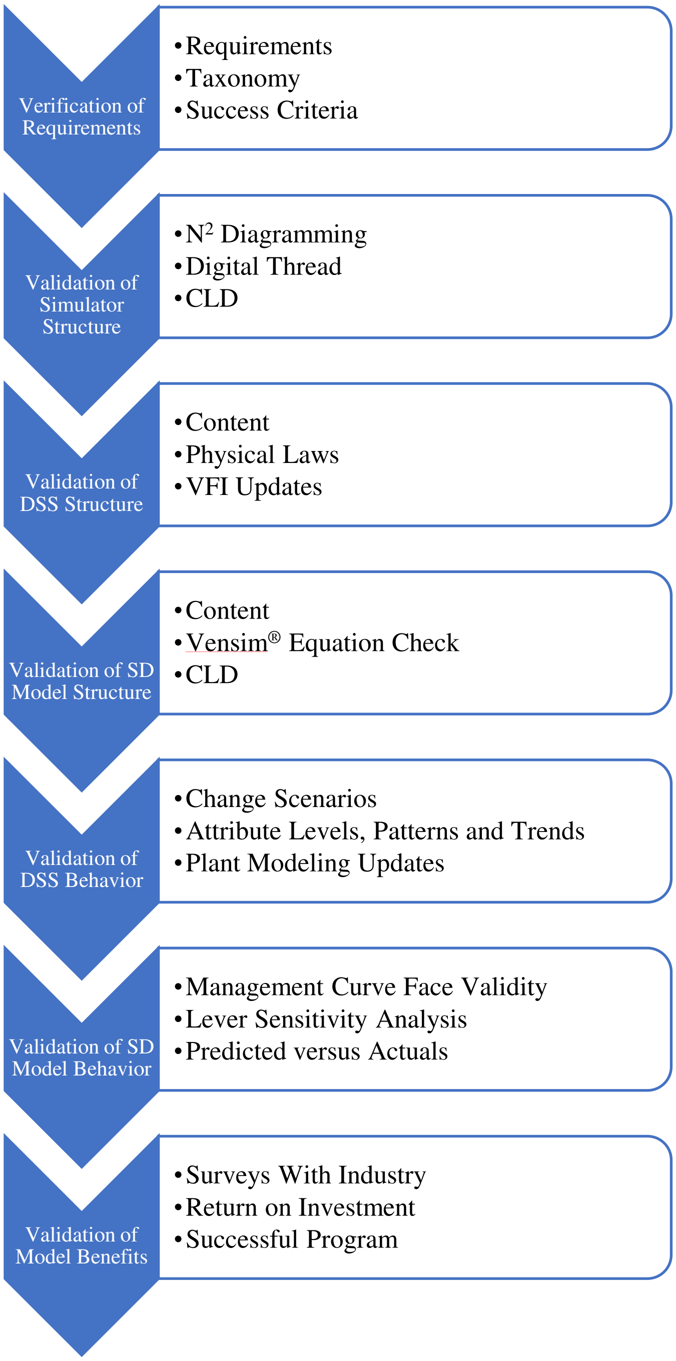


Figure 9.1. Management Flight Simulator Verification and Validation Methodology

9.5.1 *Verification of Requirements*

The Integration Strategy and Response Strategy discussed in the current study may be traced back to supporting theories and laws as listed in Table 9.1.

Table 9.1. Integration Strategy Elements Mapped to Supporting Theories, Laws and The Response Strategy

Theory, Laws and The Response Strategy					E1 Integration Strategy
		B1 Systems Theory	B1.1 System Dynamics	B2 Knowledge Theory	E1.1 Systems Thinking and SD
				B1 Systems Theory	E1.2 SE
			B1 Systems Theory	B5 Social Sciences	E1.3 Selection of Models
				B1 Systems Theory	E1.4 Digital Thread
		B4 Decision Theory	B4.1 Ashby B4.2 Stacey	E2 Response Strategy	E1.5 Set-Based Robust Design
B2 Knowledge Theory	B2.1 Jaque's Law B2.2 Revan's Law	B3 Game Theory	B5 Social Sciences	E2 Response Strategy	E1.6 Action Learning and Agile
	B3 Game Theory	B4 Decision Theory	B4.1 Ashby B4.2 Stacey	E2 Response Strategy	E1.7 Interdisciplinary Decision-Making

The enabling elements of the Integration Strategy may be mapped to common integration themes, as listed in Table 9.2.

In verifying the simulator against requirements, common themes for information and organizational integration, a taxonomy for multi-disciplinary tools, and success factors are assessed from previous chapters. These requirements are summarized in Table 9.3.

Table 9.2. Common Themes for Integration Mapped to Integration Strategy Elements

E1 Integration Strategy	Common Themes for Integration				
E1.1 Systems Thinking and SD	R5 Mental Models	R2 Simulation	R6 Knowledge		
E1.2 SE	R1 Communication	R2 Simulation	R3 Quality		
E1.3 Selection of Models	R2 Simulation				
E1.4 Digital Thread	R1 Communication	R2 Simulation			
E1.5 Set-Based Robust Design	R2 Simulation	R3 Quality	R4 Decisions	R6 Knowledge	
E1.6 Action Learning and Agile	R1 Communication	R2 Simulation	R4 Decisions	R6 Knowledge	R5 Mental Models
E1.7 Interdisciplinary Decision-Making	R2 Simulation	R4 Decisions	R6 Knowledge		

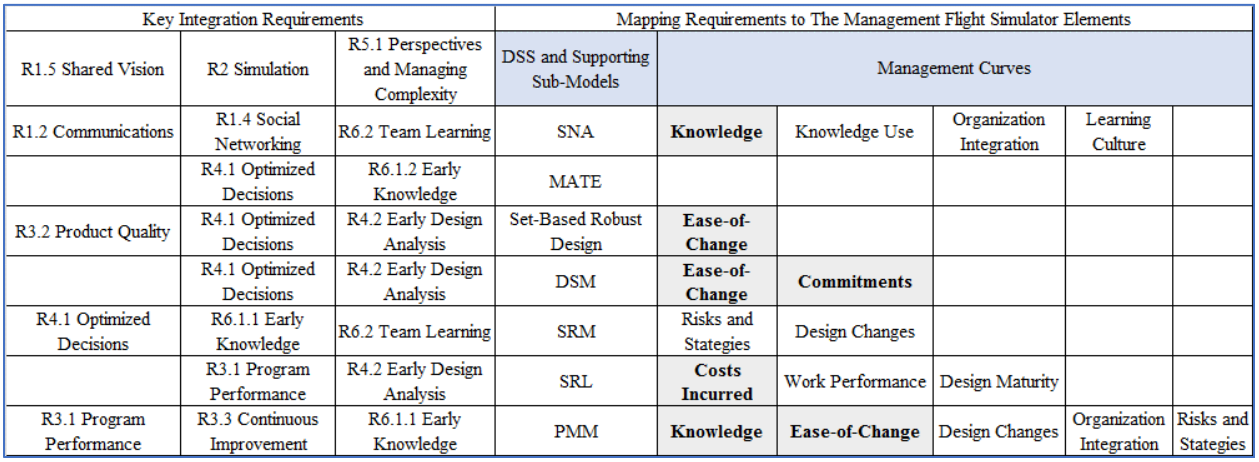
Table 9.3. Summary of Integration Requirements and Associated Criteria

Common Themes for Integration (Chapter 7)	Taxonomy for Multi-Disciplinary Tools and Assessment Criteria (Chapter 3)	Success Criteria for Integration of Information (Chapter 7)
Communication, collaboration, social networking, and stakeholder perspectives (R1)	Simplicity (M1)	Accessibility (S1)
Simulation, manipulation and integration of data and information (R2)	Efficiency and Portability (M2)	
Quality, continuous improvement and performance management (R3)	Accuracy (M3)	Usefulness (S2)
Optimized decision process based on objective attributes (R4)	Transparency (M4)	Aids decision-making (S3)
Mental models including visualization of patterns and trends (R5)		
Early knowledge of the design space, learning culture and early design analysis (R6)	UX and Automation (M5)	Has a positive impact on the organization (S4)

These requirements are addressed in development of the simulator. Accessibility is achieved through a common platform and non-dimensional language. Usefulness is achieved through a return on investment of early knowledge, product and project benefits. Decision-making is enhanced through using the DSS for tradeoff analysis and what-if scenarios. The learning culture can be positively influenced through use of the simulator. Moreover, use of the simulator can help automate routine decisions and provide the underlying reasoning behind those decisions.

The integration requirements may be mapped to simulator elements, as listed in Table 9.4.

Table 9.4. Integration Requirements Mapped to Simulator Elements



Key Integration Requirements			Mapping Requirements to The Management Flight Simulator Elements					
R1.5 Shared Vision	R2 Simulation	R5.1 Perspectives and Managing Complexity	DSS and Supporting Sub-Models	Management Curves				
R1.2 Communications	R1.4 Social Networking	R6.2 Team Learning	SNA	**Knowledge**	Knowledge Use	Organization Integration	Learning Culture	
	R4.1 Optimized Decisions	R6.1.2 Early Knowledge	MATE					
R3.2 Product Quality	R4.1 Optimized Decisions	R4.2 Early Design Analysis	Set-Based Robust Design	**Ease-of-Change**				
	R4.1 Optimized Decisions	R4.2 Early Design Analysis	DSM	**Ease-of-Change**	**Commitments**			
R4.1 Optimized Decisions	R6.1.1 Early Knowledge	R6.2 Team Learning	SRM	Risks and Stategies	Design Changes			
	R3.1 Program Performance	R4.2 Early Design Analysis	SRL	**Costs Incurred**	Work Performance	Design Maturity		
R3.1 Program Performance	R3.3 Continuous Improvement	R6.1.1 Early Knowledge	PMM	**Knowledge**	**Ease-of-Change**	Design Changes	Organization Integration	Risks and Stategies

The current study validates the purpose and functionality of the management flight simulator in addressing the need for an integrated data analytical model that provides informed decision-making and brings together the disciplines of systems engineering and project management.

The need for an integrated analytical decision model was validated through a literature review [3] [8] [16]. This need is further validated through interviews and surveys with industry experts.

9.5.2 *Validation of Overall Structure of The Management Flight Simulator*

In the current study, the DSS, SD and supporting models are linked through key transformational variables. Together, these models provide for a comprehensive view of real-world design change problems and the consequences from decision-making.

Validation of the structure of the model was carried out through N^2 diagramming and development of model linkages as described in the knowledge graph.

9.5.3 *Validation of Structure of the DSS*

In the current study, the DSS model is functionally tested using data from the IPS case study. The content of the DSS includes system components and attributes that were selected based on QFD and AHP techniques. These components were validated through a literature review and consultation with industry experts.

The underlying physical laws with the original MATE reference model and DSS were validated through assessing the behavior of design attribute levels as affected by changes in design variables.

As VFI is gathered throughout the design cycle, updates to component specifications are expected where system attributes such as size, weight and power can be validated within the model. This also provides validation of underlying equations and metrics such as power-to-weight ratios.

9.5.4 *Validation of Structure of the SD Model*

In predicting the behavior of phenomena such as weather, the economy, and even the current knowledge-design change study, key factors need to be considered in order to represent reality within the model. These include driving factors that affect behavior such as flow rates and the scenarios that reflect reality [110]. Key techno-socio-economic and cultural factors are identified in the current study for model development.

Validation is concerned with model results being correct for its intended range of application [126]. In the current study, this range applies to both DSS output values and the range assigned to SD model policy and process levers.

To test the model as a representation of reality, its structure can be assessed against knowledge of the real system. This knowledge was established through a literature review, engagement with shipyards and industry, and from author experience.

The structure of the model can be assessed against extreme condition testing and through evaluating the model equations and resulting behavior against what would be expected in the real world [121]. This assessment includes dimensional consistency of left and right-hand sides of the equations. It also includes the checking of units used in these equations. In the current study, model equations are validated using Vensim® software, with results provided in Appendix D.

9.5.5 *Validation of DSS Behavior*

The external IPS plant model, Homer Pro®, was used to validate the sizing of system components in accordance with requirements. Plant model updates are also used to validate DSS parameter levels throughout the design cycle.

The validation of system attribute levels between lower and upper thresholds is assessed using process variability measures of C_{py} and C_{pyk}, as discussed in previous chapters.

The validation of fraction of components difficult to change is assessed through the updating of DSM change propagation matrices as well as the linked SRM risk levels associated with system components.

The risks listed in the SRM and the associated primary components may be assessed at risk review meetings. When risks are updated, the DSM changeability values can be affected as well as the Ease-of-Change curve.

9.5.6 *Validation of SD Model Behavior*

In the current study, the model can be assessed through observing the behavior of the DSS attribute levels and SD model management curves against adjusted system, policy and process improvement levers. Several levers and causal factors are included in the model that affect knowledge level, ability to implement design changes, ease-of-change, and program performance.

The behavioral patterns of actual data curves can be compared to both historical reference modes and predicted optimal curves. Model levers may be adjusted to improve system and management curve behavior where insights may be shared among multiple stakeholders. Face validity of these curves includes an assessment by the author and industry experts who can validate the correct response of these curves to system changes.

In the current study, usefulness of the SD model can be assessed through observing the behavior of the model where levers are applied. The range of these levers and their effect on management curves may be assessed and validated through sensitivity analysis using Vensim® software.

The SD model can confirm, clarify and challenge existing mental models. The behavioral patterns of the management curves may be compared to real world reference modes. These reference modes are based on actual data from a past similar project. Similarly, actual data may be compared to predicted optimal curves resulting from adjusted levers.

The real data that can be made available during application of the management flight simulator includes the number of design changes, VFI maturity and the ratio of strategies to risks. For comparison purposes, the traditional earned value management (EVM) measure of schedule performance index (SPI) may be compared to that captured within the SD model.

In validating predicted management curves against actual data, the measures of cross correlation and convergence-divergence may be applied. These measures can be of interest should the current management flight simulator be used in industry. Comparison against actual data can also help in calibration of the SD model and its levers of influence, thereby increasing fidelity and accuracy of the model.

9.5.6.1 *Cross Correlation Function*

The normalized cross correlation function (CCF) estimates a phase lag between the simulated and actual time pattern [128]. In the current study, the predicted optimal management curve or reference mode curve can represent a leading indicator that may be compared to the actual management curve values.

$$Corr_{Norm}\, y_1 y_2 = \frac{\sum_{t=0}^{T-1} y_1(t) y_2(t)}{\sqrt{\sum_{t=0}^{T-1} y_1{}^2(t) \sum_{t=0}^{T-1} y_2{}^2(t)}} \qquad (9.1)$$

where t represents time (months), y_1 the predicted optimal curve, and y_2 the actual management curve values gathered in near real time. The CCF normalized values range from a poor correlation of -1 for a paired inverted curve to a strong correlation of +1 for overlapping curves.

9.5.6.2 *Convergence Divergence Function*

The convergence divergence function (CDF) is used to determine behavior between two functions in a cartesian coordinate system as convergent, parallel or divergent [129].

The CDF may be used in the current study to distinguish the behavior of actual management curve data from the predicted optimal management curve or the historical reference mode curve.

$$CDF\ (t) = \lim_{\varepsilon \to 0^+} \frac{f_1(t+\varepsilon) - f_2(t+\varepsilon)}{f_1(t) - f_2(t)} \tag{9.2}$$

where ε is small and f_1 and f_2 are management curve functions of time (t). CDF values greater than one represent divergence; less than one convergence, and equal to one parallel curves.

9.5.6.3 *Sample Comparison of Actual Data to Predicted Management Curves*

As indicated in Table 8.2 and Figure 8.27, the actual data for number of design changes and VFI maturity were readily available from a similar IPS design project in an east coast shipyard. These formed both reference modes and calibrated baseline curves within the SD model. The reference modes and associated baseline curves for knowledge, commitments and ease-of-change were based on literature [4] [10] [11].

The actual number of design changes may be used to estimate costs incurred. Likewise, actual VFI maturity may be used to estimate design maturity as described in the causal loop diagrams (CLD’s).

The simulator prototype has not yet been applied in industry but for the purposes of showing how actual values could be compared to the current month predicted values is presented. The comparison of actual values to predicted for number of changes and VFI maturity may take the form depicted in Figures 9.2 and 9.3 respectively.

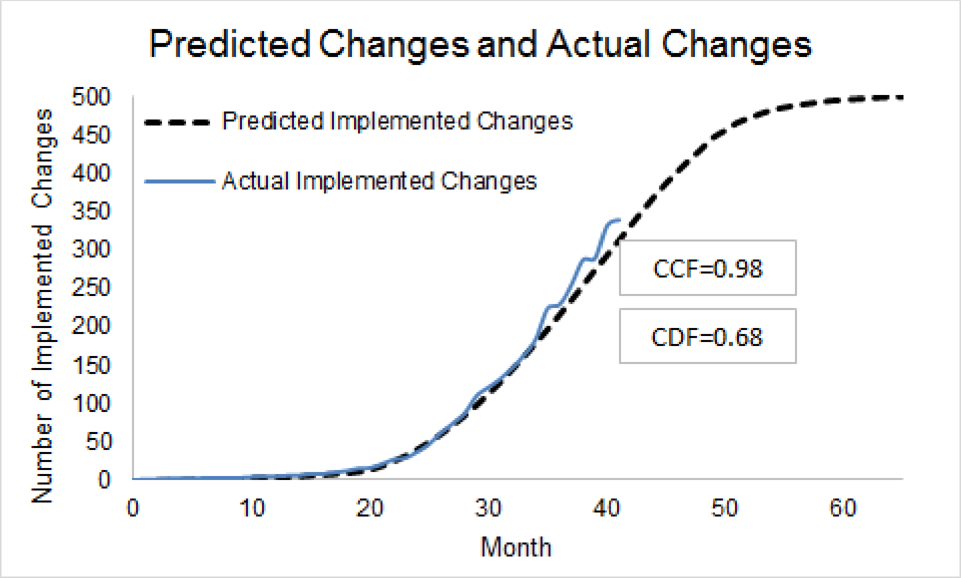


Figure 9.2. Predicted Design Changes and Actual Changes

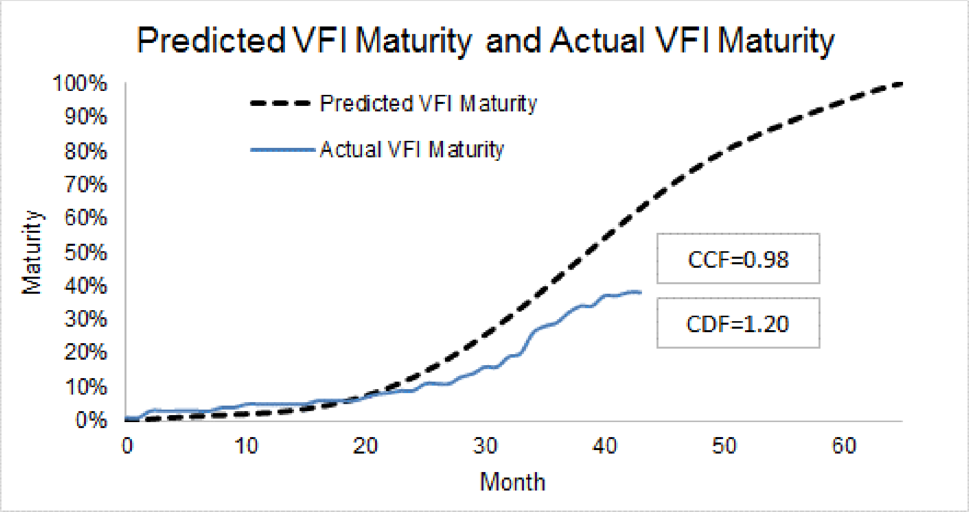


Figure 9.3. Predicted VFI Maturity and Actual VFI Maturity

The costs and schedule performance curves within the SD model provide another perspective on project performance management. Using another model in parallel to the traditional earned value management (EVM) project management technique can help challenge and validate project performance measures. For example, the SD model predicted schedule performance index (SPI) values may be compared to the EVM SPI values, this comparison is depicted in Figure 9.4.

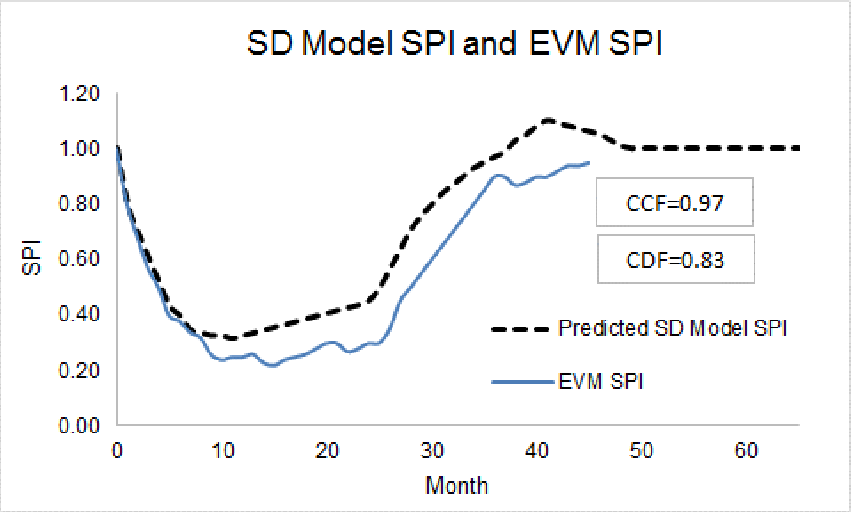


Figure 9.4. SD Model Predicted SPI and EVM SPI

The ratio of risks to strategies is adjusted in the model where a variety of six strategies may be played out in response to one risk. This reflects the six different teams discussed in the current study. As depicted in Figure 9.5, this ratio may be adjusted. On the other hand, the monthly actual average number of strategies played out against a risk may be used as an input into the model.

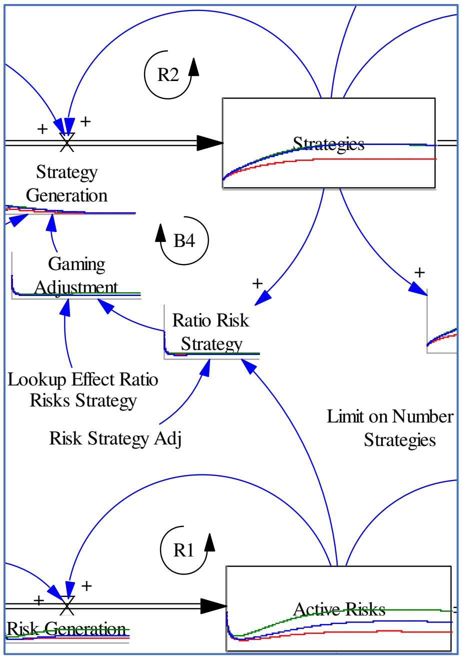


Figure 9.5. Ratio of Risks to Strategies and Actual Ratio

9.5.7 *Validation of Simulator Benefits*

Concerns have been raised with respect to the lack of interest and buy-in from high technology organizations in embracing and adopting systems engineering models and tools. It was found that a low percentage of these organizations use model-based systems to capture data, whereas; a high percentage still rely on document-based systems [130]. Moreover, the improper matching of models and immature methods can make industry hesitant to adopt MDO models [49]. Other reasons why industry may be hesitant may be found within integrated model assessment and success criteria. As discussed in Chapter 3, key assessment criteria include simplicity, transparency, efficiency, UX and automation. Key success criteria include accessibility and usefulness for decision-making.

It may be argued that meeting these criteria can lead to MDO and MBSE integrated models and tools being more readily accepted and promoted.

The advantages from using the simulator include the potential to reduce costs and schedule delays, increase competency, and provide the ‘big picture’ perspective of the system and project. Other advantages include effective management of system attributes, their linked requirements and design cycle management curves. Furthermore, the use of several models can validate results and increase confidence and credibility in these models as the design matures and policies are implemented.

The usefulness and return on investment from using the simulator is demonstrated in the costs incurred and schedule performance index (SPI) management curves where costs and schedule delays can be reduced. Intangible benefits include increased learning, knowledge, and an improved organizational culture. Another added benefit is in the automation and tracking of decisions, thereby allowing more time for critical and strategic thinking.

Program management includes the coordination of transformation activities to achieve outcomes and benefits [131]. Use of the management flight simulator is viewed as a transformation activity that provides the benefit of reduced costs, schedule delays and increased organizational competency.

Program management governance themes relevant to the current study include stakeholder engagement, defining team roles and authorities in gaming solutions, benefits management, risk management, and quality management. These themes are addressed in development of the management flight simulator.

Stakeholder engagement is enhanced through the gaming and strategizing of design change solutions using the management flight simulator. Successful benefits management is realized through reduced costs, schedule delay and increased organizational capability and competency.

Successful program management includes the capability to manage uncertainty, complexity and ambiguity [131]. This can include tools to aid decision-making. Use of the simulator in adapting to these conditions was discussed in the previous chapters.

Quality management is viewed as a key governance theme in the current study from both a product and organizational quality perspective. The scope of quality can be broad and can include people, communication, supply chain, process, information, and asset management [131]. These elements are included in the management flight simulator.

9.5.7.1 *INCOSE IW2020 and Validation of Simulator Benefits*

The common themes for integration requirements were translated into questions that formed part of a survey with 28 SE and PM participants at the International Council on Systems

Engineering (INCOSE) International Workshop (IW) 2020 on MBSE. The results of this survey are presented in the section on validation of model benefits in this chapter.

The standard 'z' normal distribution may be used for statistical analysis when the sample size is at least 30 [132]. In the current survey, the response to questions range from 26 to 28 observations where the 't' distribution is used rather than the 'z' distribution.

Questions are grouped where possible in accordance with the implicit integration requirements, the associated system dynamic interrelationships and influencing factors.

The typical statistical values of mean, mode, standard deviation and variance for the survey samples are measured. The mean value $\bar{X}$ takes the form:

$$\bar{X} = \frac{\sum X}{n} \tag{9.3}$$

where X represents individual response values and n, the number of responses.

The mode value represents the most frequent response value. The standard deviation s value takes the form:

$$s = \sqrt{\frac{\sum(X-\bar{X})^2}{n-1}} \tag{9.4}$$

To compare dispersion among the responses to the eleven questions, the sample variance for each question is assessed and takes the form:

$$s^2 = \frac{\sum X^2 - \frac{(\sum X)^2}{n}}{n-1} \tag{9.5}$$

In addition to these typical statistical measures, the 95 percent confidence interval for the mean and hypothesis testing of validation criteria are measured to prove both single and grouped questions.

The confidence interval provides a range of values where the population mean is likely to fall within. The confidence interval for the sample mean using the 't' distribution takes the form:

$$\bar{X} \pm t \frac{s}{\sqrt{n}} \tag{9.6}$$

where $\bar{X}$ is the sample mean, the *t* value is based on the number of degrees of freedom (n-1) and the confidence level, *n* is the number of observations, and *s* is the sample deviation.

For the grouping of questions, the number of observations is greater than 30, representing a normal 'z' distribution. In this case, the confidence interval takes the form:

$$\bar{X} \pm z \frac{s}{\sqrt{n}} \tag{9.7}$$

where the value of *z* may be found within tables and depends on the level of confidence.

To test the validity of the sample mean *s* in representing the population mean μ, a hypothesis statement is formed. In the current study and survey, the null hypothesis H_o is that the population mean μ for each response to a question is at least 3.5 (70 percent) on the scale of 1 to 5. This would indicate a moderately high to very high potential for the management flight simulator to meet integration requirements. The alternate hypothesis H_1 is that the population mean is less than 3.5.

The null hypothesis statement is subject to evidence that helps to validate it, in this case the sample survey results serve as evidence. Having stated the null hypothesis, a level of significance, test statistic and decision rule are selected. For typical research projects and surveys, a typical level of significance is selected at 0.05 [132]. The level of significance represents the probability of committing a Type I error, rejecting the null hypothesis when it is true. The value of the test statistic *t* for a sample of less than 30 observations is:

$$t = \frac{\bar{X} - \mu}{{}^{s}/_{\sqrt{n}}} \tag{9.8}$$

where μ is the hypothesized population mean.

The decision rule is based on a comparison of the critical test value based on level of significance to the computed sample test value *t*. The critical value at a 0.05 significance level for a one-tailed test is -1.708 for 26, -1.706 for 27, and -1.703 for 28 observations.

Any computed sample test values greater than the critical value fall within the region of acceptance, supporting the null hypothesis. Conversely, sample test values less than the critical value fall within the region of rejection. These areas of acceptance and rejection are depicted in Figure 9.6.

For the grouping of questions where the number of total observations is greater than 30, the value of the test statistic *z* takes the form:

$$z = \frac{\bar{X} - \mu}{\sigma / \sqrt{n}} \tag{9.9}$$

where σ is the standard deviation of a normally distributed sample.

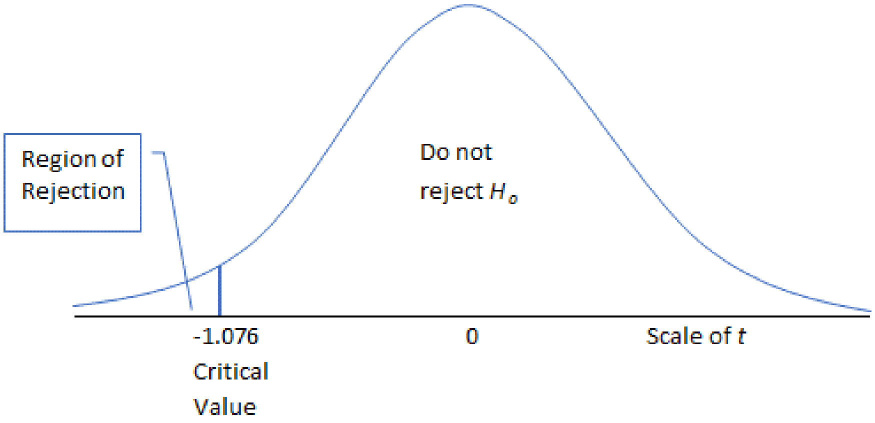


Figure 9.6. Regions of Rejection and Acceptance for the Null Hypothesis [132]

In this case, the critical ‘z’ value, at a 0.05 significance level for a one-tailed test, is -1.65. Any computed sample test values greater than the critical value fall within the region of acceptance, supporting the null hypothesis. Conversely, sample test values less than the critical value fall within the region of rejection.

The survey also allowed for free text where respondents could enter additional feedback following the presentation and demonstration of the flight management simulator. Salient points from this additional feedback are noted.

9.6 Results

The management flight simulator was used in the current study to assess the impact of design change scenarios from both a project management and systems engineering perspective. The SD model was used to assess the behavior of key management curves and to explore the effect of adjusting key policy and process improvement levers.

How the IPS case study system and management curves respond to risks and issues is played out through three typical change scenarios in the current study. This includes how the system can maintain critical parameters within defined limits by adjusting DSS input variables as well as consideration to the behavior of affected management curves in the SD model.

The first scenario to play out within the DSS model involves a regulatory risk (R4) that affects the type of diesel generator (DG) required within the IPS. This component change affects team SNA measures and performance attribute levels.

The second scenario involves a risk (R2) where required power for the gas turbine (GT) must be increased. This parameter change affects team SNA measures and performance attribute levels.

The third scenario involves risk (R8) where both the technical probability of the event and probability of impact on rework are increased due to a larger than expected DG physical size. This component change affects team SNA measures and performance attribute levels

In the current study, the strategies played out in resolving design problems may be saved as scenarios both in Microsoft Excel® for the DSS and in Vensim® software for the SD model. Typical design change scenarios from past similar projects may also be saved within the software. In Chapter 3, typical design change scenarios were identified and validated.

Teams play out and game different strategies in resolving design change problems that are based on risk elements and the primary system components affected. The set of system attributes within the DSS affected by each strategy is assessed in terms of overall C_{pky} and C_{py} values, as well as the fraction of system components difficult to change. The DSS, SRL, SNA, and PMM may be updated on a monthly basis and used as input into the SD model.

9.6.1 *Verification of Requirements*

As indicated in Chapter 5, the need for an analytical decision model such as the management flight simulator was validated through a questionnaire with a west coast shipyard. The need was rated moderately high at a mean of 2.8 out of 5.0 with a standard deviation of 0.8.

From interviews with IMP Aerospace and Boeing in California, usefulness of the simulator was assessed with positive feedback provided in Table 9.5.

Table 9.5. Interviews With Senior Managers in Industry on Usefulness of The Simulator

Question	IMP Aerospace Executive Engineering Director	Boeing Project Manager
Would the Management Flight Simulator be useful to your organization and its projects?	Viewed as a positive step for bringing multiple stakeholders together with a common view.	Yes, at the senior management level so as to gain insights into the different perspectives of multiple disciplines and project performance.
What would be the prominent features of interest in the simulator for your organization?	Requirements and risk management early in the program given tight timelines with a recent contract.	Risks and incurred costs. The model would provide insights, appreciation and increased communication between program management and engineers. This includes requirements and system attributes.
Additional Comments	Interested in 'black box' underlying equations and validating accuracy.	Suggested investigation into a different spend plan by government sponsors given predicted reduced incurred costs in model i.e. spend and invest more upfront to reduce costs later

9.6.2 *Validation of the Structure of the DSS, Supporting Models and The SD Model*

Validation of the DSS model, supporting models and the SD model includes both testing of their structure and assessing accuracy in their behavior in terms of reflecting reality.

Validation of the internal structure of the DSS model was conducted in terms of its functionality and adherence to the underlying physical system laws. Validation of the SNA, SRL and PMM supporting models was conducted through repeated updates.

Validation of the structure of the SD model includes verification of the underlying equations for relationships within the model. It also includes verification of the correct units used in these equations. The SD model in the current work was validated in its equations and units, Appendix D provides a list of these equations and units.

Another structural test involves stressing the policy and process lever parameters throughout their range without any model errors. This was confirmed through SD model testing with Vensim® software and its model error checking feature.

9.6.3 *Validation of the DSS and Supporting Models' Behavior*

The results from gaming the three change scenarios in the DSS model and supporting models are provided in Table 9.6.

The resulting attribute behavior for each scenario was as expected and in accordance with the underlying physical system laws.

9.6.4 *Validation of the SD Model Behavior*

Behavioral accuracy of the SD model is performed through relationship testing and sensitivity analysis.

Table 9.6. DSS and Supporting Models' Change Scenario Results

	C_{py}	C_{pky}	Fraction Difficult Components	SRL	SNA			Risk Intensity
					Density	CPL	Power Std Dev	
1.Change DG Type (R4)	0.52	0.35	0.17	0.45	0.60	1.40	0.19	0.20
2. GT Speed Increase (R2)	0.57	0.38	0.17	0.45	0.73	1.27	0.13	0.20
3. DG Physical Size Risk (R8)	0.57	0.38	0.33	0.45	0.73	1.27	0.13	0.22
End-Month Values for SD Model	0.57	0.38	0.33	0.45	0.69	1.31	0.15	0.22
SD Model Baseline 0	0.50	0.50	0.33	0.50	0.75	1.25	0.25	0.30
SD Model Primary Variables Affected	Ease of Change	Ease of Change	Ease of Change	Work, Design Maturity, Costs	Strategy	Culture, Knowledge Use	Culture	Risks

9.6.4.1 *SD Model Relationship Testing*

The testing of behavioral relationships involves changing a policy lever, process improvement lever, introducing a new set of DSS outputs for the SD model, and then evaluating the behavior of SD model output variables against what might be expected in the real world. The seven policy and seven process improvement levers and their baseline values were presented in Chapter 8.

Reference mode data, baseline calibration data, and DSS and supporting model values are entered into the SD model. Dependent on the position of affected management curves, key levers are adjusted independently to improve behavior and the likelihood of project and product success.

The optimal setting of selected levers can be based on those having the greatest effect in improving SD model output variables including management curves of interest, Table 9.7 provides a list of these levers.

Table 9.7. Effect of Levers on SD Model Output Variables

Levers Adjusted to Maximum Range and Having Greatest Effect	Other Levers Adjusted to Maximum Range with Lesser Effect	SD Model Primary Output Variables Affected
Knowledge Management Process, Colocation, Gaming Intensity	Relational Contracting Effort, Paying for VFI, OJT Effort	Knowledge Advanced
Colocation, Gaming Intensity	Communication Management Process	Knowledge Use (increased and to left)
Risk Management Process, Engineering Principles	Gaming Intensity	Risks (reduced)
Colocation, Gaming Intensity	Relational Contracting, Paying for VFI	Rework (reduced)
Colocation, Gaming Intensity	Relational Contracting, Paying for VFI	SPI (increased)
Colocation, Gaming Intensity	Relational Contracting, Paying for VFI	Design Maturity (increased)
Colocation, Gaming Intensity	Strategic Management Process	Strategies (increased)
Applying Engineering Principles	Nil	Ease-of-Change (increased)
Relational Contracting Effort, Paying for VFI	Supply and VFI Management Process	VFI Maturity (increased)
Colocation, Gaming Intensity	Learning Effort	Proposed Changes Advanced
Change Management Process	Nil	Proposed Changes Advanced
Colocation, Gaming Intensity	Learning Effort	Cumulative Changes (reduced)
Colocation, Gaming Intensity	Nil	Incurred Design Change Costs (reduced)
Colocation, Gaming Intensity	Integration Management Process	Organization Integration (increased)
Colocation, Relational Contracting, Paying for VFI	Nil	Learning Culture Advanced

As listed in Table 9.8, a minimum number of the most effective levers are adjusted to improve management curves affected by the design change scenarios and DSS and supporting models' output values. Other levers remain at their baseline values to avoid any undue increase in level of effort and investment.

Table 9.8. Optimal Setting of SD Model Levers in Response to Design Change Scenarios

Lever	Adjusted Lever
OJT Effort	1.25 Baseline
Gaming Intensity	**1.1** (increased from 0.9 Baseline)
Learning Effort	4.0 Baseline
Team Colocation	0.8 Baseline
Applying Engineering Principles	**0.5** (increased from 0.1 Baseline)
Paying for VFI	0.4 Baseline
Relational Contracting Effort	**0.7** (increased from 0.3 Baseline)
Knowledge Management Process	**0.8** (increased from 0.6 Baseline)
Change Management Process	0.8 Baseline
Risk Management Process	0.8 Baseline
Communication Management Process	0.8 Baseline
Integration Management Process	0.8 Baseline
Supply and VFI Management Process	0.8 Baseline
Strategic Management Process	0.8 Baseline

The three design change scenarios were applied to the DSS with a resulting change to attribute levels. Based on this change, teams can play our change scenarios by adjusting parameter and component levers in order to obtain an optimal balance of attribute levels.

Based on DSS, SRL SNA, and PMM updates to their values at the end of the month, the management curves are influenced through the digital thread of transformational variables. In turn, the SD model is automatically updated and reviewed.

With investment and adjustment to just a few levers within the SD model, the behavior and position of several management curves is improved upon. This cascading effect is viewed as resulting from the rich network of SD model entities and feedback loops.

The following sections provide the results from end-month inputs into the model and the predicted management curves positively changed by the key process and policy levers discussed.

9.6.4.1.1 *Knowledge Curve*

As depicted in Figure 9.7, the Knowledge curve is advanced in design cycle.

With an increase in the levers of gaming intensity and knowledge management process improvement, early knowledge in the design cycle is achieved.

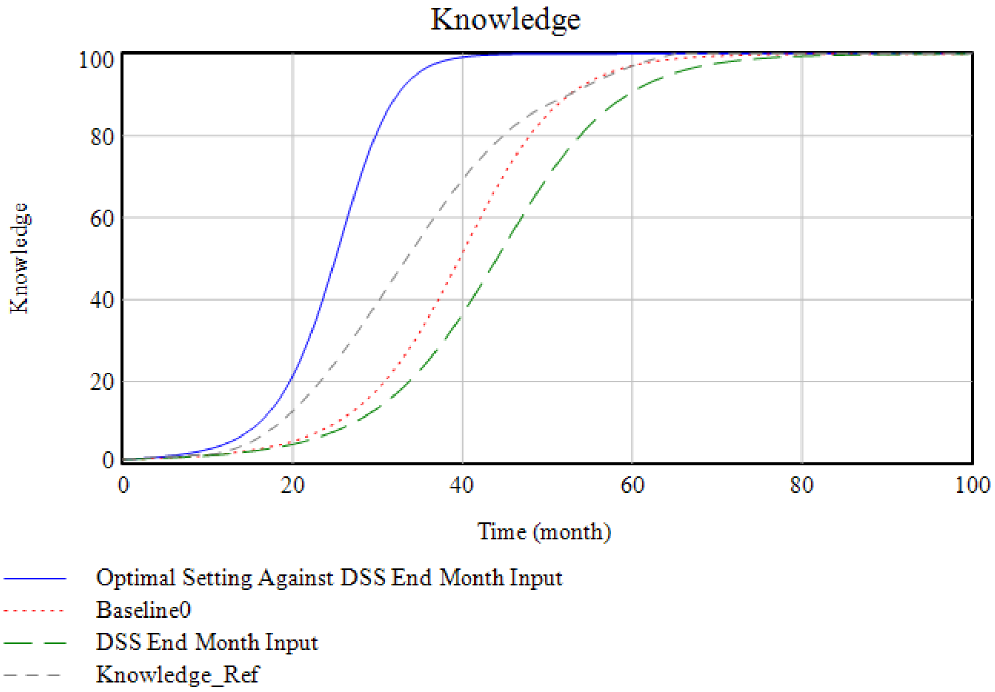


Figure 9.7. Knowledge Curve Advanced in The Design Cycle

9.6.4.1.2 *Commitments Curve*

As depicted in Figure 9.8, the secondary effects of improving ease-of-change through increased application of design principles acts to postpone commitments.

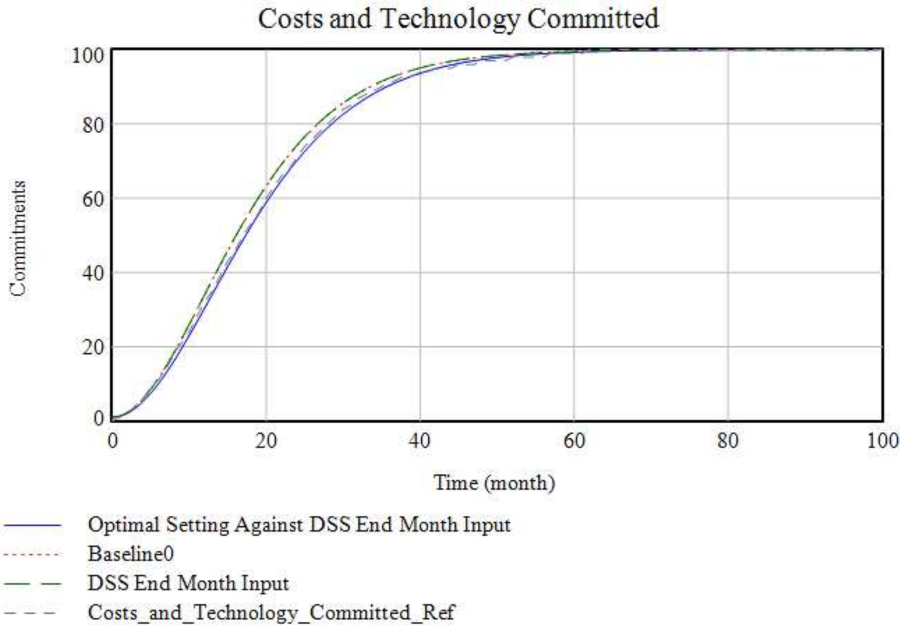


Figure 9.8. Commitments Postponed

9.6.4.1.3 *Knowledge Gap Curve*

In the current study, the difference between commitments and knowledge is represented by a knowledge gap. With postponed commitments and early knowledge, the knowledge gap is reduced as depicted in Figure 9.9.

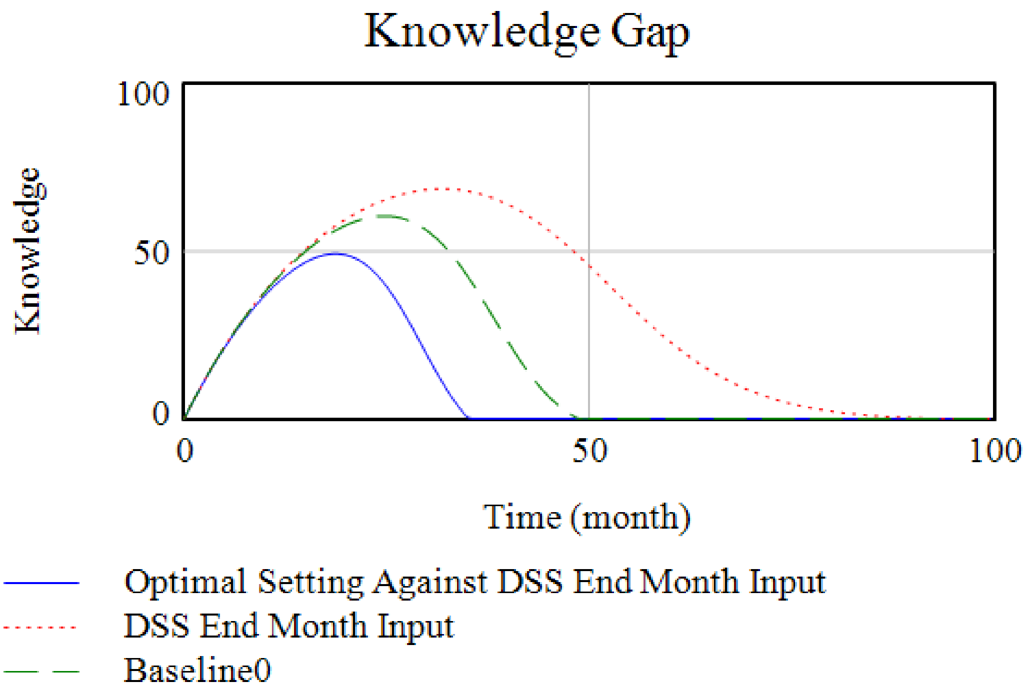


Figure 9.9. Knowledge Gap Reduced (Commitments minus Knowledge Level)

9.6.4.1.4 *Ease-of-Change Curve*

With an increase in the application of engineering principles, the Ease-of-Change curve is pushed up, as depicted in Figure 9.10.

9.6.4.1.5 *Implemented Design Changes and Costs-Incurred Curves*

With an increase in gaming intensity, early knowledge helps to rationalize and reduce the number of design changes and associated costs, as depicted in Figure 9.11.

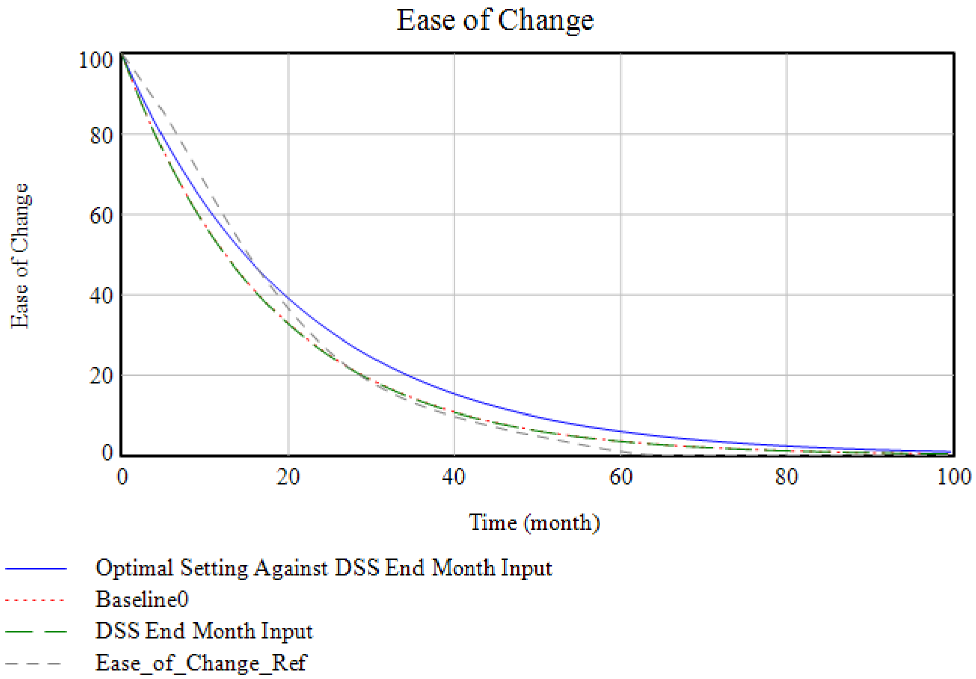


Figure 9.10. Ease-of-Change Curve Moved Up

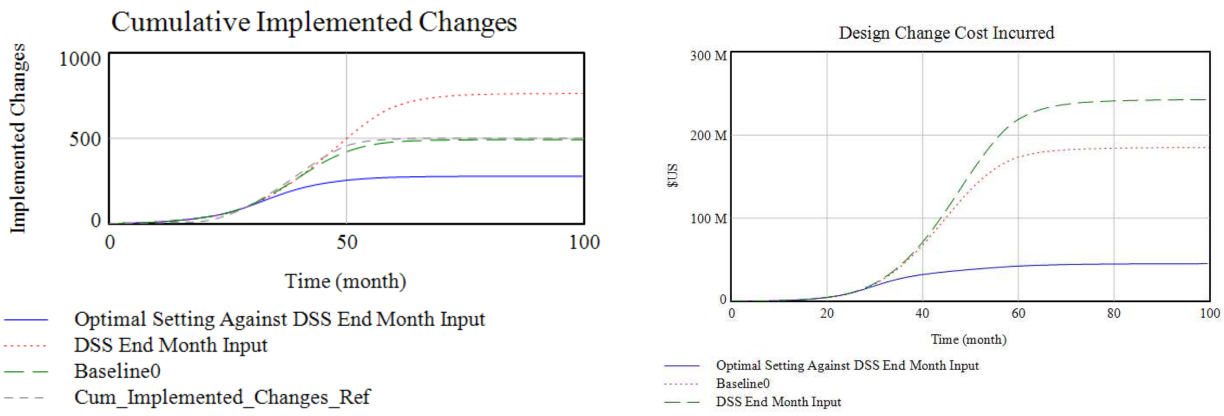


Figure 9.11. Reduced Implemented Design Changes and Costs-Incurred Costs

9.6.4.1.6 *Risks-Strategies Curves*

The ratio between risks and strategies is maintained at a reasonable level as depicted in Figure 9.12.

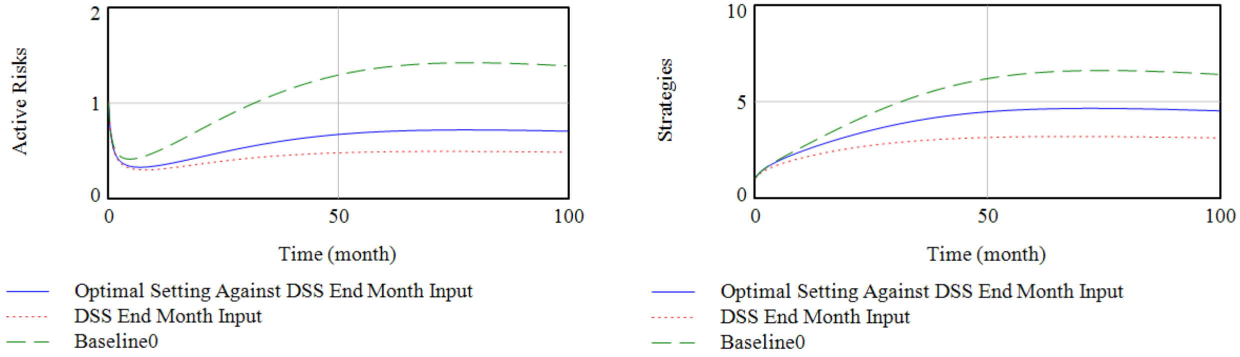


Figure 9.12. Risks-Strategies Curves

9.6.4.1.7 *VFI Maturity and Design Maturity*

With an increase in relational contracting, VFI is advanced and Design Maturity is increased, as depicted in Figure 9.13.

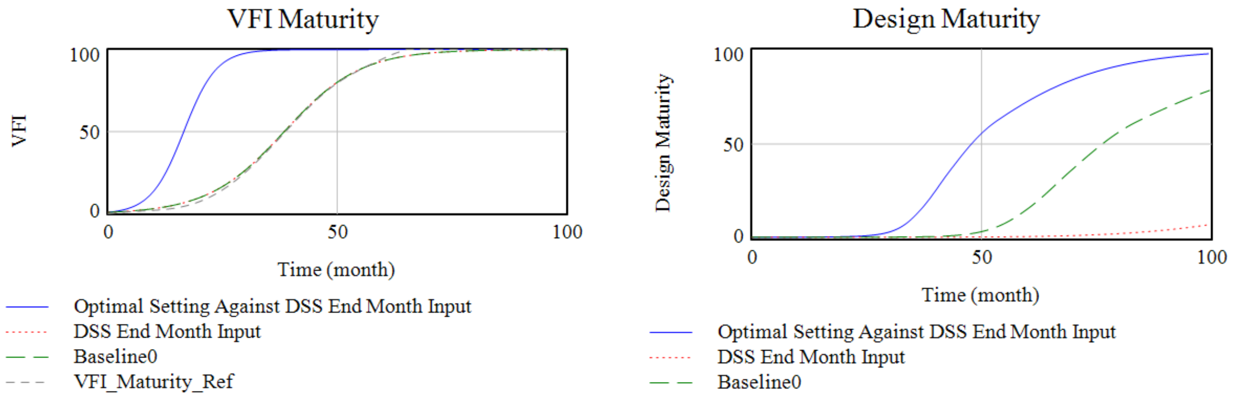


Figure 9.13. Increased VFI and Design Maturity

9.6.4.1.8 *Work Performance and SPI*

With advanced VFI, early knowledge and reduced changes, rework is reduced and SPI increased, as depicted in Figure 9.14.

9.6.4.1.9 *Organizational Integration and Learning Culture*

As depicted in Figure 9.15, with increased gaming intensity, the level of organizational integration is increased. With increased gaming intensity and advanced knowledge, learning culture is increased.

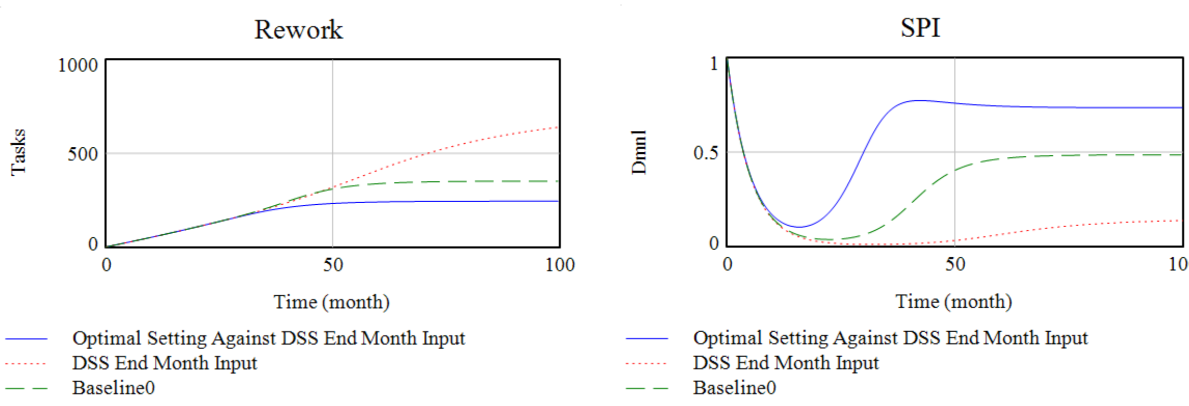


Figure 9.14. Rework Reduced and SPI Increased

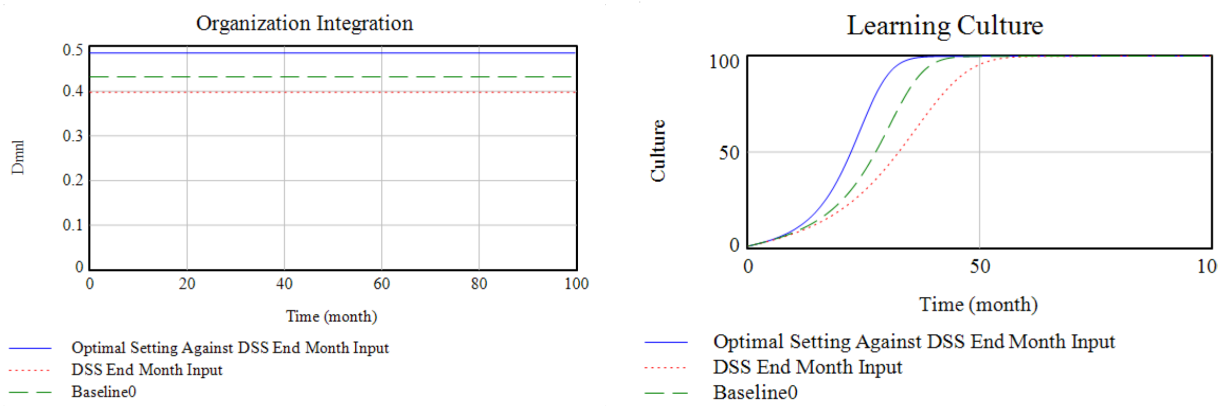


Figure 9.15. Increased Organizational Integration and Advanced Learning Culture

9.6.4.2 *SD Model Sensitivity Analysis*

Sensitivity analysis was performed through use of the Vensim® software associated feature. This is achieved through identification of key policy and process improvement lever parameters and output variables of interest. The focus in the current study is on advancing the Knowledge curve and moving the Ease-of-Change curve up in order to reduce costs, reduce schedule delays and to better accommodate design changes and technology insertion. The key policy levers for reducing costs and schedule delays are gaming intensity and colocation, both have similar effectiveness on output variables. The key lever for accommodating design changes is the application of engineering principles.

The output variables of interest affected by gaming intensity are knowledge, SPI, and incurred design costs. The output variable of interest affected by application of engineering principles is ease-of-change.

The key policy levers for increasing VFI Maturity are paying early for VFI and increasing relational contracting, both have similar effectiveness on VFI Maturity as well as secondary effects on design maturity and the knowledge level.

The key process improvement lever in moving the Knowledge curve forward in the design cycle is the knowledge management process lever.

The optimal lever parameter level and associated minimum and maximum levels were used for a triangular distribution with 200 iterations of random values as part of the sensitivity analysis. In the sensitivity charts that follow, the dark denser area represents the more populated 50 percentile.

The sensitivity analysis for the lever of gaming intensity and its effect on knowledge is depicted in Figure 9.16.

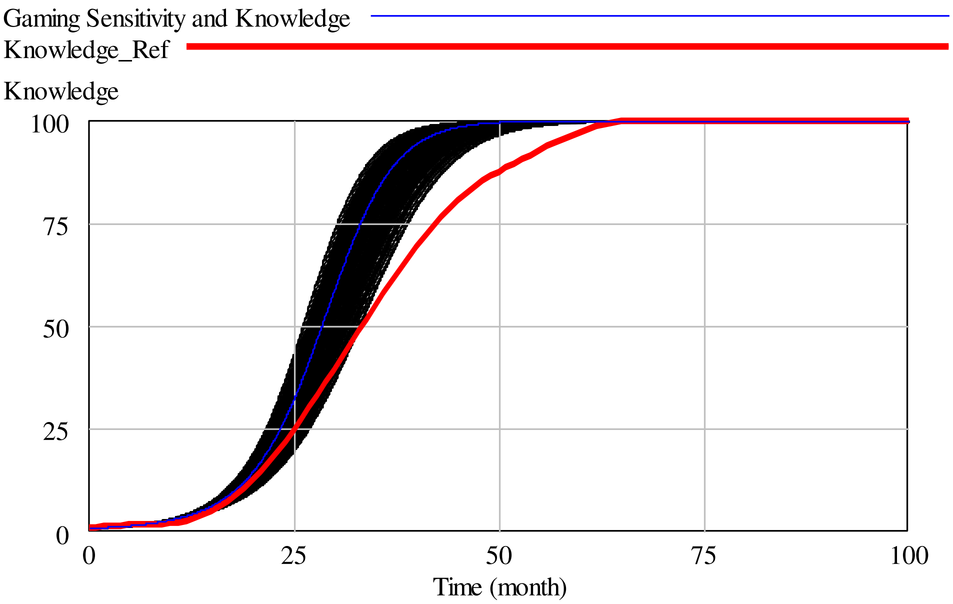


Figure 9.16. Sensitivity of Gaming Intensity Lever and Knowledge

The sensitivity analysis for the lever of knowledge management process maturity and its effect on knowledge level is depicted in Figure 9.17.

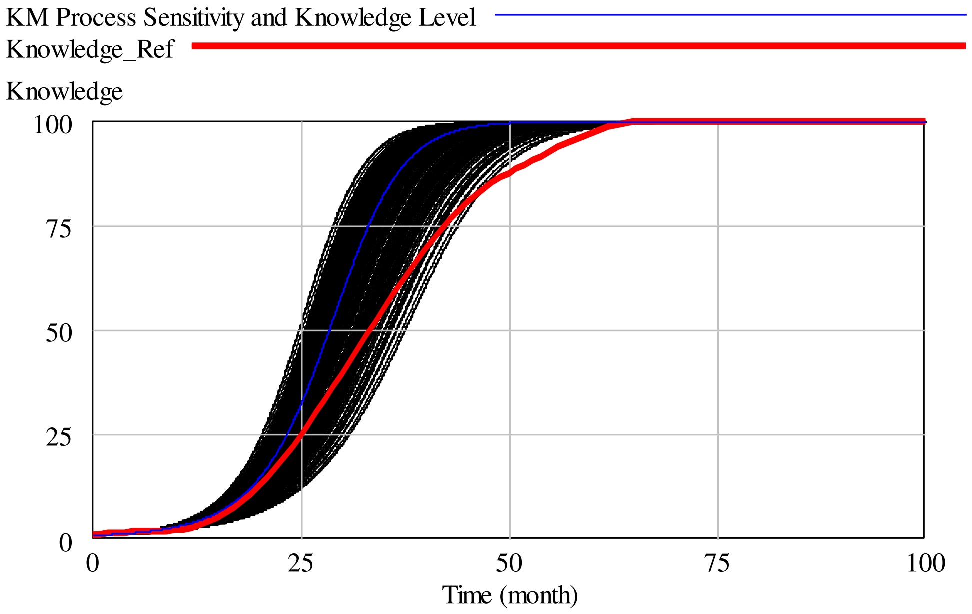


Figure 9.17. Sensitivity of Knowledge Management Process Improvement Lever and Knowledge

The sensitivity analysis for the lever of application of engineering principles and its effect on ease-of-change is depicted in Figure 9.18.

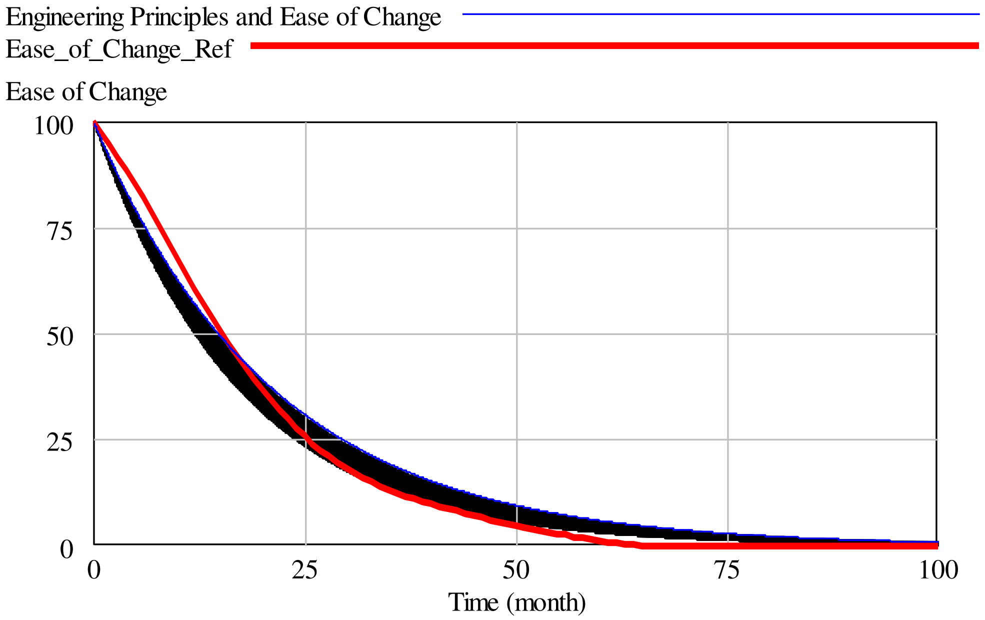


Figure 9.18. Sensitivity of Engineering Principles Lever and Ease-of-Change

The sensitivity analysis for the lever of gaming intensity and its effect on design change costs incurred is depicted in Figure 9.19.

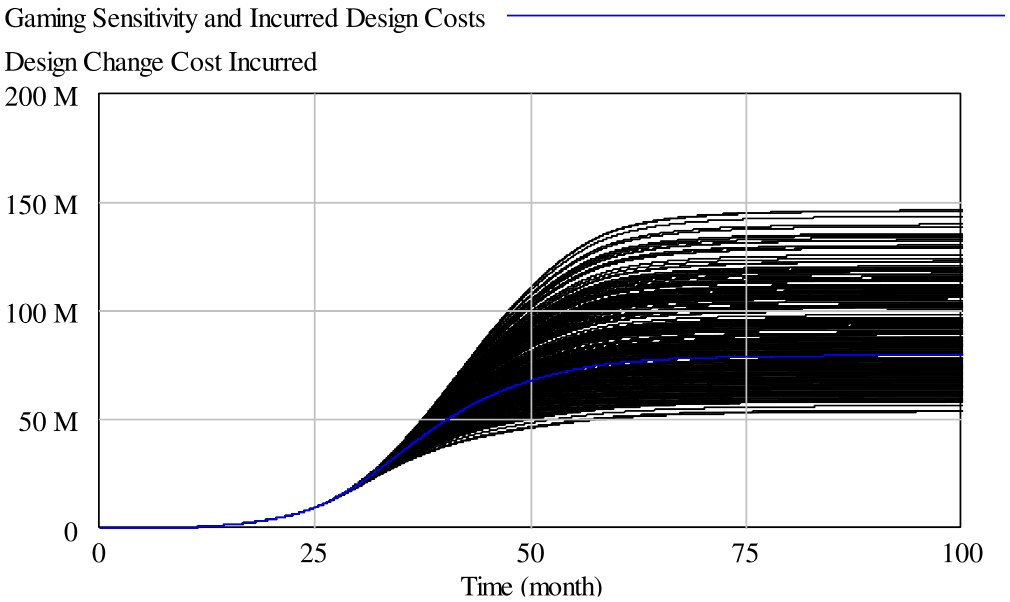


Figure 9.19. Sensitivity of Gaming Intensity Lever and Design Change Costs Incurred

The sensitivity analysis for the lever of relational contracting and its effect on VFI Maturity is depicted in Figure 9.20.

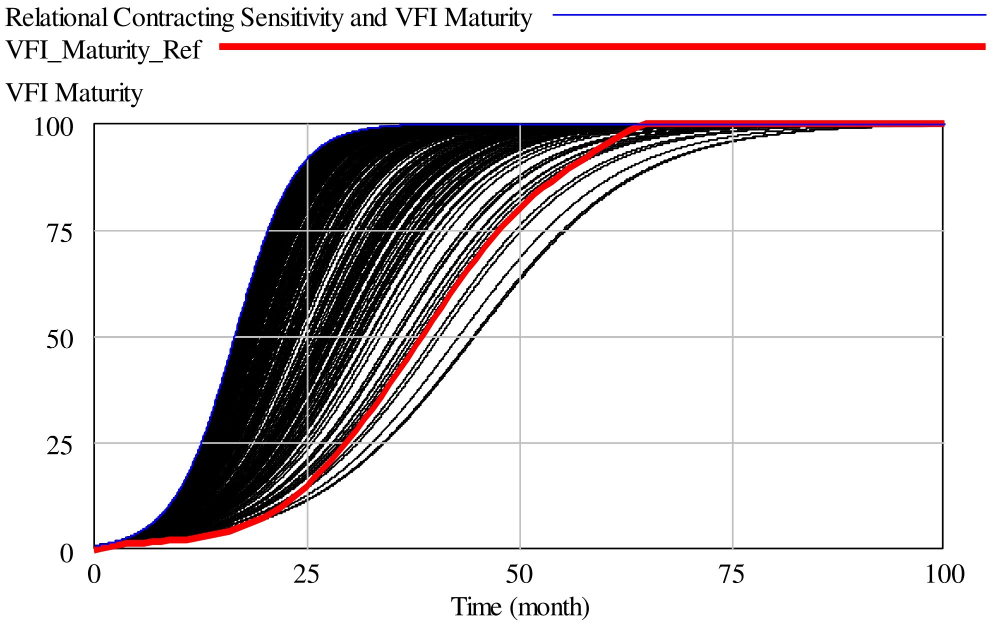


Figure 9.20. Sensitivity of Relational Contracting Lever and VFI Maturity

The sensitivity analysis for the lever of gaming intensity and its effect on SPI is depicted in Figure 9.21.

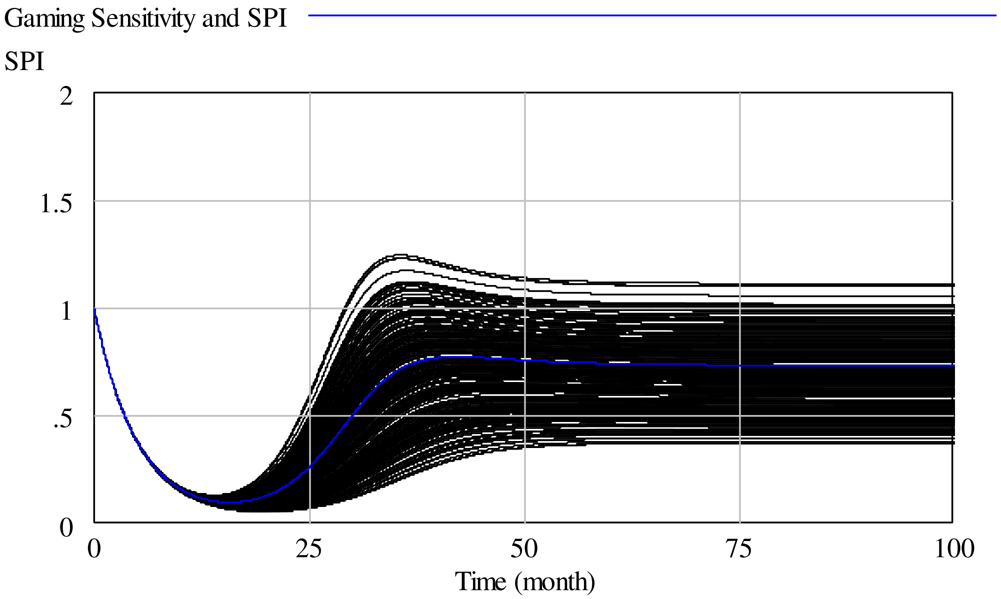


Figure 9.21. Sensitivity of Gaming Intensity Lever and SPI

9.7 Validation of Model Benefits

The simulator working prototype was presented at the INCOSE IW2020 workshop on MBSE with 28 PM and SE members participating in the survey following the presentation.

The purpose of the INCOSE PM-SE integration working group is to identify and promote opportunities associated with the effective integration of SE and PM disciplines. This includes exploring the linkages necessary to create effective integration and collaboration between these disciplines. One of the goals of the group is to bring external thinking into the SE and PM communities to facilitate thinking outside of the box [133].

Common themes for integration requirements were translated into survey questions, as listed in Table 9.9. These eleven questions pertain to the purpose, requirements, and potential benefits from using the simulator in the real world.

Table 9.9. Survey Questions Related to Integration Requirements and Benefits

Q	How do you rate (*Low 1 to Very High 5*) the potential of the Management Flight Simulator to:
Q1	Improve Communication and Collaboration?
Q2	Increase early Knowledge, Learning and provide Mental Models?
Q3	Proactively address risks and promote a Risk Management culture?
Q4	Promote learning and application of Systems Engineering and its models?
Q5	Provide different Perspectives for addressing Complexity?
Q6	Enhance Tradeoff Analysis and Optimize design change Decisions?
Q7	Increase Product Quality?
Q8	Improve Project Performance and foster Continuous Improvement?
Q9	Address techno-socio-economic and cultural factors?
Q10	Represent real world systems, predict and analyze behavior?
Q11	Advance the field of Systems Engineering and Project Management integration?

The response to these questions is based on a rating from low (1) to very high (5) in terms of satisfying the integrated approach and ability of the flight management simulator to meet key integration requirements. This satisfaction scale takes the form of low (1), somewhat (2), moderately high (3), high (4) and very high (5), in accordance with the widely used Likert scale. In assessing the responses to the survey, statistical analysis is performed.

From the survey, the response for each question is analyzed for the statistical measures of mean, mode, standard deviation, and variance. As well, the 95 percent confidence interval around the mean and hypothesis validation criteria are tested.

The eleven questions are also grouped in accordance with implicit integration requirements and associated system dynamic relationships and influencing factors. The groups of questions are listed in Table 9.10.

Table 9.10. Grouping of Survey Questions

Question Group	System Dynamic Related Entities	Survey Question – Integration Requirement – Benefit
Group 1: Knowledge Management	Knowledge Use	Q1 Communication and Collaboration (Gaming and Teaming)
	Knowledge Gain	Q2 Early Knowledge and Learning
	Learning Culture Rate	Q4 Promotes Learning and Application of SE Tools
Group 2: Risk and Strategy Management	Active Risks	Q3 Proactive Risk Management
	Strategy Generation	Q5 Perspectives to Address Complexity
		Q6 Enhance Tradeoff and Decision-Making
Non-Group Distinct Questions	Error Rate and Ease-of-Change Depletion (Technical)	Q7 Increase Product Quality
	Error Rate	Q8 Improve Project Performance
	Ease-of-Change Depletion, Costing Changes, Learning Culture Rate	Q9 Address techno-socio-economic-cultural factors
	Practical integrated model with case study for credibility	Q10 Represent Real Systems
	Set-Based Design, Agile approach and a practical integrated model	Q11 Advance PM-SEI Field

9.7.1 *Statistical Results For The Eleven Questions*

The mean, mode, standard deviation, and variance values for each of the eleven questions are depicted in Figure 9.22.

The top three, highest mean, responses are related to the ability of the simulator to: Q5 (provide different perspectives to address complexity), Q6 (enhance tradeoff analysis and optimize design change decisions), and Q11 (advance the field of project management and systems engineering integration).

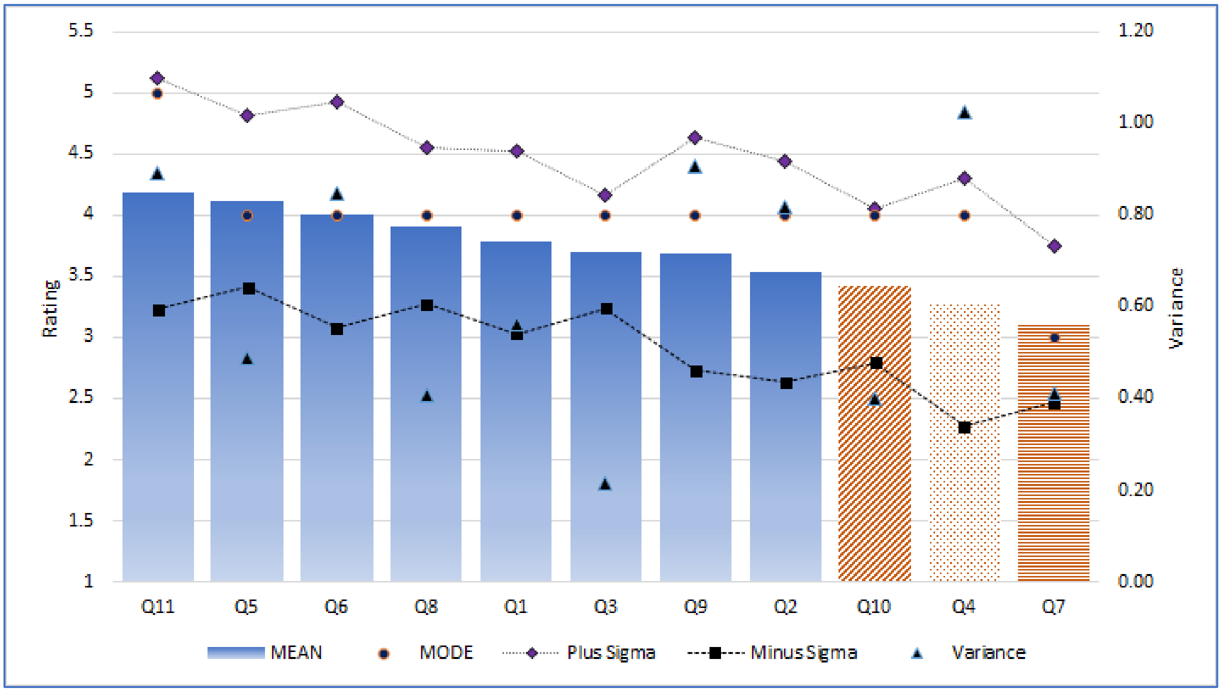


Figure 9.22. Statistical Measures for The Eleven Survey Questions

Of these responses, Q5 has the lowest variance and standard deviation. Providing different perspectives can allow for team members to gain an appreciation of other team concerns. Of note in a separate survey, over half of organizations expressed doubt in their ability to manage complexity [134].

In the top 5 for highest mean value is Q1 (improve communication and collaboration). This question addresses the importance of communication in gaining knowledge and reducing project and design change costs. In a separate study, it was noted that two-thirds of all design changes could be prevented through better communication and integration [65].

In the current survey, Q3 (proactively address risks and promote a risk management culture) has the lowest variance and standard deviation of all questions. This question is related to the fact that many organizations continue to react to problems and lack proactive risk management [5]. Within the proposed simulator, risks are proactively managed, system knowledge is gained, design attributes managed, and design changes played out in the form of what-if scenarios where the impact is predicted.

The bottom three, lowest mean, responses are related to the ability of the simulator to: Q4 (promote learning and application of Systems Engineering and its models), Q7 (improve product quality), and Q10 (represent real world systems, predict and analyze behavior). Of note, Q4 has the highest variance and standard deviation of all questions. As noted in a separate survey, only three percent of high technology organizations use model-based systems engineering tools to capture data and only 29 percent use a MBSE approach [130]. In the same survey, the quality of great models most difficult to achieve in MBSE was noted as model credibility. The response to Q10 in the current survey reinforces this challenge in achieving model credibility.

In Chapter 3, assessment and success criteria for integrated models were adopted for the simulator in the current study. This included accessibility, accuracy and efficiency in these models. By meeting these criteria, it may be inferred that Q4 and Q10 may have been scored differently. Improving use of the simulator in this respect can help decision makers avoid resorting to shifting-the-burden and quick decisions.

As depicted in Figure 9.23, a SD model was developed to show the effect of improving ease of use of the simulator.

In this model, two balancing loops (B1, B2) act to reduce change problems. In resorting to quick intuitive decisions within a stressful, time-constrained environment can lead to side effects and a vicious problem reinforcing loop (R1).

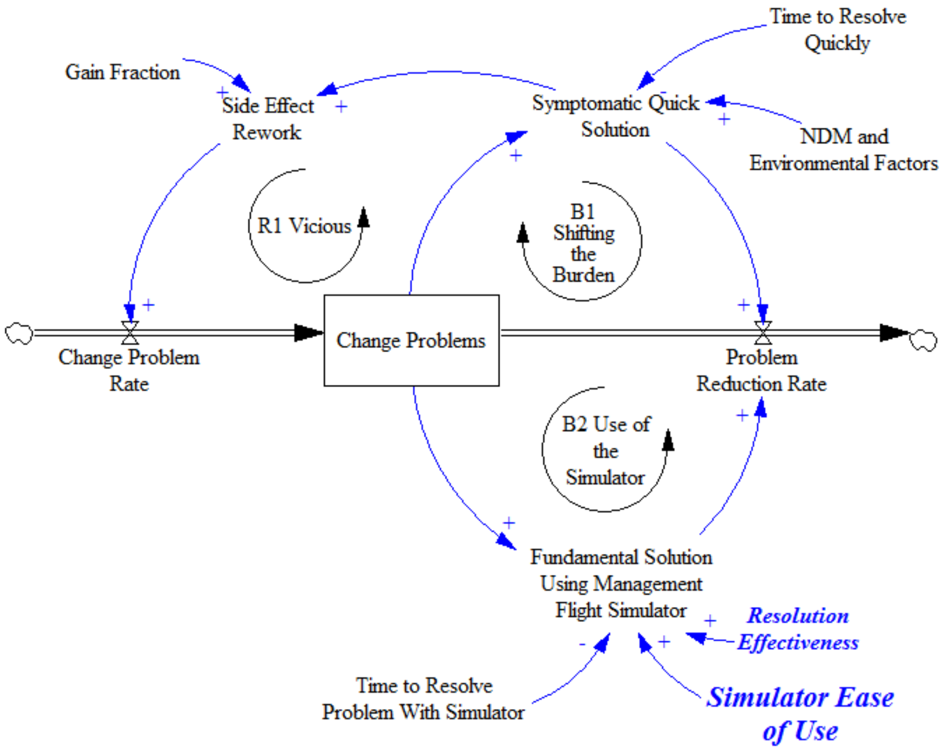


Figure 9.23. Promoting Use of The Simulator and Avoiding Shifting-The-Burden

As depicted in Figure 9.24, the result can be an increase in rework. On the other hand, promoting simulator ease of use can lead to long-lasting better decisions with fewer recurring problems and rework.

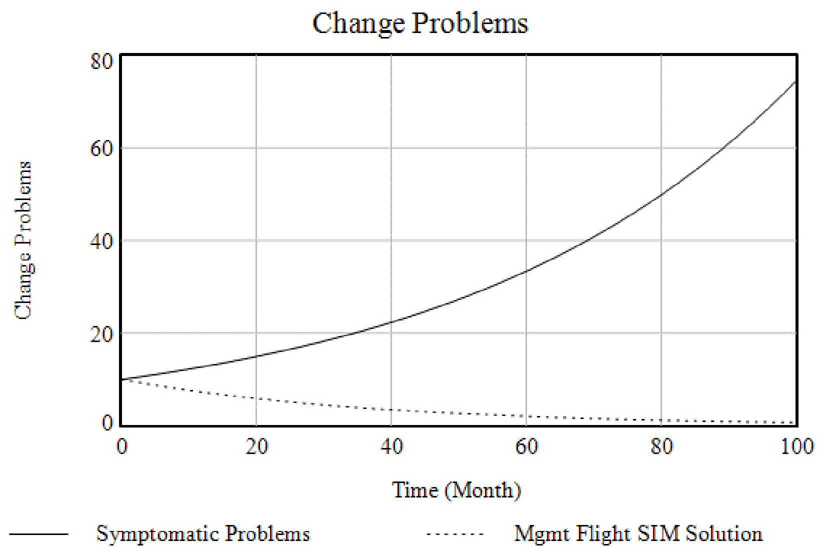


Figure 9.24. Fundamental Solutions Using the Simulator versus Symptomatic Solutions

The 95 percent confidence interval around the mean values for each survey question is depicted in Figure 9.25.

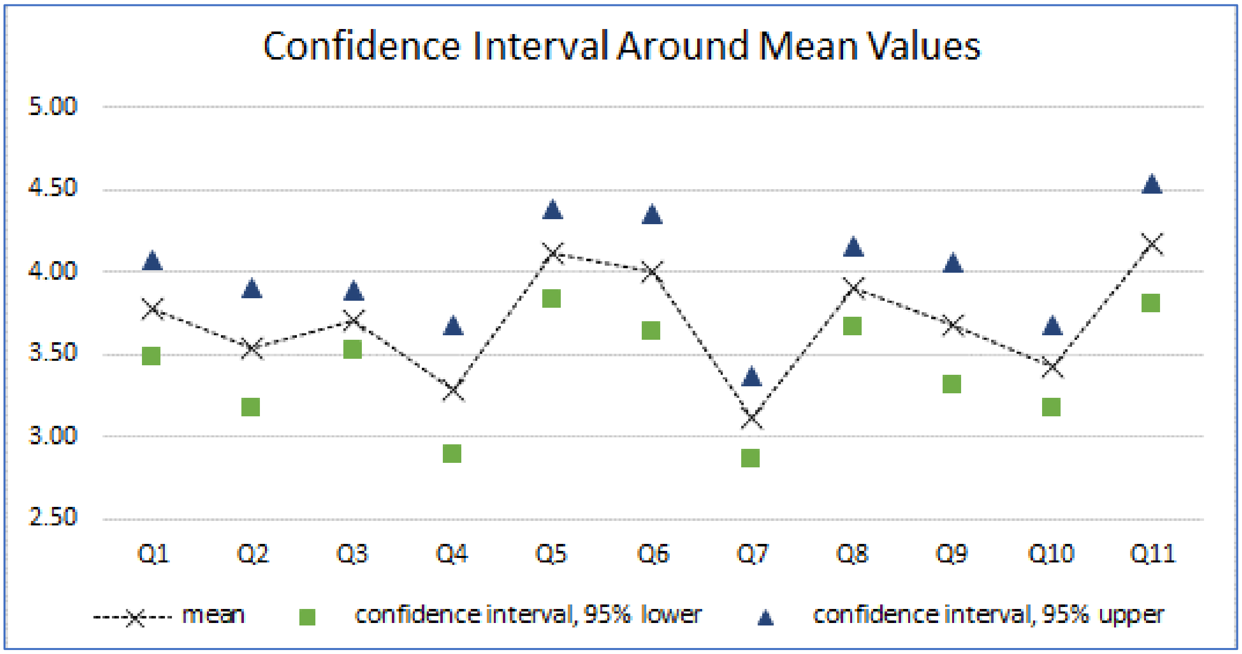


Figure 9.25. Confidence Intervals Around Mean for The Eleven Survey Questions

The narrowest confidence interval is for Q3 (proactively address risks and promote a risk management culture), from 3.52 to 3.89 around a mean value of 3.70. The widest confidence interval is for Q4 (promote learning and application of Systems Engineering and its models), from 2.89 to 3.68 around a mean value of 3.29.

The contribution of responses within quartiles for the eleven questions is depicted in Figure 9.26.

The highest 25th to 75th percentile from 4.0 to 5.0 pertains to the ability of the simulator to address: Q5 (provide different perspectives to address complexity) and Q11 (advance the field of project management and systems engineering integration).

The lowest 25th to 75th percentile from 2.2 to 4.0 pertains to the ability of the simulator to address Q4 (promote learning and application of Systems Engineering and its models).

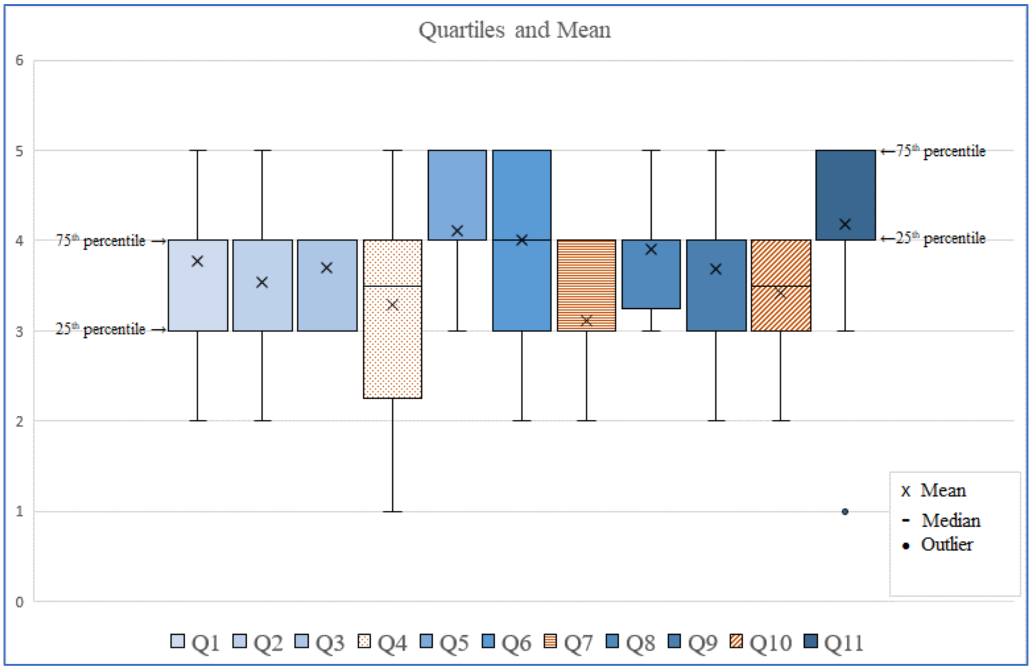


Figure 9.26. Quartiles and Mean for The Eleven Questions

All responses to questions fall within ± 3 sigma except for Q11 (advance the field of systems engineering and project management integration), as depicted in Figure 9.27.

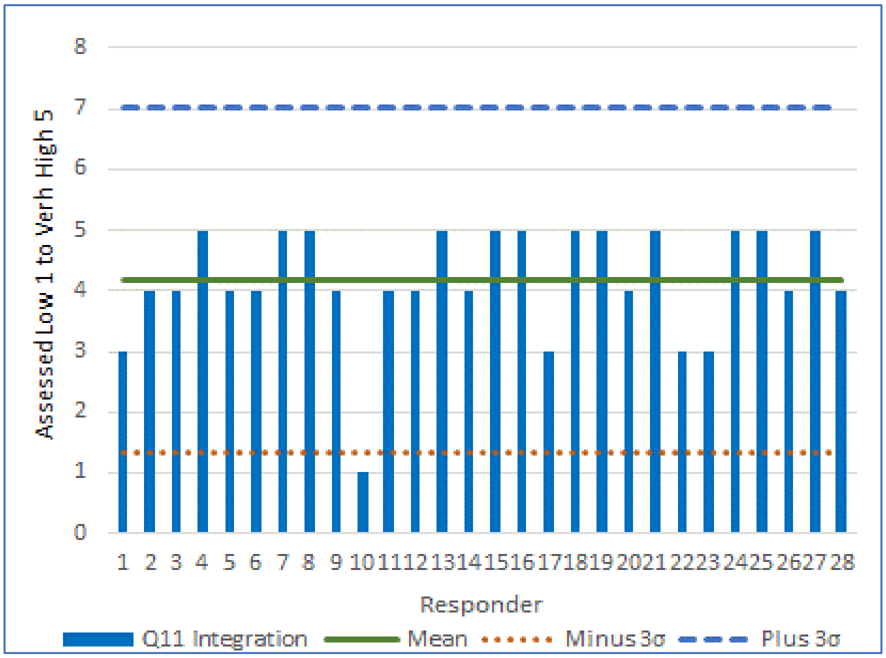


Figure 9.27. Question Number 11 Respondent Ratings

The histograms for the eleven questions are provided in Appendix E. These histograms depict the contribution of responses according to rated values. Of interest is the contribution to ratings greater or equal to 3.0 where the null hypothesis might be accepted.

For the eleven questions and responses, the null hypothesis H_o of a population mean μ of at least 3.5 (70 percent) is validated using the *t* test statistic for samples of less than 30 observations. With the possibility of this hypothesis being rejected for one or more questions, a second and third null hypothesis are formed to investigate a range of potential population mean values, these include a population mean of 3.25 and 3.75 on the scale of 1 to 5. The results for these hypotheses are provided in Table 9.11.

Table 9.11. Testing of Null Hypotheses for Expected Population Mean Values

Measure	Q1	Q2	Q3	**Q4**	Q5	Q6	**Q7**	Q8	Q9	**Q10**	Q11
Critical *t* at *p* 0.05	-1.706	-1.708	-1.706	-1.703	-1.706	-1.706	-1.706	-1.703	-1.706	-1.706	-1.703
1st Hypothesis Population Mean	3.50	3.50	3.50	3.50	3.50	3.50	3.50	3.50	3.50	3.50	3.50
Computed Sample *t*	1.92	0.22	2.27	-1.12	4.55	2.82	-3.15	3.40	1.01	-0.61	3.80
Accept/Reject Hypothesis	Accept	Accept	Accept	Accept	Accept	Accept	Reject	Accept	Accept	Accept	Accept
2nd Hypothesis Population Mean	3.25	3.25	3.25	3.25	3.25	3.25	3.25	3.25	3.25	3.25	3.25
Computed Sample *t*	3.65	1.63	5.07	0.19	6.41	4.24	-1.13	5.47	2.37	1.45	5.20
Accept/Reject Hypothesis	Accept	Accept	Accept	Accept	Accept	Accept	Accept	Accept	Accept	Accept	Accept
3rd Hypothesis Population Mean	3.75	3.75	3.75	3.75	3.75	3.75	3.75	3.75	3.75	3.75	3.75
Computed Sample *t*	0.19	-1.19	-0.52	-2.42	2.69	1.41	-5.18	1.33	-0.35	-2.67	2.40
Accept/Reject Hypothesis	Accept	Accept	Accept	Reject	Accept	Accept	Reject	Accept	Accept	Reject	Accept

For the first null hypothesis where the population mean is 3.5 (70 percent), only the response to question 7 is rejected. This question pertains to the ability of the management flight simulator to improve product quality.

In the current study, the set-based design approach, Ease-of-Change management curve, rework and error rate relationships address product quality. While these relationships are captured within the simulator and system dynamics sub-model, demonstration of these aspects was not provided at the working group given time constraints. Product quality remains an important requirement for project management and systems engineering integration. It has been noted that rework and changes can consume 30 to 70 percent of the design effort [4].

In investigating an expected population mean where the sample mean for question 7 might be accepted, a second null hypothesis is formed for a lower expected population mean of 3.25. In this case, all sample means support acceptance of the null hypothesis.

A third null hypothesis was formed for a higher expected population mean of 3.75 (75 percent). In this case, the sample mean values for questions 4, 7 and 10 are rejected.

9.7.2 *Statistical Results For Groups of Questions*

Questions were grouped into the categories of knowledge and risk and strategic management. These categories are key components and enablers within the simulator.

Statistics and results from the ‘z’ distribution testing of the null hypothesis for the two groups of questions are listed in Table 9.12.

Both groups of questions fall within the null hypothesis acceptance region where a population mean of at least 3.5 can be expected.

Table 9.12. Statistics and Null Hypothesis Testing for Two Groups of Questions

Measures	Group 1 Knowledge (Q1, Q2 and Q4)	Group 2 Risks-Strategies (Q3, Q5 and Q6)
sample size	81	81
Mean	3.53	3.94
Mode	4	4
sample standard deviation	0.91	0.73
sample variance	0.83	0.53
confidence interval, 95% lower	3.33	3.78
confidence interval, 95% upper	3.73	4.10
critical z at *p* 0.05	-1.65	-1.65
Hypothesis population mean	3.50	3.50
Computed sample *z*	0.31	5.40
Accept/Reject Hypothesis	Accept	Accept

The contribution of responses within quartiles for the two groups is depicted in Figure 9.28.

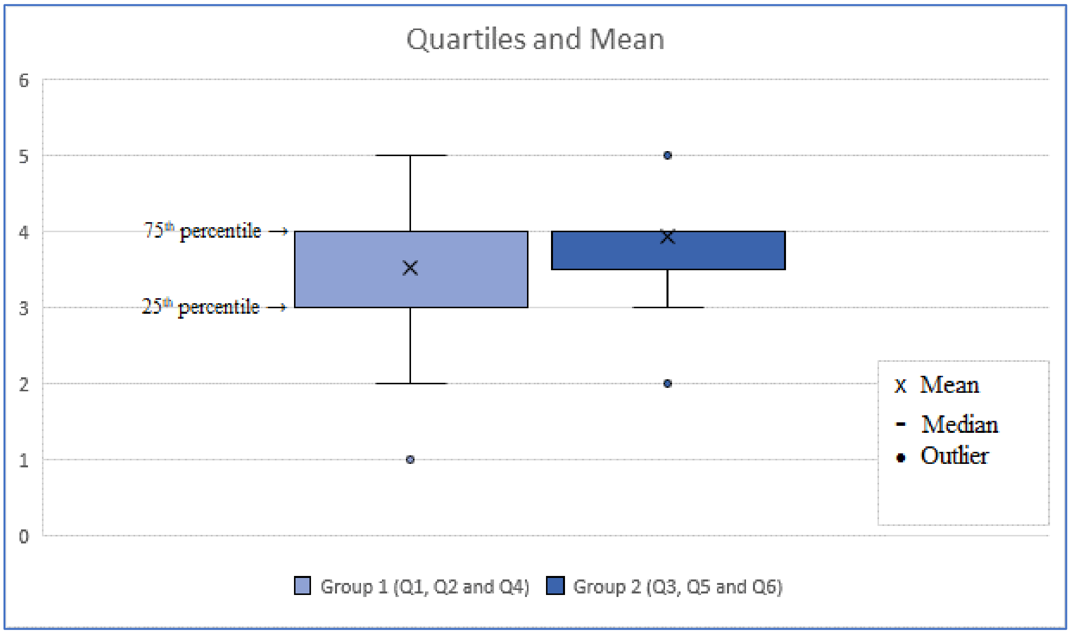


Figure 9.28. Quartiles and Mean Values for The Two Groups of Questions

The histograms for these two groups of questions are provided in Appendix E.

9.7.3 *Demographics of Respondents and Statistical Results*

When assessing the responses to the eleven questions, the PM versus SE discipline composition of the working group is of interest in terms of determining consensus in their responses. In distinguishing between these two fields, the composition of the working group was estimated from individual job titles. From this estimate, 71 percent of respondents were SE, while 29 percent were SE.

As depicted in Figure 9.29, there is strong cross-discipline consensus in the ability of the simulator to: Q3 (proactively address risks and promote a risk management culture) and Q5 (provide different perspectives for addressing complexity).

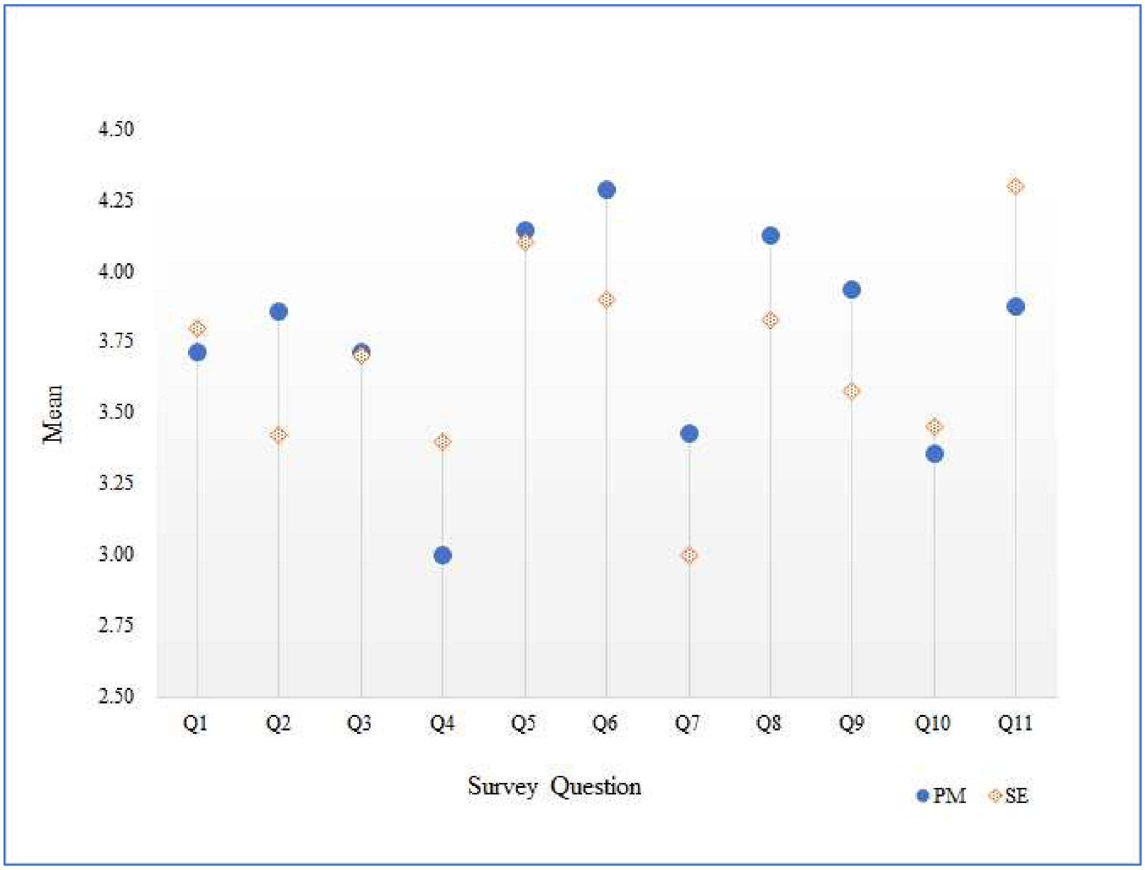


Figure 9.29. SE versus PM Responses to The Eleven Survey Questions

Also, of interest is any disparity between executives, managers and specialist among respondents. The composition of this group consists of 28 percent executives, 29 percent managers and 43 percent system engineers.

As depicted in Figure 9.30, executives rated several questions higher than did others, they rated Q3, Q6, Q8 and Q9 higher. These questions include aspects of risk management, decision-making, program performance, techno-socio-economic and cultural factors. These questions appear to be more orientated and of interest to executives and top management.

Managers rated Q7 higher than did others, this question pertains to the ability of the simulator to improve product quality.

System engineering specialists rated Q4, Q10 and Q11 higher than did others. These questions include promoting learning, SE tools, representation of real systems and advancing the field of PM and SE integration.

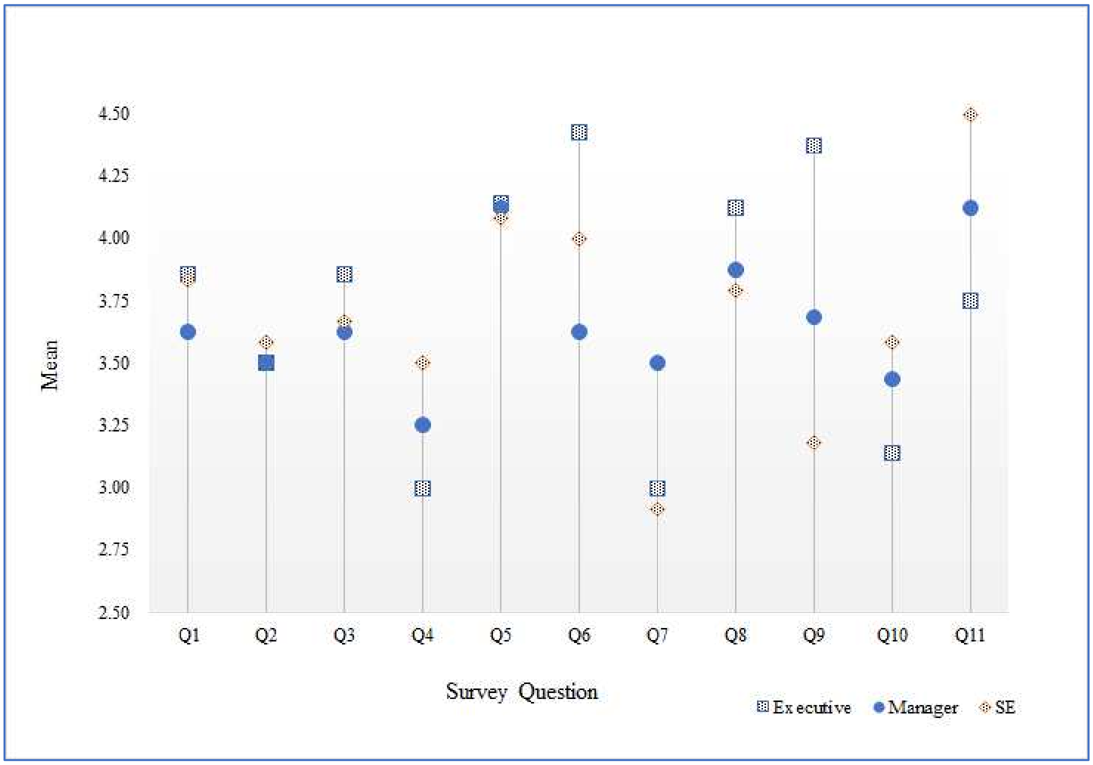


Figure 9.30. Different Roles and Responses

9.7.4 *Additional Feedback From Respondents*

From the free text additional feedback portion of the survey, perceived advantages, disadvantages, proposed improvements, and follow-up questions are listed in Table 9.13.

Table 9.13. Additional Narrative Feedback From Survey Respondents

Advantages	Viewed as worthwhile in working toward defining knowledge maturity
	Potential to show many complex aspects of a project and its interrelationships
Disadvantages	Skill level to use simulator viewed as one step below management
	Two respondents had difficulty seeing real world application
Proposed Improvements	Customize views to respective teams for better communication
	Link outputs to management reports
Follow-up Questions	Would like to see underlying connections within model
	Would like to better understand levers and their impact
	Would like to see connection to SysML and MBSE
	Would like see how model would work within an agile project

At the end of the presentation at INCOSE IW2020, follow on questions and author responses are provided in Table 9.14.

Table 9.14. Additional Oral Feedback From Survey Respondents

End of Session Questions and Comments	Presenter Response
How would one know which levers to adjust? Perhaps optimization of levers could be looked at.	A sensitivity analysis was conducted to determine the most effective levers. The comment with respect to optimization of levers has been considered as future work with the model providing augmented intelligence.
How can the results in the model be trusted?	The use of several sub-models provides cross-validation and credibility where over time, fidelity of the simulator should increase.
How can the simulator improve project management?	The simulator system dynamics sub-model with its management curves provides for a different perspective on project performance predictive measures compared to traditional earned value management (EVM) passive measures.
Will teams provide true social network analysis (SNA) input measures?	As members of a team, anonymous input should represent true SNA input values but

	agreed that culture may have a negative impact.
Is the simulator applicable to other generic systems and is it scalable?	Yes, the decision support system (DSS) design attributes for a number of systems can aggregate up into a higher-level system-of-systems (SoS) architecture and DSS.

9.7.5 *Summary of Validation Activities Against Simulator Elements*

The simulator elements have been mapped to key integration requirements, as listed in Table 9.4. The validation activities against the simulator elements are summarized in Table 9.15.

Table 9.15. Summary of Validation Activities Against Simulator Elements

Management Flight Simulator Elements	Item Validated	Validation Activity	Date	Chapter Artifact	Validation Comments
	Ability of Management Flight Simulator to Meet Requirements	Presentation to IMP Aerospace Sr VP Engineering, Teleconference with Boeing Sr Project Manager, and INCOSE IW2020 Survey.	Sep 19, Oct 19 and Jan 2020 respectively	Chp 9 IW2020 Validation Results and Appendix E	https://www.incose.org/iw2020/program/mbse-initiative
SNA	SNA Survey	Survey with west-coast Vancouver Shipyards through the Senior Program Manager.	Nov-18	Tables 4.1, 4,2 and Figures 4.6 and 4.7, Appendix C	Limited to one SNA type, could investigate other types of SNA such as competency
DSS General	Information and Design Change Process	Survey with west-coast Vancouver Shipyard through the Senior Program Manager, Presentation at SysCon 2017.	11/18/2020 and Apr 2017	Table 5.2 Results, Information and Change process issues validated in survey, positive response from SysCon	https://ieeexplore.ieee.org/document/7934781

MATE	IPS Case Study Components	Self-Check, Attribute and Cost Sensitivity Analyses validated a robust selected design. Validation of MATE new value space approach at smc 2017 conference.	10/1/2018 and Oct 2017 smc conference	Chp 2, and Appendices A & B. positive response from smc 2017	https://ieeexplore.ieee.org/document/8122788
Set-Based Robust Design	Approach	Literature Review	2018	Figure 3.19 Figure 5.6	Could validate with other subject matter experts
DSM	Approach to Linking DSM to Changeability Chart	Literature Review	2017	Tables 3.5 to 3.12 incl., and Figure 3.16	Novel link of SRM-DSM and Changeability Chart could be further validated
SRM	Typical Design Changes	Literature Review, Interview with east-coast Irving Shipyard VP Operations, Interview with eastern Davies Shipyard VP Contracts, Telecons with GE Power Director and Quebec Hydro Director.	Nov-Dec 2017	Table 3.3 Figure 3.15	Novel link of SRM-DSM and Changeability Chart could be further validated
SRL	Approach	Literature Review	2016	Figure 3.20	Nil
PMM	Approach	Literature Review	2019	Table 6.1	Nil
SD Model Curves General		Presentation at SysCon 2019	Apr-19	Positive Response from SysCon	https://ieeexplore.ieee.org/document/8836740
Knowledge Curve	Model Structure and Behaviour Validation	Vensim® software checks and sensitivity analysis	2018-2019	Chp 9 and Appendix D	Needs further investigation in relating Knowledge to Commitments curve

Ease-of-Change	Model Structure and Behaviour Validation	Vensim® software checks and sensitivity analysis	2018-2019	Chp 9 and Appendix D	Limited influence of Ease-of-Change on Commitments, could investigate other relationships
Commitments Curve	Model Structure and Behaviour Validation	Vensim® software checks and sensitivity analysis	2018-2019	Chp 9 and Appendix D	Needs further investigation in relating Knowledge to Commitments curve
Costs-Incurred Curve	Model Structure and Behaviour Validation	Vensim® software checks and sensitivity analysis	2018-2019	Chp 9 and Appendix D	Typical Costs/Change used, needs validation with actual costs
IPS Case Study	Functionality within DSS	Self-check, Presentation to east-coast Irving Shipyard VP Engineering, and Mari-Tech Conference Presentation.	Sep-18	Chp 3, Positive Response from presentation and conference	http://mari-tech.org/mari-tech-2017-home/program-mt2017/

9.8 Conclusion

Multi-discipline integration principles and information integration criteria and objectives were addressed in development of the simulator. Its functionality was validated through a IPS case study, design change scenarios, verification of SD sub-model behavior, and interviews with SME's.

With adjustment to a few levers, knowledge can be gained early in design and system ease-of-change increased, leading to reduced design change costs and schedule delays. Other management curves positively influenced by adjusted levers include the number of design changes, design maturity, schedule performance, learning culture, and the knowledge gap.

From the statistical analysis of the eleven questions posed at INCOSE IW2020, Q7 (improve product quality) caused the null hypothesis of an expected population mean of 3.5 to be rejected. All other questions supported this null hypothesis. The value of 3.5 represents moderately high compliance on a scale from 1.0 to 5.0.

The top three, highest mean, hypothesis compliant responses are related to the ability of the simulator to: Q5 (provide different perspectives to address complexity), Q6 (enhance tradeoff analysis and optimize design change decisions), and Q11 (advance the field of project management and systems engineering integration).

Of all questions, the response to Q3 had the lowest variance, lowest standard deviation, narrowest confidence interval, and highest cross-discipline consensus in the ability of the simulator to proactively address risks and promote a risk management culture. All responses to this question were at a rating of 3 or 4, with a mean value of 3.70 (moderately high to high).

Q1 (improve communication and collaboration) had the fifth highest mean value response. This integration requirement is viewed as an important aspect to the management flight simulator for gaining knowledge, reducing design change costs and in achieving integration.

Chapter 10 – MBSE, The Management Flight Simulator and The Enterprise System

10.1 Introduction

MBSE was introduced in Chapter 2 as a viable option to describe systems and their behavior to various stakeholders. At the same time, MBSE was not viewed as appropriate for initial development of the management flight simulator as a prototype. Nevertheless, it is of value to discuss the merits of MBSE and where it may fit within the context of the simulator as well as within enterprise systems. The INCOSE Vision 2020 defined MBSE as:

"the formalized application of modeling to support system requirements, design, analysis, verification and validation activities beginning in the conceptual phase and continuing throughout development and later life cycle phases." [7].

The focus of MBSE appears to be on managing information about product requirements and specifications, this includes taking a modeling approach over a document-centric approach. As well, systems engineering processes are viewed as the foundation of MBSE.

In the current study, a similar approach is taken with application of the management flight simulator. However, instead of requirements, design attributes that are inherently linked to IPS functional and non-functional requirements are managed. In this approach, both systems engineering and project management cross-functional processes are viewed as foundational to development of the management flight simulator.

The integration requirements for the management flight simulator are also discussed in this chapter as they relate to the requirements traceability aspect of MBSE. The hierarchy of requirements for the simulator were discussed in Chapter 9 as part of requirements verification. In the current chapter, key requirements that link to element groups within the simulator are presented. These groups are derived from clusters within the N^2 diagram that was presented in Chapter 7.

MBSE may also be viewed as a universal language and best practice for managing complexity and optimizing delivered capabilities [135]. In the current study, the management flight simulator and design change response strategy are also viewed as enablers for managing complexity and optimizing delivered capabilities.

There are several similarities and differences between both approaches that are discussed in this chapter.

10.2 Motivation

With increasingly complex projects comes an increase in the amount of information including both technical and project performance type information. With this, engineers can spend a significant portion of their time searching for information. Moreover, with disparate tools and sources for managing information, there can be inconsistency in system requirements, specifications and in the tracking of design changes.

MBSE has attracted attention as a tool to help manage complexity and requirements traceability during product development. It is an approach that is focused on the evolving product, its information and can be the source of truth about the system [136].

The extent of alignment between MBSE to the current study and the management flight simulator may be of value to investigate as part of a broader integrated enterprise model perspective.

10.3 Background

While engineering models have a long history, MBSE is relatively new and goes back to the 1990's with the introduction of mathematical models for the coupling of systems and the connection of requirements [136]. More recently, MBSE involves requirements elicitation, trade studies and verification and validation activities throughout the system's lifecycle.

10.3.1 *MBSE*

MBSE may be viewed as the working fluid and language of systems engineering processes including architecting systems, requirements traceability and trade studies [135]. This includes component structures, relationships describing system behavior, rules and principles.

MBSE methodologies can include a collection of related processes, methods and tools to support a specific discipline such as the systems engineer [7].

The department of defense, NASA and the aerospace industry are increasingly using MBSE to better trace needs to requirements and for early tradeoffs of requirements [135].

10.3.2 *MBSE Benefits*

MBSE is known for enhancing the ability to manage information associated with product requirements and specifications [7]. This includes the application of architecting principles in describing the system where requirements are linked to system components within different viewpoints and where requirements may be managed [135].

MBSE has been promoted as an approach to overcome deficiencies in system architecture and challenges early in the design that can lead to downstream challenges [136].

In the management of this information, several benefits can be realized including improved communication, increased ability to handle complexity, improved quality though an unambiguous model, enhanced knowledge capture, and reduced risks and costs through early design analysis [7]. In the current study, these benefits form part of the requirements for development of the management flight simulator.

From a MBSE architecting perspective, benefits include better understanding of the system and issues that can be effective in optimizing costs, schedule and quality.

10.3.3 *MBSE for Replacing Traditional Systems Engineering Documentation*

In the traditional SE document-based approach, information is generated by way of specifications, interface control documents, trade studies, and several reports [7]. The management of this information can be a challenge, especially with complex product management and increasingly more information as the system evolves. In MBSE models, some of this information can be captured using models, architectures and viewpoints.

10.3.4 *MBSE Challenges and Combining Models*

While MBSE is viewed by some as key to reducing costs and improving quality, there are some that see challenges in MBSE substantially integrating sub-systems.

One of the challenges with MBSE is in reaching the wider audience including non-technical stakeholders. This also includes the challenge with MBSE acceptance by systems acquisition and program management communities [136].

In helping non-expert stakeholders understand MBSE, it has been suggested that visualization and experimental views be added where there can be timely and meaningful feedback [136]. In the current study, these experimental views are represented by what-if design change scenarios and visualization of the impact from changes on both technical and program measures.

In a separate survey involving sample sizes between 200 and 1000 participants, only 3 percent use models to capture system data and 29 percent use a MBSE approach [130]. On the other hand, in the same survey 63 percent believed that MBSE was sufficiently mature to warrant adoption.

Rather than starting with a clean sheet using MBSE, most organizations tend to prefer combining existing models together [130]. Reasons include the challenge seen in rebuilding existing models into a clean sheet approach and the use case for MBSE being too specific.

Concerns with combining models include ensuring consistent semantics across models, what quality attributes to include and how knowledge and decisions can be captured [136].

In order to promote and gain acceptance of MBSE, a cultural change may be required that is supported by government, acquisition stakeholders and industry [136]. Moreover, the return on investment from using MBSE must be seen by stakeholders. In supporting a cultural change, the executive leadership may be required in championing efforts for incorporating MBSE as well as the management flight simulator.

In the current study, ease of use, the user experience and automation are viewed as other key enablers for acceptance of models. This can also helping avoid shifting-the-burden away from using better decision-making models where they can take time and effort to use within a turbulent environment.

Providing the right level of automation for the right function of a task can optimize the user's workload and situational awareness. It was found that high levels of automation in information analysis and action implementation can enhance team performance and reduce workload [51]. Furthermore, decision-support systems can reduce biases, but this depends on how the information is represented and how decision-making processes are supported [137].

10.3.5 *MBSE Architecting*

System architecture defines the structure, behavior and other relevant aspects of the system where views are organized to support understanding and reasoning about the system [136]. MBSE architecture can form a baseline configuration as a single source of truth early in the design cycle where the largest solution space exists and where early design decisions can avoid increased costs later in the design cycle. Given this, a rigorous architecture is required early to understand the system and its requirements [136]. This rigor includes showing links between system components and requirements where all requirements are accounted for.

In MBSE architecting, SysML object-oriented software such as IBM Rational Rhapsody and its application is viewed as a best practice tool [7].

The MBSE architecture addresses complexity through decomposition and composition of lower lever components as well as through requirements traceability to components. The abstraction of complex systems through object orientation and MBSE tools can provide underlying patterns and common characteristics.

Similarly, the management flight simulator and its sub-models can provide for attribute and management curve patterns with common linkages between models.

10.4 Context of the Management Flight Simulator, MBSE and The Enterprise System

Team collaboration is an important aspect in decision-making and exchanging the right information across the enterprise system is at the core for effective informed decision-making.

Several systems engineering and enterprise systems may be leveraged for exchanging information across the organization leading to both increased PM-SE collaboration and effective decision-making. As most organizations prefer combining existing models over a clean sheet approach with MBSE, combining enterprise models may make sense for exchanging information.

For manufacturing organizations, this exchange of information includes consideration to models that reside within the value chain of estimating, engineering, planning and scheduling, supply, quality and production. In shipbuilding, product information is often captured in Product

Life-Cycle Management (PLM) and Product Data Management (PDM) systems. Other models are used throughout the value chain. Together, these models often form the Manufacturing Resource Plan (MRP) or Enterprise Resource Plan (ERP) with a philosophy of providing distinct and shared services to both internal and external stakeholders. These enterprise models and services may be described through a Services Orientated Architecture (SOA).

In the current study, the SOA can include both MBSE and the management flight simulator, each providing distinct and complementary services. As previously discussed, data exchange standards and a common taxonomy of terminology are required for the exchange of information across model. This applies to exchanging information between MBSE architecting tools, the management flight simulator and enterprise systems.

10.5 Services Orientated Architecture

Service oriented architecture (SOA) is a paradigm for organizing a set of capabilities that can be distributed across enterprise systems. This set of capabilities or services can be used to solve business problems, and in the case of the current work, design change problems. In SOA, services are made visible to potential users where a series of information exchanges occur. The detailed sequence of actions carried out by the service may involve any number of operations such as database queries, data transformations, execution of models, and formatting of displays [135]. The use of information made available through these operations may be documented through stakeholder analysis and uses cases.

10.6 Stakeholder Roles and Use Cases

For both MBSE and the management flight simulator, stakeholder roles can be common between both applications.

It was also noted that undefined authorities can lead to unproductive tension between PM and SE disciplines [5]. It is important to define the roles in the current study that are associated with use of the management flight simulator. Accordingly, the roles of the systems engineer, project manager and the six cross-functional teams are discussed. The role of trainer or facilitator for both the simulator and agile practices is also discussed.

10.6.1 *Stakeholder Roles*

10.6.1.1 *Systems Engineer Role*

As earlier discussed, the systems engineer can play an integrating role across the organization to support collaboration [1]. In the context of SNA, the systems engineer can act as a boundary spanner between network clusters, an information broker, as well as facilitator in bringing teams together in using decision tools such as the management flight simulator.

10.6.1.2 *Project Manager Role*

The project manager role incudes leading the project throughout its lifecycle. The manager's role includes conflict resolution and the escalation of issues to senior leadership [70].

10.6.1.3 *Six Cross-Functional Teams*

The six cross-functional teams discussed in the current study are the primary users of the management flight simulator for the IPS case study. They span the value chain in a design and manufacturing resource plan (MRP). These teams include the program manager, electrical and mechanical engineers, supply chain management, planning and scheduling, and production. In the context of the current study, representatives from each department may be offered for participating in use of the simulator.

10.6.1.4 *Simulator and Agile Practice Trainer*

To create and sustain an agile approach in use of the simulator, a trainer can help facilitate this. Agile teams focus on rapid development of the product in increments and collaborate in various ways to promote problem-solving. These increments can include the iterative gaming of solutions to change problems.

10.6.2 *Use Cases*

The use case diagram provides a high-level diagram of how stakeholders use of the management flight simulator to achieve goals and objectives including reducing the number of changes, costs and schedule delays. The use case is also part of the universal modeling language (UML) or SysML.

The use case can be a set of activities that the simulator needs to perform. The primary steps for using the management flight simulator are stated within the DSS sub-model and summarized using use cases.

10.7 Requirements Traceability and Element Groups Within the Management Flight Simulator

From the hierarchy of simulator and PM-SE integration requirements discussed in Chapter 9, several were traced to simulator elements. With use of the N^2 diagram in Chapter 7, key simulator requirements can be traced to groups or clusters of elements within the simulator. These groups represent coupled elements along the N^2 diagonal that are dependent on each other through an iterative cyclic process. Other elements within the diagram take on feedback and feed forward sequential characteristics.

The feed forward elements reside in the lower region below the diagonal; the feedback elements reside above the diagonal. Elements within rows are dependent on later occurring feedback elements. In developing the N2 diagram, several iterations were performed in re-organizing elements so that most would reside below the diagonal to achieve sequential feed forward operations. These feedback, feed forward and coupled simulator element groups and their related requirements are provided in the results section of this chapter.

10.8 Results

10.8.1 *Level of Alignment Between MBSE and The Management Flight Simulator*

In comparing benefits of MBSE to what the management flight simulator may offer, there is alignment. As listed in Table 10.1, this alignment includes traceability of attributes within the simulator, a common language, capture of tradeoffs, a tool for communication, knowledge capture, learning of SE fundamentals, and a model for networking and enterprise processes.

The capture of tradeoffs and the impact of design changes is important in the current study. In addressing changes, both MBSE architecting and use of the simulator include the application of engineering principles for a robust design. These principles include modularity of components and loose coupling across module boundaries. This is viewed as a strategy to allow for a flexible design in accommodating changes and in reducing complexity.

Table 10.1. Alignment Between MBSE Benefits and The Management Flight Simulator

MBSE Benefits [7] [135] [136]	Management Flight Simulator	Alignment
Requirements and Specifications Traceability [136]	Attribute management and traceability, inherently linked to requirements.	Partial
Potential as Source of Truth for System Information and system baseline. Ensures consistency in language and terms. Allows for Error Checking. Can reduce costs. [135] [136]	Sub-set of system information and common language. Provides a baseline and trending of design and project attribute levels.	Partial
Different System Architecture Viewpoints for Multiple Stakeholders, the ‘Big Picture’ [135] [136]	System measures and management curves; a different set of views and perspectives.	Partial

Manage complexity through multiple views and manage impact from changes [7]	The DSS, supporting sub-models and SD sub-model provides for different views and interactive UX to help adapt to complexity.	Yes
Allows for Views of 'Instances' for Different Configurations and Trade-offs [135]	Trade-off what-if design change scenarios can be saved.	Yes
Enable communication through understanding of all aspects of the design [7] [136]	Enables PM-SE collaboration and high-level understanding of design.	Yes
Improves quality through unambiguous view and clear understanding of the system [7]	Quality of design through DSS.	Partial
Knowledge capture and reuse of information [7]	Design change scenarios and decisions can be saved within the simulator. The reuse of MATE design variant attribute information serves as a useful reference.	Yes
Improve ability to teach and learn SE fundamentals [7]	The SRM-DSM and SD sub-model provide for SE learning.	Yes
Can use MBSE for networking and enterprise processes [135]	Can use simulator for networking and enterprise processes.	Yes

In comparing typical elements of MBSE to elements within the management flight simulator, there is alignment where elements complement one another, Table 10.2 lists these elements.

Table 10.2. Alignment Between Typical MBSE Elements and Simulator Elements

MBSE Typical Elements [135]	Management Flight Simulator Elements	Alignment
Methods, tools and processes.	Methods, tools and processes.	Yes
Artifacts linked to requirements.	Artifacts linked to attributes, inherently linked to requirements.	Partial
Sub-system and component interfaces.	Changeability of components measures (SRM-DSM and dynamic chart).	Yes
Basis for system measures.	Includes sub-set of system and program measures.	Partial
'Big Picture' of system with hierarchy of viewpoints.	Big Picture of system and management curves.	Partial

Rules for decisions	Governance and Design Change Strategy.	Yes
Reuse of proven architectures and design solutions from a Reference Architecture (RA) library.	Reuse of typical design change solutions and MATE reference design variants saved within simulator.	Partial
Describes system in mathematical model using mature system modeling language (SysML) and object orientation to define complex systems.	Non-dimensional attributes, transformational variables and management curve contribution values.	No
Rapid proto-typing and what-if changes in architecture.	Rapid what-if changes and impact on attributes and management curves.	Yes

10.8.2 *Management Flight Simulator Context Diagram and a Conceptual SOA*

The management flight simulator (MFS) provides a different perspective on system, organizational and management performance with several variables, parameters and attributes that may be shared or captured using other system and enterprise software.

As depicted in Figure 10.1, MBSE SysML software may be used to capture and possibly replace the management flight simulator. SysML can be integrated with other engineering models and tools to support engineering analysis [7]. At the same time, the simulator incorporates organizational and management information that may be of interest to other enterprise and manufacturing entities. A key consideration in integrating user defined models (UDM) and systems is a common language or primary keys within the integration backbone.

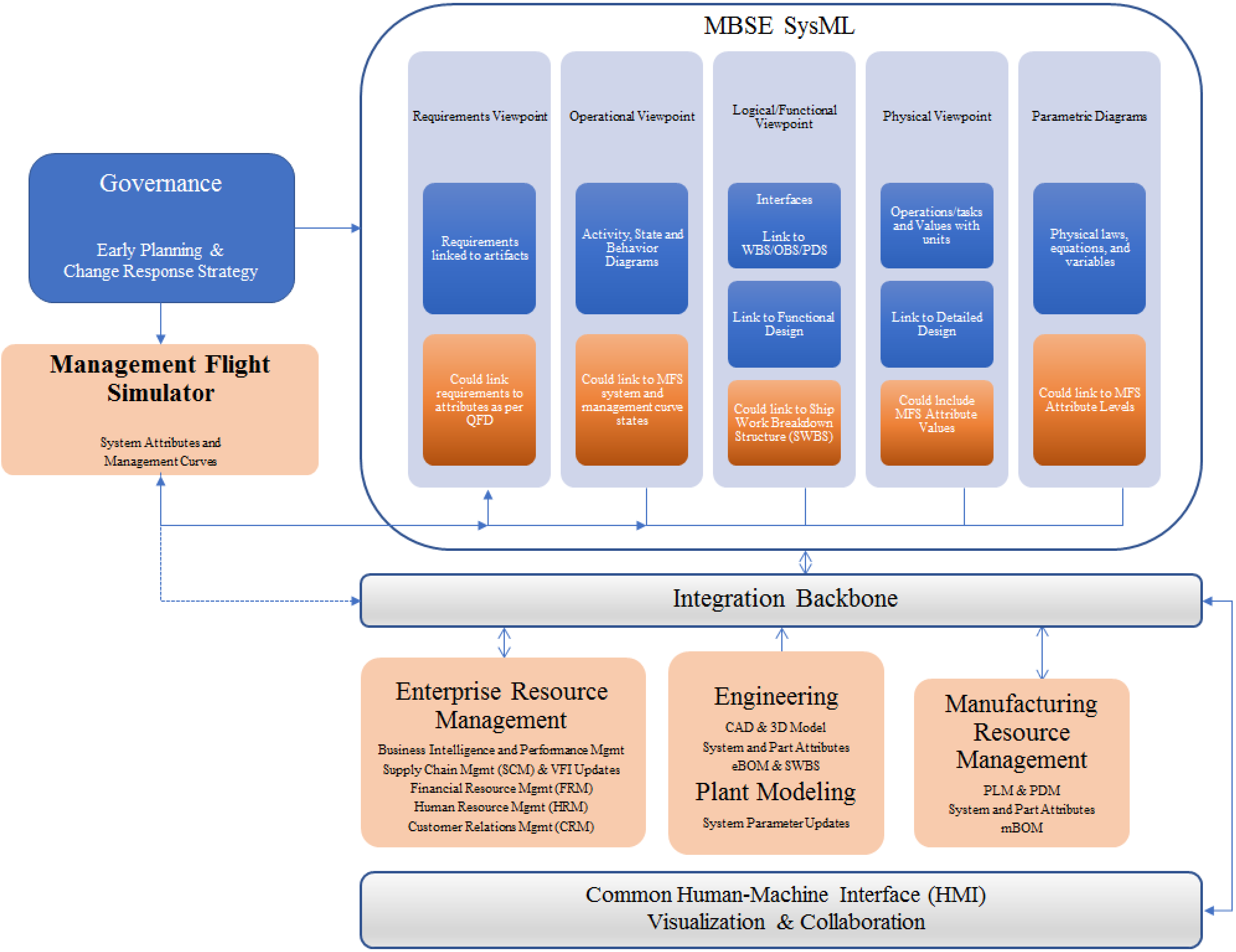


Figure 10.1. Simulator Context Diagram and Conceptual SOA

10.8.3 *Stakeholder Roles and Use Cases*

The primary stakeholder roles and use cases for using the management flight simulator are presented in this section.

10.8.3.1 *Stakeholder Roles*

The stakeholder roles depicted in Figure 10.2 include management flight simulator (MFS) key participants, support teams, PM and SE roles.

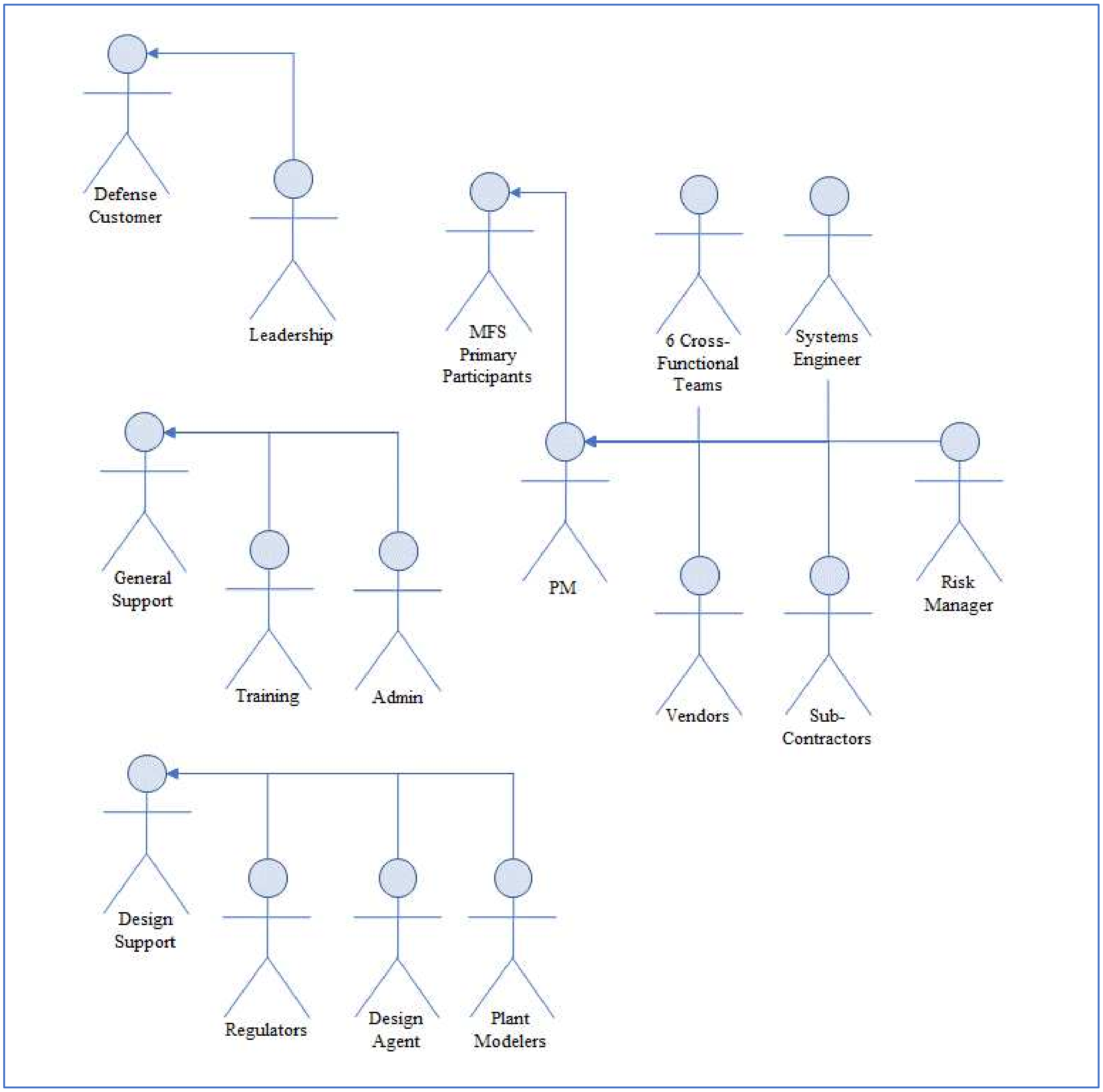


Figure 10.2. Management Flight Simulator Actors

10.8.3.2 *Management Flight Simulator Use Cases*

The use cases associated with use of the management flight simulator are depicted in Figures 10.3 and 10.4.

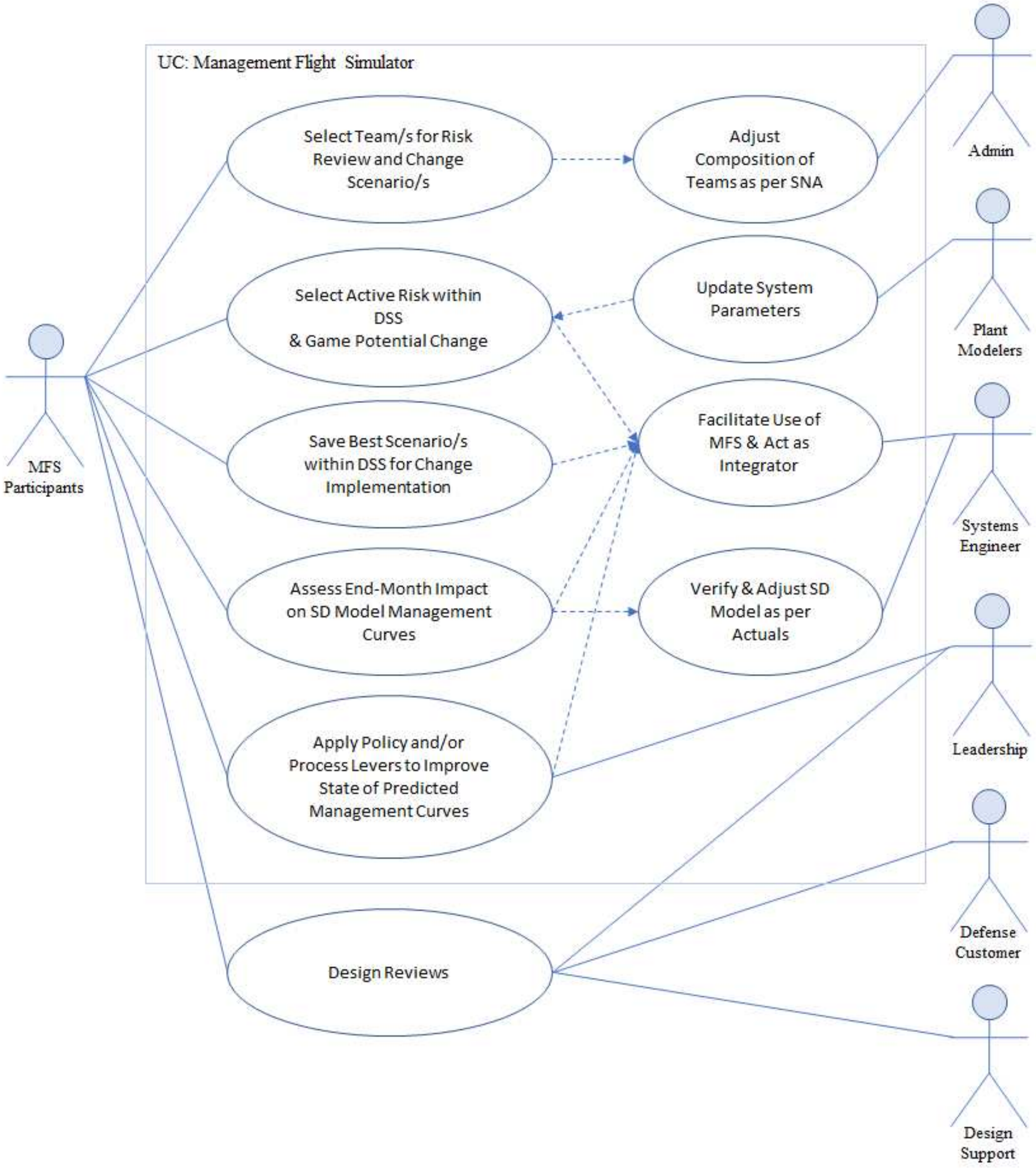


Figure 10.3. Management Flight Simulator Use Case

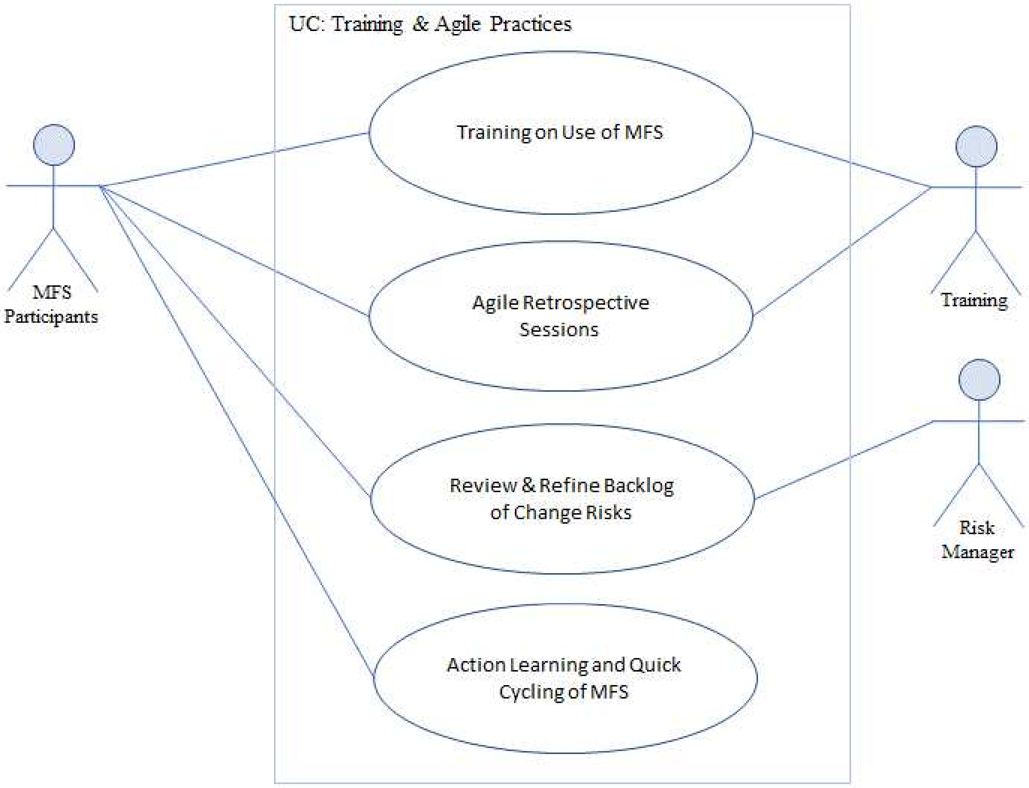


Figure 10.4. Management Flight Simulator Training and Agile Practices

10.8.4 *Requirements and* N^2 *Diagram Simulator Element Groups*

The N2 diagram consist of simulator elements, tasks and levers. The following sections present simulator groups of elements and their mapped integration requirements.

10.8.4.1 *Feedback Simulator Elements*

The simulator elements that depend on feedback are depicted in Figure 10.5. For instance, work error rate is dependent on VFI maturity, quality of specifications and drawings, SPI and the task completion rate. This coincides with the error rate inputs presented in the work performance CLD presented in Chapter 8. The other elements awaiting feedback include the task completion rate, knowledge and strategies. The same logic applies with their feedback elements used as inputs for the respective CLD diagrams.

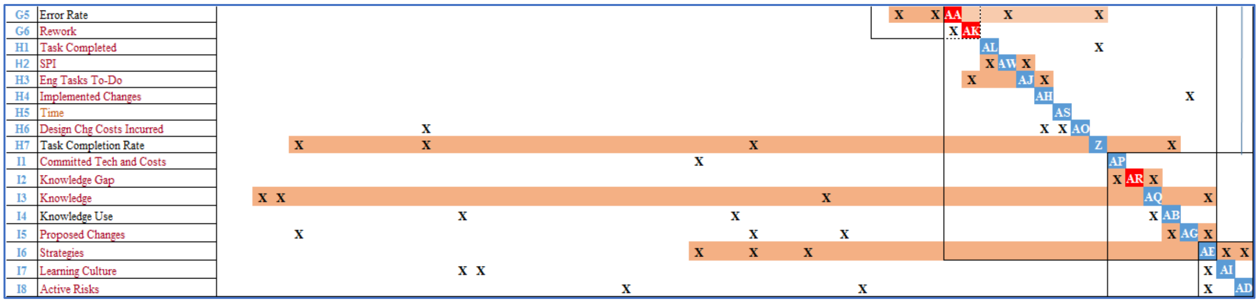


Figure 10.5. Feedback Loops Within the N^2 Diagram

10.8.4.2 *Feed Forward Simulator Elements*

The feed forward elements reside below the N2 diagonal with sequential dependency, key elements are depicted in Figure 10.6. For instance, ease of change requires the sequential steps of applying engineering principles, assessing attribute variability measures and visualizing those system components difficult to change. These steps also consist of inputs into the Ease-of-Change CLD.

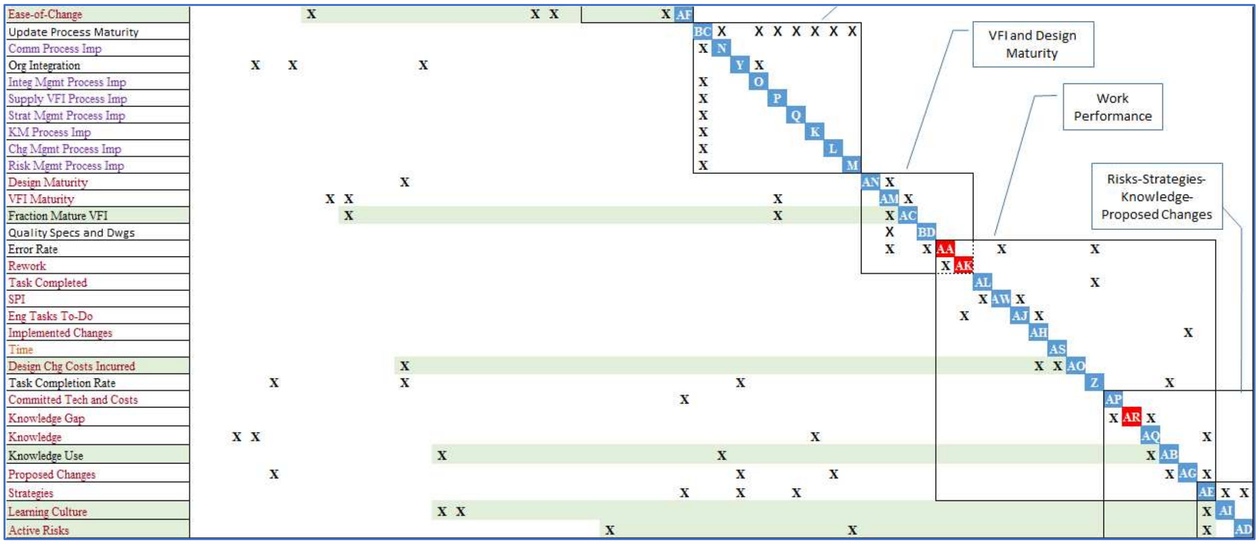


Figure 10.6. Feed Forward Loops Within the N^2 Diagram

10.8.4.3 *Groups of Simulator Coupled Elements*

The groups of closely related and coupled simulator elements help in organizing parts and interfaces of the simulator. These groups include set-based design and ease-of-change entities as depicted in Figure 10.7. The common entity between these groups is the design change decision task.

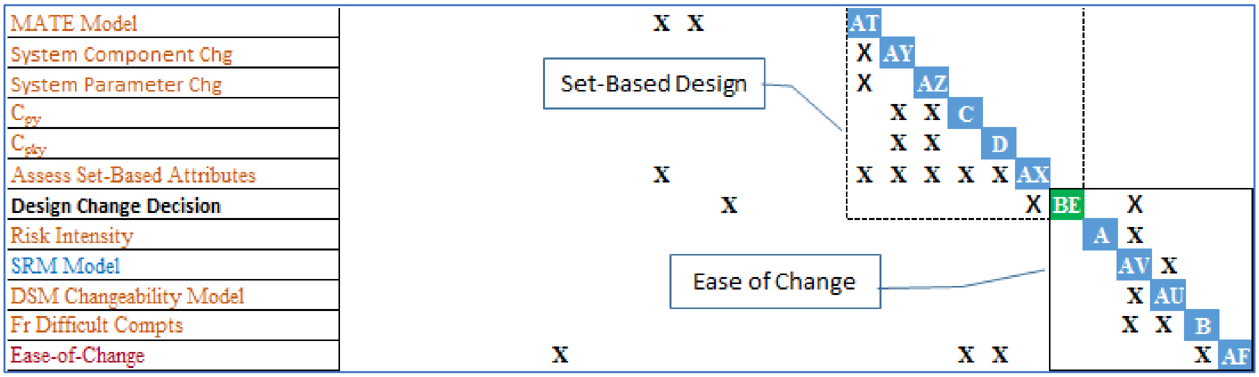


Figure 10.7. Groups of Set-Based Design and Ease-of-Change Entities

As depicted in Figure 10.8, the group of process improvement levers within the simulator is tightly coupled.

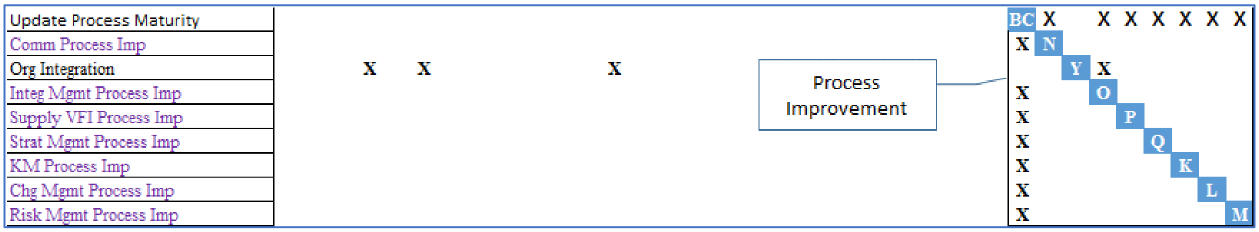


Figure 10.8. Process Improvement Levers Group

As depicted in Figure 10.9, intersecting coupled groups include VFI and design maturity, work performance and risks-strategies-knowledge-changes. The common elements between the VFI-design maturity and work performance group are rework and error rate. One of the common elements between work performance and risks-strategies-knowledge-changes is strategies.

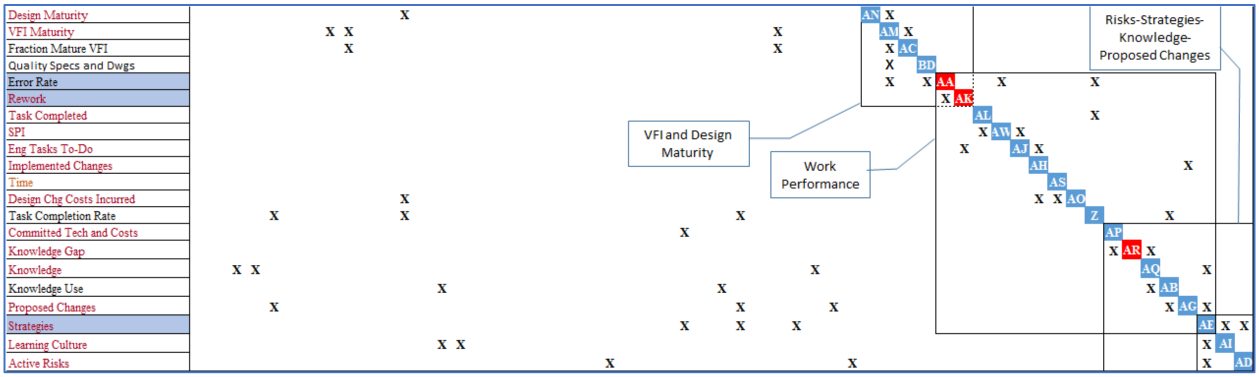


Figure 10.9. Groups of Work Performance and Risks-Strategies-Knowledge-Changes

10.8.4.4 *Integration Requirements Linked to Simulator Coupled Groups*

As listed in Table 10.3, the coupled groups of simulator elements may be linked key integration requirements. From this mapping, the prominent higher-level integration requirements for coupled groups include set-based design, quality, decisions, early knowledge and team learning.

Table 10.3. Coupled Simulator Entities and Integration Requirements

Coupled Entities	Coupled Entities Integration Requirements	Common Entity	Common Entity Integration Requirements
Set-Based Robust Design	E1.5 Set-Based Robust Design	Design Change Decisions	R3.2 Product Quality R4 Decisions
Ease-of-Change			
Process Improvement Levers	R3.1 Program Performance R3.3 Continuous Improvement R6.1.1 Early Knowledge		
VFI and Design Maturity	R3.1 Program Performance R4.2 Early Design Analysis	Rework and Error Rate	R3.2 Product Quality
Work Performance			
Work Performance	R3.1 Program Performance R4.2 Early Design Analysis	Strategies	R3.1 Program Performance R3.3 Continuous Improvement

Risks-Strategies-Knowledge-Changes	R3.1 Program Performance R4.1 Optimized Decisions R6.1.1 Early Knowledge R6.2 Team Learning R3.3 Continuous Improvement		R6.1.1 Early Knowledge

10.9 Conclusions

In comparing MBSE and MFS, cross-functional processes are common for developing both systems. Also common is their ability to help navigate complexity in design and project management. With an increase in product complexity can lead to an increase in information that may be inconsistent across disparate and different enterprise systems. In linking information systems, a common language, increased automation of tasks and UX are desired.

In comparing the benefits of MBSE and the MFS, there is strong alignment, including requirements and attribute management, trade-off analysis, communication and collaboration. In comparing typical MBSE elements to MFS elements, there is weak alignment. While both provide viewpoints and visualization, the MFS incorporates sub-models that span across the enterprise including PM and SE.

For data integration to be successful, a SOA strategy is proposed that describes the interfaces across the different software platforms and how information will be used by stakeholders.

The N^2 diagram is viewed as a useful tool in organizing elements and tasks within the management flight simulator. The results for this diagram include several feedback, feed forward loops and coupled elements that help in developing the simulator in a structured manner. Several iterations were performed in developing the N2 diagram to position as many elements below the diagonal. While this is close to an optimal solution, future revisions may improve upon it.

Chapter 11 – Conclusions

11.1 Conclusions

The problems associated with the lack of PM and SE integration were discussed in the current study. These problems include PM-SE unproductive tension, different objectives, different perspectives, social factors and the use of disparate models and tools. Moreover, integrated model-based tools have not gained traction in many industries.

The consequences of this include failed products and projects, an inability to adapt to design changes and new technology insertion, and poor decision-making.

The simulator presented in the current study was developed based on an integration strategy that includes common themes for integration, systems thinking, systems science, and SE methods. The simulator is viewed as a practical tool to help close the PM-SE gap that is not obvious due to complex interrelationships. Moreover, the simulator provides a ‘big picture’ perspective and total solution not possible with the use of separate engineering and management models

Use of the simulator is based on a proposed response strategy that provides adaptability to complexity, design changes and technology insertion during the design cycle.

Integrated information system assessment and success criteria were established for development of the simulator. Ease of use of the simulator is viewed as a key factor in promoting its use for decision-making and helping decision-makers from resorting to shifting-the-burden and quick ill-fated symptomatic decision-making.

The hypothesis in the current study was validated through application of a ‘non-toy’ case study and it was demonstrated that by advancing the Knowledge curve and pushing up the Ease-of-Change curve that other management curves could be positively influenced.

Use of the simulator can help to promote collaboration and enable adaptive double-loop learning through what-if scenarios and visualization of impacts of change in system, project and organizational performance.

The management flight simulator presented in the current study provides a glimpse into the future of where MBSE philosophy and tools can mature to support project management and systems engineering integration. The simulator offers a novel holistic approach and practical models-based tool as a common application that may be used by multiple disciplines across the value chain.

11.1.1 *Novel Aspects of The Management Flight Simulator*

Novel aspects of the simulator include:

- a coupled SRM-DSM and dynamic system component changeability chart
- coupled risk-strategy casual feedback loops based on Lotka-Volterra relationships
- the social aspect of decision-making through linked SNA metrics
- the linking of SE-PM entities and measures through a digital thread
- a common language of non-dimensional attribute values and management curve contribution values
- provides a different perspective on performance management of the system, project and organization that may be complementary to traditional tools
- practical model and a common platform for applying set-based design, engineering principles and agile management principles

11.1.2 *New Knowledge From The Current Research*

The current research provides new knowledge and contributes to fields of SE-PM integration, decision theory and intelligence augmentation. Related theories that were leveraged in the development of the simulator include Knowledge Theory, Decision Theory and Game Theory. The current research also resurrects SD modeling, SNA and Knowledge-based systems at an opportune time where they are leveraged in development of the simulator.

The simulator in the current study and its validation represents the first published results for a practical SE-PM integrated model.

11.1.3 *Key Take-Aways*

There are several key take-aways from the current research, these include:

- Knowledge and Ease-of-Change curves are key enablers to product and project success
- use of the management flight simulator can promote collaboration, provide different perspectives in resolving design problems and help navigate complexity
- What-If scenarios can generate tacit knowledge where strategies in response to change risks can be tested prior to any commitments
- leveraging mature models, matching of models, adequate fidelity, and a common platform (HIL and UX) are key success criterion in simulator development
- the value of the emergent properties of the simulator is greater than the sum of its parts
- it is not easy to promote the use of practical SE-PM model-based tools but it can be worth it

11.2 Limitations With The Current Work

The simulator as a prototype has some limitations. The simulator and its MATE model have been based on a limited number of design variants and component options. To revise the simulator to include additional options will require significant upfront work.

In simulator development, assumptions and simplification of interrelated equations and entities means that not all aspects of the real world may have been considered. Nevertheless, the simulator is viewed as a mechanism to help gauge relative performance of both technical and programmatic measures.

Finally, the simulator has been limited to the IPS case study; however, it can be scaled and adapted to other systems, but again significant upfront work would be required.

11.3 Future Work

The INCOSE IW 2020 survey results and additional feedback provide areas for follow-on research and improvements to the management flight simulator.

From group feedback, future considerations for research include applying another real-world case study, artificial intelligence by way of optimized levers in response to different system states and capturing simulator measures within MBSE and SysML platforms.

The simulator in the current study is a customized user-defined model (UDM) that took considerable time to develop and is expected to take considerable time in managing should it be further exploited with industry. Future work can include searching for a suitable commercial platform for the simulator. This platform may be assessed against interoperability requirements, and the integrated system assessment and success criteria discussed in the current study.

11.4 Bottom Line

This thesis develops and validates a practical model(s)-based approach for the integration of systems engineering and program management for a military marine system application.

Development of the management flight simulator was validated through liaison with senior subject matter experts from two aerospace companies, three shipyards, two hydro-electric companies, and through attending several conferences. The simulator and approach for using it were demonstrated and validated by 28 INCOSE members focused on SE-PM integration.

This validation shows that the current thesis and model represent a significant step toward a future generic framework for model-based integration of SE-PM disciplines that will be essential to developing and managing future complex engineering systems and projects.

Chapter 12 – Reflections

12.1 Introduction

Reflections on the current study include questioning and assessing the approach taken to integrating the sub-models of the management flight simulator and its use.

12.2 Reflecting on Integration Requirements for Simulator Development

In the mapping of requirements for simulator development, some requirements were not fully addressed and require further investigation. Of the six dimensions of PM-SE integration, the principle of effective integration was considered inherent in the objectives of the current study. Under the organization environment and people competencies dimensions, the element of leadership was not addressed in the current study [5]. This is of importance for organizational change management and promoting the use of model-based systems.

Other requirements not fully addressed include cultivating knowledge [107] and personal mastery [113]. These requirements form part of knowledge and competency-based management and may be further investigated in future work.

12.3 Reflecting on Social Network Analysis

The current study includes SNA results from a survey of six cross-functional team representatives. The survey was limited to a small number of participants as it took them away from their work duties. While the survey was limited to this small group, the benefits of SNA can be better realized through expanding participation. In this case, insight can be gained from emerging star players within informal networks.

Moreover, a different type of SNA survey can be explored in terms of knowledge and competency within the organization. This can provide a deeper understanding of the knowledge-based relationships within the organization and their effect on knowledge levels and the learning culture.

The number of participants, roles and type of SNA can impact the management flight simulator in terms of its structure, behavior and fidelity of SNA measures.

12.4 Reflecting on Other Applications in Industry

Development of the management flight simulator for the IPS case study required significant upfront level of effort in establishing variables, attributes and underlying equations. This level of effort may be reduced through reference libraries and architectures that may in turn be leveraged in building other systems within the simulator. With several system-of-systems architectures and associated attributes, the simulator may provide a ship-level perspective.

MBSE and its parametric diagrams may provide a suitable platform for system equations and reference architectures (RA).

The marine industry and warship design teams are immature in their adoption of MBSE and SysML modeling software. On the other hand, MBSE has made significant inroads toward its adoption within the aerospace industry.

12.5 Reflecting on SD Sub-Model Management Curve Behavior

As indicated during validation of the behavior of management curves within the SD sub-model, some curves are more sensitive than others. This is due to the structure of causal loop relationships and the associated gains that were calibrated in development of the SD sub-model. These gains were calibrated to reflect relative position of the four management curves while at the same time ensuring stability of the model under extreme range testing.

From the sensitivity study conducted using Vensim® software, it became obvious that the Knowledge curve was more sensitive than the Ease-of-Change curve, dependent on the respective influencing factors and their gain values.

Moreover, the shape of the Ease-of-Change curve requires further investigation. The rate of decay in ease-of-change may be viewed as unique to the type of system being developed. Additionally, it may be a challenge in moving the Ease-of-Change curve up where engineering principles such as modularity cannot be applied or where there are stringent project constraints.

The sensitivity of levers can be further explored in terms of calibration against real-world actual values. For instance, the actual number of design changes and associated costs may be compared to predicted Number of Changes and Costs-Incurred management curves.

12.6 Reflecting on SD Model Structure and Causal Loop Relationships

The current study represents a practical proof-of-concept model that is based on assumptions and simple relationships. For instance, ease-of-change only affects the position of the Commitments and number of Strategies curves. The relationship between knowledge and commitments is not well defined in the current study. As knowledge increases, it might be expected that commitments may be increased. On the other hand, postponing commitments may allow for just-in-time technology insertion. Commitments to costs and technology may be viewed in terms of the number of purchase orders (PO) issued against scheduled PO's and the level of relational contracting. Commitments can also be influenced by design and build phase contract award dates and milestone payments. These other factors may be investigated in future iterations of the simulator.

The Knowledge-Commitments Gap curve provides an indication of where action may be taken such as advancing the Knowledge curve. However, this gap curve is not used within the model structure and requires further investigation on where it may have an influence. While knowledge level is used as an influencing factor on the learning culture, the influence of the Knowledge Gap curve on culture may also be considered.

These and other relationships may be further explored in future iterations of model development.

12.7 Reflecting on Actual Reference Modes

The current study is based on a limited number of reference modes. As knowledge and ease-of-change levels are not yet measured in the real world, the relative position of these curves was used. The Commitments management curve is based on the 85 percent level typically attained prior to detailed design. The Costs-Incurred curve is a difficult curve to base on a reference mode where the current study relied on a typical cost per change.

On the other hand, there are reference modes where actual values for similar designs can be used. In the current study, these reference modes included VFI maturity and actual number of proposed and implemented changes.

While predicting program measures of incurred costs, schedule performance and rework, actual EVM values may be further validated.

12.8 Reflecting on Ability of the Simulator to Reduce Design Change Knock-On Effects

With early knowledge, design flexibility and risk reduction, the number of changes may be reduced as predicted with use of the simulator. Despite a predicted reduction in changes, each change can have its own ripple effects. For instance, adding component weight can lead to requirements to increase machinery raft weight and increases to generator capacity to meet vessel speed requirements. Other factors leading to knock-on effects include the ability to estimate risks and address them quickly in order to avoid a backlog. Another factor that may lead to knock-on effects is where an attribute level may be relaxed below its lower threshold. This may have a knock-on effect on other SoS at the ship design level.

In preventing a design change knock-on effect, the response strategy in the current study, including attribute management, is viewed as a mitigation strategy. Both a robust design and the feed forward feature of early risks reduction can help maintain stability of the simulator.

12.9 Reflecting on What is Missing for Implementing a PM-SE Integrated Framework

In the current study, a governance framework and response strategy were proposed for using the management flight simulator. As previously stated, the integration principles of leadership and cultivating knowledge were not fully explored in developing the integration strategy. Collaborative leadership and cultivating knowledge can extend out to the institutions, standards organizations and working groups involved in systems engineering and project management.

The mission of the INCOSE PM-SE working group (WG) includes identifying and promoting opportunities for PM-SE integration and exploring linkages. While the PMI has contributed toward this integration effort, its core values have remained project management centric. Despite integration efforts, both INCOSE and PMI are long standing institutions with deeply rooted values and loyalties. Moreover, their guidance documents for their respective practices do not include practical PM-SE integration methods and tools. There is a need to illuminate the possibility of practical PM-SE integrated methods, models and tools and to demonstrate their value.

There can be several different approaches to documenting and promoting practical integrated methods, models and tools. One approach might be to add another initiative to the existing INCOSE PM-SE WG; however, limited resources can slow down the process. Another approach that could achieve a breakthrough would be to stand up a new impartial institution for this effort, one with a mission and core values that include integration of disciplines, cross-functional processes, shared outcomes, a transdisciplinary holistic value space, and demonstration of the value in integrated methods, models and tools.

A common ground for cross-functional processes includes knowledge, risk and change management, where knowledge and learning are core elements for collaboration. Demonstrating the value in SE-PM integrated methods, models and tools includes continued efforts to reach out to the PMI wider audience whose membership far outweighs INCOSE's membership. It includes demonstration of integrated models that are built on a common platform using a common language that provide simplicity, transparency, automation of tasks, and an enjoyable user experience (UX).

The current study offers a structured approach to model integration that may be adopted in developing a suite of generic system models that may be reused and customized for specific product design and project applications. Showcasing useful SE-PM generic models can help avoid the confusion in what models should be used for integration.

Regardless of the approach taken, opportunities and partnerships with industry, academia, INCOSE, PMI, as well as other institutions will continue to be important in developing a PM-SE framework that works for everyone developing and managing complex products and projects.

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Appendix A - Integrated Power System Case Study Functional and Non-Functional Requirements

Table A-1. IPS High-Level Functional Requirements

Requirements System	High-Level Functional Requirements	Standards
Generator Sets	Operate near peak Specific Fuel Consumption (SFC) efficiency for majority of operating profile time. Includes Algorithms for optimum number of generators. Requires a set of ship operating profiles.	
	Recovery time (5 sec) for sudden large transient loads i.e 100% load removed from one generator set.	Canadian Naval Internal Specification for Load Bank Trials
	High Power Density per Space Limitations.	
	Generators sized such that in single fault, essential loads maintained, and vessel maintained in position. Overall generating plant capacity based on maximum speed powering requirement or sustained speed requirement plus the maximum of Battle I or II state. Requires Battle I or II state load requirements including Rail Gun.	ABS Naval Vessel Rules [27]
	Voltage (VAC ±5.0% permanent or ±16% transient for 2 s) and Frequency (±3% permanent or ±4% transient for 2 s).	MIL-STD-1399, Section 300
	Power Failure scenario with alternate generator set recovery. Ship service power and main propulsion restored within 30-45 s.	ABS Naval Vessel Rules [27] (ABS Rules for IPS to be developed)
IPS Plant General	Reduced emissions with consideration in choice of prime mover and IPS.	
	Low vibration with consideration to resilient raft mounted generator sets.	
	Low Noise with consideration to acoustic enclosures and choice of prime movers.	
	Configure for fault tolerance and graceful degradation.	
	Reduced harmonics, total harmonic distortion (THD) in voltage waveform in distribution systems not to exceed 5%	ABS Naval Vessel Rules [27]

Requirements System	High-Level Functional Requirements	Standards
	and any single order harmonics not to exceed 3%, some exceptions apply.	
	IPS to supply all propulsion and electrical loads using AC power of high quality through control, transformers, and filtering.	MIL-STD-1399, Section 300, ISO 8528-1 (Rating to be determined)
Power Management Controller (PMC)	Optimize configuration of IPS with least number generators in operation for maximum speed availability with redundancy. Includes listing Optimization Algorithms.	
	At least 2 PMC's to be provided for redundancy.	ABS Rules for IPS [27]
	Supply propulsion power of at least 7 knots or ½ design speed (whichever is less) with one generator out of service.	ABS Rules for IPS [27]
	Automatic power management for load sharing, blackout prevention, load shedding, propulsion power limiting, and maintaining essential services and minimum propulsion loads.	ABS Rules for IPS [27]
	Recommend optimum machinery usage based on ship operating profiles. Anticipate future loads.	
	Maintain steady state service loads and ship's speed with execution of pulse loads.	
Integrated Platform Management Systems (IPMS)	Start–Stop Generators Sets as per sequence diagrams.	
	Perform Synchronization of Generators Sets onto Switchboards.	
	Start stand-by generator set with IPS at 80% of load.	Canadian Naval Internal Specification for Electrical Systems
	Generate Power Generation and Distribution (PG&D) alerts and reports.	
Switchboards	Shed (110% of generator set rated load) and bring on electrical loads as required through switching.	Canadian Naval Internal Specification for Electrical Systems
High Energy Storage Device	Charge while generator sets are under high load and peak efficiency.	
	Charge and discharge rate as per Rail Gun pulse load profile.	

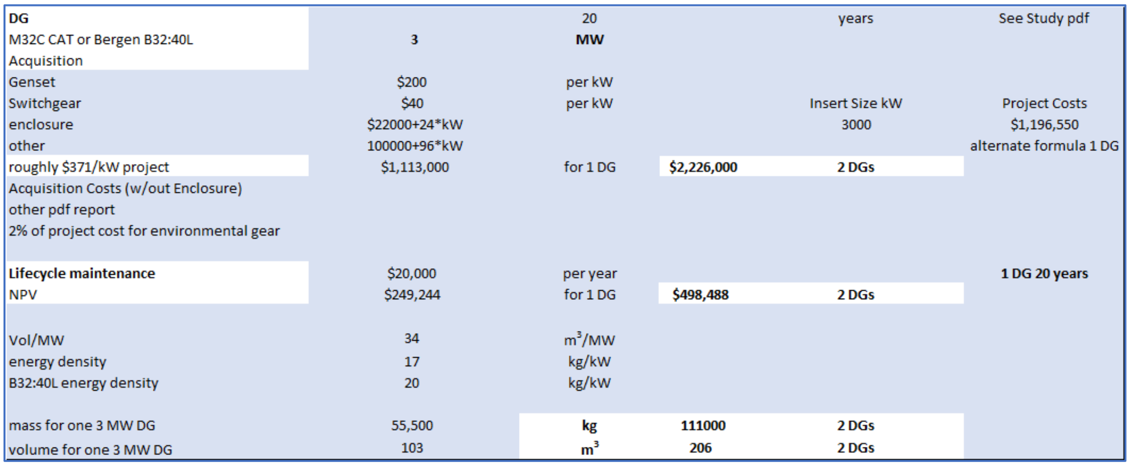
Requirements System	High-Level Functional Requirements	Standards
	Storage capability to meet platform survivability and ride through and recovery requirements.	ABS Rules for IPS [27]
	High Power Density per Space Limitations.	

Table A-2. IPS High Level Non-Functional Requirements

Requirements Area	High-Level Non-Functional Requirements	Standards
Systems Engineering and Program Management	Reduced procurement costs and through-life costs.	
	Margins for systems and sub-systems (mass, electrical load, thermal dissipation, electro-magnetic interference (EMI)).	
	Sufficient Technology Readiness Level (TRL).	
Availability	Reliability with minimum number of operational failures. IPS Failure Modes and Effects Analysis required. (Quality of Service [QOS]).	ABS Rules for IPS [27]
	Redundancy built-in for Survivability. System control is distributed among electrical equipment zones to enhance survivability.	Canadian Naval Internal Specification for Electrical Systems, ABS Naval Vessel Rules [27]
Supportability	Sufficient number of Critical Spare Parts available.	
Safety	Minimize safety incidents and accidents.	
Operational Capability	Achieve high level of operational capability.	

Appendix B - IPS Component Sizing Data (Microsoft Excel® Excerpts)

Table B-1. DG Set SWaP and Cost Metrics

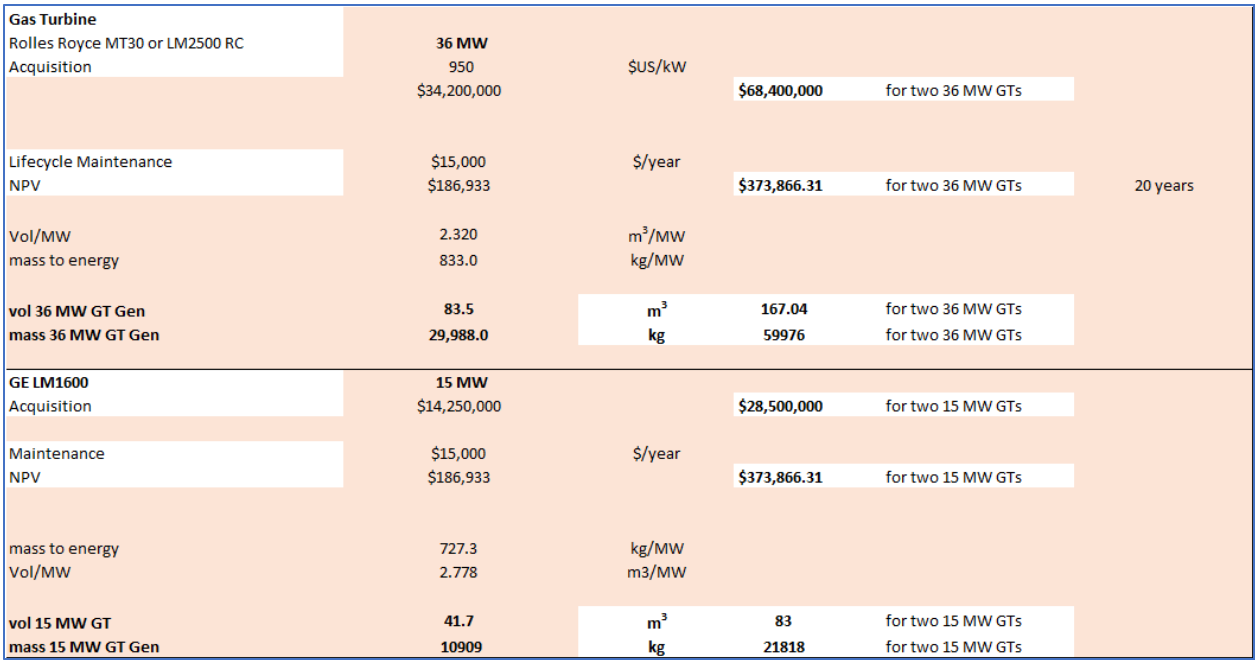


DG		20		years	See Study pdf
M32C CAT or Bergen B32:40L	**3**	**MW**			
Acquisition					
Genset	$200	per kW			
Switchgear	$40	per kW		Insert Size kW	Project Costs
enclosure	$22000+24*kW			3000	$1,196,550
other	100000+96*kW				alternate formula 1 DG
roughly $371/kW project	$1,113,000	for 1 DG	**$2,226,000**	**2 DGs**	
Acquisition Costs (w/out Enclosure)					
other pdf report					
2% of project cost for environmental gear					
Lifecycle maintenance	$20,000	per year			**1 DG 20 years**
NPV	$249,244	for 1 DG	**$498,488**	**2 DGs**	
Vol/MW	34	m^3/MW			
energy density	17	kg/kW			
B32:40L energy density	20	kg/kW			
mass for one 3 MW DG	55,500	**kg**	**111000**	**2 DGs**	
volume for one 3 MW DG	103	**m^3**	**206**	**2 DGs**	

Table B-2. WHR SWaP and Cost Metrics

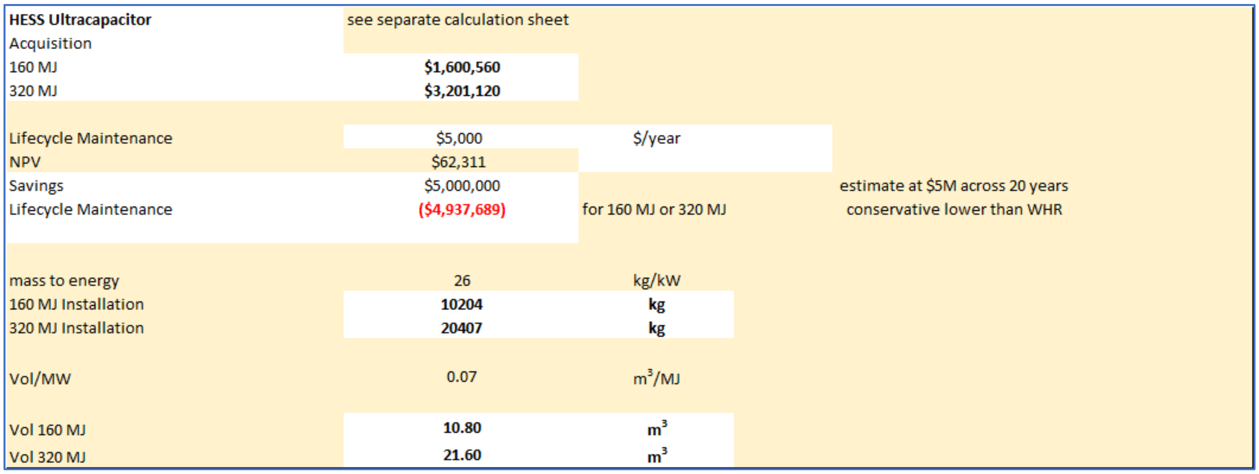
pdf WHR	**SST-040 Steam Turbine**				
3 MW DG WHR	300 kW				
15 MW GT WHR	1500 kW				25 knots max
36 MW GT WHR	3600 kW				30 knots max
Acquisition					
300 kW WHR System	**$900,000**		$1,800,000	for two 3 MW DGs	
1500 kW WHR System	**$2,700,000**		$5,400,000	for two 15 MW GTs	
3600 kW WHR System	**$6,480,000**		$12,960,000	for two 36 MW GT	
Maintenance	**$9,746**	per year		300 kW	20 years
NPV	**$121,456**			for one 3 MW DG	
Savings	**$1,787,619**				
Lifecycle maintenance	**($1,666,163)**	($3,332,326.61)		for two 300 kW WHR Systems	
Maintenance	**$48,730**	per year		1500 kW	
NPV	**$607,279**			for one 15 MW GT	
Savings	**$8,938,095**				
Lifecycle maintenance	**($8,330,817)**	($16,661,633.04)		for two 1500 kW WHR Systems	
Maintenance	**$116,951**	per year		3600 kW	
NPV	$1,457,468			for one 26 MW GT	
Savings	**$21,451,428**				
Lifecycle maintenance	**($19,993,960)**	($39,987,919.29)		for two 3600 kW WHR Systems	
Vol/kW	75.0	m^3/MW			
mass to energy	20.0	kg/kW			
mass one 300 kW WHR System	**6,000**	**kg**	**12000**	for two 300 kW WHR Systems	
volume one 300 kW WHR System	**22.5**	**m^3**	**45**	for two 300 kW WHR Systems	
mass one 1500 kW WHR System	**30,000**	**kg**	**60000**	for two 1500 kW WHR Systems	
volume one 1500 kW WHR System	**112.5**	**m^3**	**225**	for two 1500 kW WHR Systems	
mass one 3600 kW WHR System	**72,000**	**kg**	**144000**	for two 3600 kW WHR Systems	
volume one 3600 kW WHR System	**270.0**	**m^3**	**540**	for two 3600 kW WHR Systems	

Table B-3. GT Set SWaP and Cost Metrics



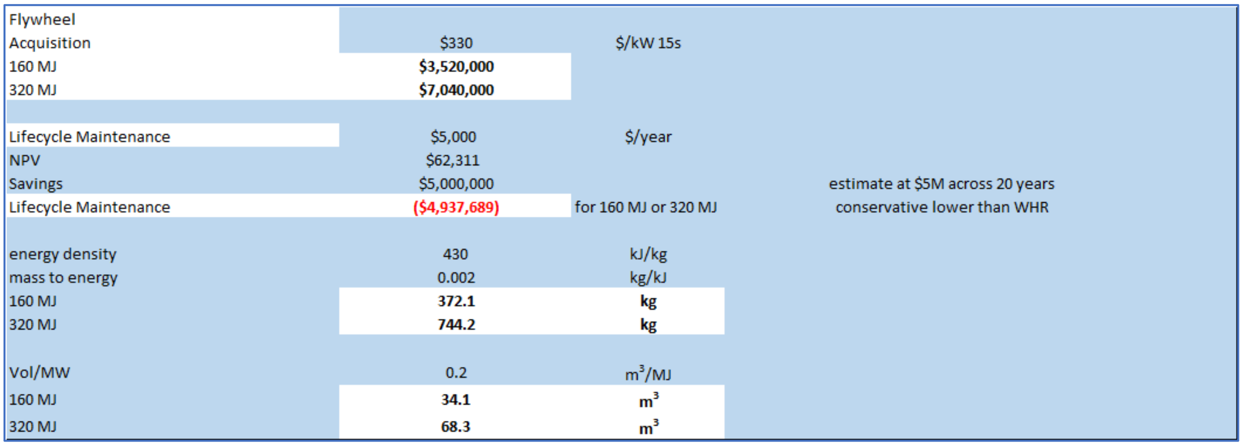
Gas Turbine					
Rolles Royce MT30 or LM2500 RC	**36 MW**				
Acquisition	950	$US/kW			
	$34,200,000		**$68,400,000**	for two 36 MW GTs	
Lifecycle Maintenance	$15,000	$/year			
NPV	$186,933		**$373,866.31**	for two 36 MW GTs	20 years
Vol/MW	2.320	m^3/MW			
mass to energy	833.0	kg/MW			
vol 36 MW GT Gen	**83.5**	**m^3**	**167.04**	for two 36 MW GTs	
mass 36 MW GT Gen	**29,988.0**	**kg**	**59976**	for two 36 MW GTs	
GE LM1600	**15 MW**				
Acquisition	$14,250,000		**$28,500,000**	for two 15 MW GTs	
Maintenance	$15,000	$/year			
NPV	$186,933		**$373,866.31**	for two 15 MW GTs	
mass to energy	727.3	kg/MW			
Vol/MW	2.778	m3/MW			
vol 15 MW GT	**41.7**	**m^3**	**83**	for two 15 MW GTs	
mass 15 MW GT Gen	**10909**	**kg**	**21818**	for two 15 MW GTs	

Table B-4. HESS Ultracapacitor SWaP and Cost Metrics



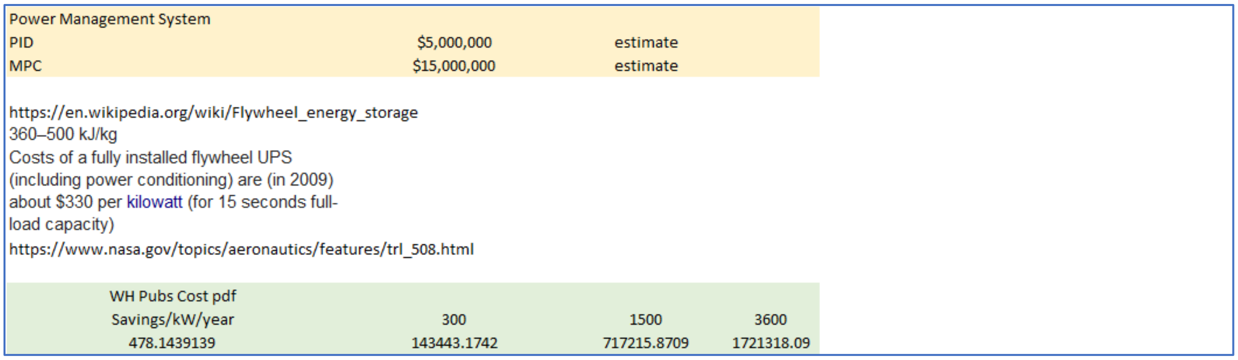
HESS Ultracapacitor	see separate calculation sheet		
Acquisition			
160 MJ	**$1,600,560**		
320 MJ	**$3,201,120**		
Lifecycle Maintenance	$5,000	$/year	
NPV	$62,311		
Savings	$5,000,000		estimate at $5M across 20 years
Lifecycle Maintenance	**($4,937,689)**	for 160 MJ or 320 MJ	conservative lower than WHR
mass to energy	26	kg/kW	
160 MJ Installation	**10204**	**kg**	
320 MJ Installation	**20407**	**kg**	
Vol/MW	0.07	m^3/MJ	
Vol 160 MJ	**10.80**	**m^3**	
Vol 320 MJ	**21.60**	**m^3**	

Table B-5. HESS Flywheel SWaP and Cost Metrics



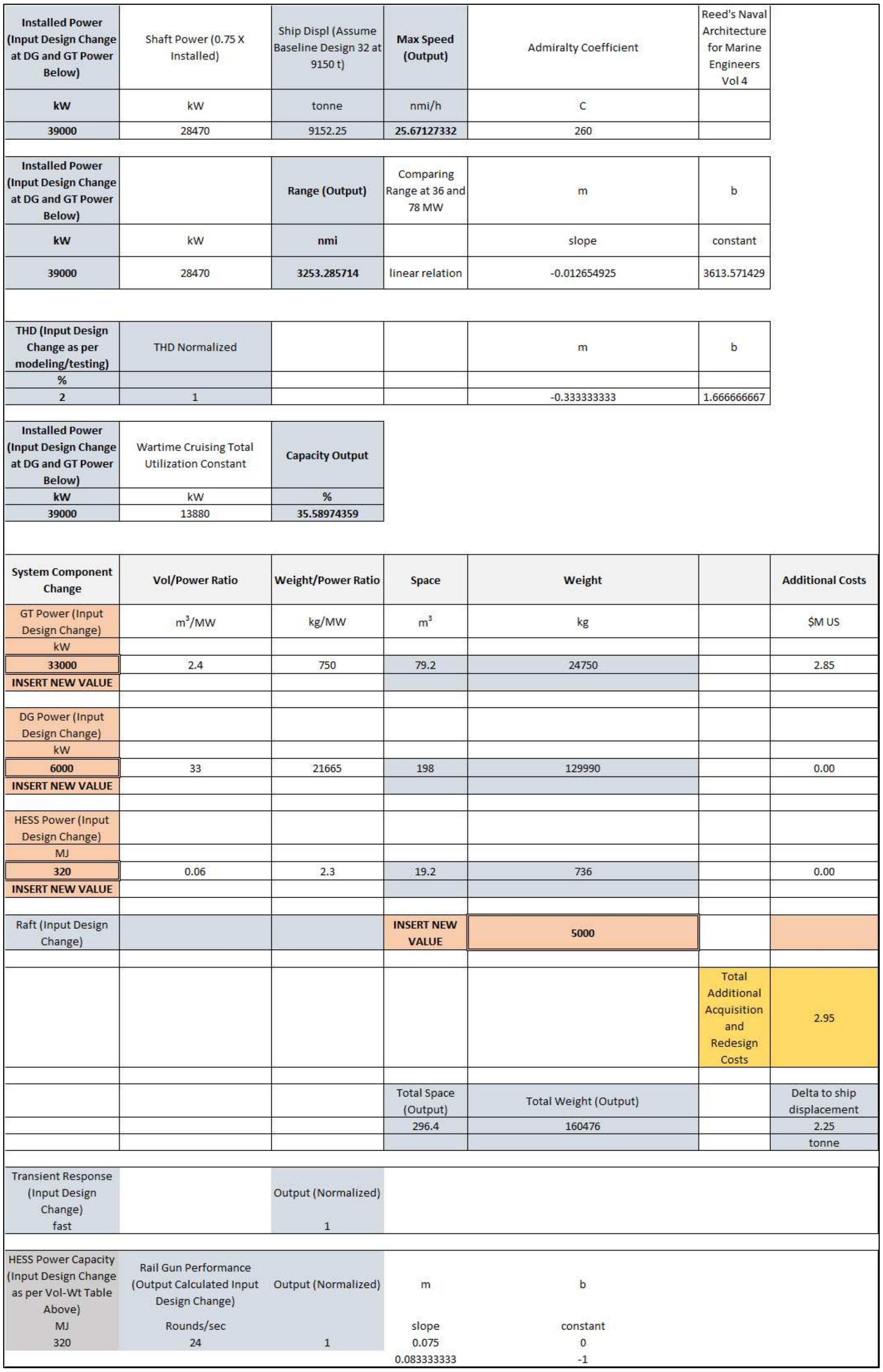
Flywheel			
Acquisition	$330	$/kW 15s	
160 MJ	**$3,520,000**		
320 MJ	**$7,040,000**		
Lifecycle Maintenance	$5,000	$/year	
NPV	$62,311		
Savings	$5,000,000		estimate at $5M across 20 years
Lifecycle Maintenance	**($4,937,689)**	for 160 MJ or 320 MJ	conservative lower than WHR
energy density	430	kJ/kg	
mass to energy	0.002	kg/kJ	
160 MJ	**372.1**	**kg**	
320 MJ	**744.2**	**kg**	
Vol/MW	0.2	m^3/MJ	
160 MJ	**34.1**	**m^3**	
320 MJ	**68.3**	**m^3**	

Table B-6. PMS Estimated Cost and Some References



Power Management System			
PID	$5,000,000	estimate	
MPC	$15,000,000	estimate	
https://en.wikipedia.org/wiki/Flywheel_energy_storage			
360–500 kJ/kg			
Costs of a fully installed flywheel UPS (including power conditioning) are (in 2009) about $330 per kilowatt (for 15 seconds full-load capacity)			
https://www.nasa.gov/topics/aeronautics/features/trl_508.html			
WH Pubs Cost pdf			
Savings/kW/year	300	1500	3600
478.1439139	143443.1742	717215.8709	1721318.09

Table B-7. Built-In IPS Variable Calculations (Sample excerpt from Excel®)



Installed Power (Input Design Change at DG and GT Power Below)	Shaft Power (0.75 X Installed)	Ship Displ (Assume Baseline Design 32 at 9150 t)	Max Speed (Output)	Admiralty Coefficient	Reed's Naval Architecture for Marine Engineers Vol 4
kW	kW	tonne	nmi/h	C	
39000	28470	9152.25	25.67127332	260	

Installed Power (Input Design Change at DG and GT Power Below)		Range (Output)	Comparing Range at 36 and 78 MW	m	b
kW	kW	nmi		slope	constant
39000	28470	3253.285714	linear relation	-0.012654925	3613.571429

THD (Input Design Change as per modeling/testing)	THD Normalized			m	b
%					
2	1			-0.333333333	1.666666667

Installed Power (Input Design Change at DG and GT Power Below)	Wartime Cruising Total Utilization Constant	Capacity Output
kW	kW	%
39000	13880	35.58974359

System Component Change	Vol/Power Ratio	Weight/Power Ratio	Space	Weight		Additional Costs
GT Power (Input Design Change)	m^3/MW	kg/MW	m^3	kg		$M US
kW						
33000	2.4	750	79.2	24750		2.85
INSERT NEW VALUE						
DG Power (Input Design Change)						
kW						
6000	33	21665	198	129990		0.00
INSERT NEW VALUE						
HESS Power (Input Design Change)						
MJ						
320	0.06	2.3	19.2	736		0.00
INSERT NEW VALUE						
Raft (Input Design Change)			INSERT NEW VALUE	5000		
					Total Additional Acquisition and Redesign Costs	2.95
			Total Space (Output)	Total Weight (Output)		Delta to ship displacement
			296.4	160476		2.25
						tonne

Transient Response (Input Design Change)		Output (Normalized)
fast		1

HESS Power Capacity (Input Design Change as per Vol-Wt Table Above)	Rail Gun Performance (Output Calculated Input Design Change)	Output (Normalized)	m	b
MJ	Rounds/sec		slope	constant
320	24	1	0.075	0
			0.083333333	-1

Appendix C – SNA Results (Inflow® Extracts)

Table C-1. Representative Survey Sheet Solicited to each Team for Input

State Your Role i.e T_1, T_2, etc…	Indicate Frequency That You Would Go to the Following People for Each Change Scenario and the Factors Considered Very Frequently: 5 Infrequently: 1	
Role: T1	Scenario 1	Scenario 2
Person You Would Seek Information	New regulation requires Diesel Generator to have Waste Heat Recovery (WHR)	Incorrect VFI leads to requirement to increase power of Gas Turbines
T_1: Program Manager	5	5
T_2: Electrical Engineering team	5	5
T_3: Mechanical and Propulsion Engineering team	5	5
T_4: Supply Chain team	3	3
T_5: Planning and Scheduling team	2	2
T_6: Production	2	2

Using survey results, Inflow® software was utilized with the following results:

Scenario 1

Group Size 6

Potential Ties 30

Actual Ties 18

Density 60%

Computing geodesics

18 paths of length 1

12 paths of length 2

0 paths of length 3

Weighted Avg. Path Length: 1.40

Group A : Degrees

1.000	T4
0.600	T1
0.600	T5
0.600	T6
0.400	T2
0.400	T3
0.600	AVERAGE
0.600	CENTRALIZATION

Group A : Betweeness : Uniform

0.600	T4
0.000	T1
0.000	T2
0.000	T3
0.000	T5
0.000	T6
0.100	AVERAGE
0.600	CENTRALIZATION

Group A : Closeness

1.000	T4
0.714	T1
0.714	T5
0.714	T6
0.625	T2

```
    0.625     T3
    0.732     AVERAGE
    0.724     CENTRALIZATION
```

```
Group A : Power
    0.800     T4
    0.357     T1
    0.357     T5
    0.357     T6
    0.313     T2
    0.313     T3
    0.416     AVERAGE
Name   CC    CPL   SC
T1     1.00  1.40  0.00
T2     1.00  1.60  0.00
T3     1.00  1.60  0.00
T4     0.40  1.00  0.00
T5     1.00  1.40  0.00
T6     1.00  1.40  0.00
Overall      0.90  1.40  0.00


Scenario 2
Potential Ties 30
Actual Ties   22
Density      73%
Computing geodesics
   22 paths of length 1
   16 paths of length 2
```

```
    0 paths of length 3
Weighted Avg. Path Length: 1.42
------------------------------------------------------------
Group A : Degrees
    1.000       T1
    1.000       T5
    0.600       T2
    0.600       T3
    0.600       T4
    0.600       T6
    0.733       AVERAGE
    0.400       CENTRALIZATION
------------------------------------------------------------
Group A : Betweeness : Uniform
    0.200       T1
    0.200       T5
    0.000       T2
    0.000       T3
    0.000       T4
    0.000       T6
    0.067       AVERAGE
    0.160       CENTRALIZATION
------------------------------------------------------------
Group A : Closeness
    1.000       T1
    1.000       T5
    0.714       T2
    0.714       T3
```

0.714	T4
0.714	T6
0.809	AVERAGE
0.515	CENTRALIZATION

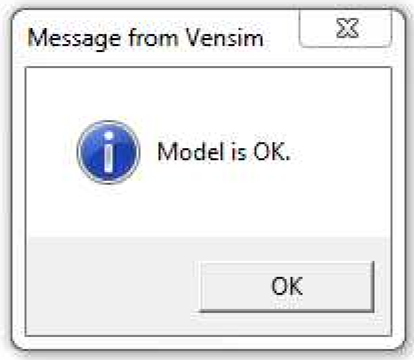
Group A : Power

0.600	T1
0.600	T5
0.357	T2
0.357	T3
0.357	T4
0.357	T6
0.438	AVERAGE

Name	CC	CPL	SC	
T1	0.60	1.00	0.00	
T2	1.00	1.40	0.00	
T3	1.00	1.40	0.00	
T4	1.00	1.40	0.00	
T5	0.60	1.00	0.00	
T6	1.00	1.40	0.00	
Overall		0.87	1.27	0.00

Appendix D – Vensim® Software Equation Consistency and Units Validation for The Management Flight Simulator

SD Model Equations and Units


Message from Vensim

Model is OK.


Message from Vensim

Units are OK.

(001) Active Risks= INTEG (Risk Generation-Risk Mitigation,1)
Units: Active Risks
Number of Active Risks

(002) Adjusted Fraction of Non-Converging Strategies=Effect of Strategy Capacity*"Normal Fraction Non-Converging
Units: Dmnl
Effect of both fraction of non-converging strategies and team capacity in developing strategies

(003) Applying Engineering Principles=0.5
Units: Dmnl
Applying engineering principles of modularity and standardization to system components difficult to change

(004) Attrition=0.2
Units: Dmnl

(005) Average Costs Per Change=5000
Units: $US/Implemented Changes
Average cost per change as per literature automotive industry as applied to IPS case

(006) Average Risk Resolution Time=0.5
Units: month
Average time to resolve risks

(007) Change Implementation Rate=Implementation Rate*Proposed Changes
Units: Implemented Changes/month

(008) Change Implementation Task Ratio=1
Units: Tasks/Implemented Changes

(009) Change Management Process Maturity=0.8
Units: 1/month

(010) Change Tasks=Change Implementation Task Ratio*Change Implementation Rate
Units: Tasks/month

(011) Commitment Fraction=0.05
Units: 1/month
Fraction commitments per month

(012) Commitment Gap=Maximum Commitment-Costs and Technology Committed
Units: Commitments
Gap between actual costs committed and maximum goal

(013) Commitment Rate=Commitment Fraction*Commitment Gap*Ease of Change Adj*2.5*(100-Ease of Change)
Units: Commitments/month
Rate of commitments per month

(014) Communication Management Process Maturity=0.8
Units: Dmnl

(015) Conversion to Changes=Change Management Process Maturity*Proposed Changes*Strategies Proposed Changes Adjustment
Units: Proposed Changes/month
Conversion of Strategies into Proposed Changes

(016) Cost Correction Factor = WITH LOOKUP (SRL,([(0,0.9)-(1,3)],(0,3),(1,1)))
Units: Dmnl
Effect of SRL on costs

(017) Costing Changes=Change Implementation Rate*Average Costs Per Change*Design Cycle Cost Factor*Cost Correction Factor
Units: $US/month
Costs per month for Implemented Changes as per point within design cycle

(018) Costs and Technology Committed= INTEG (Commitment Rate,1)
Units: Commitments
Level of costs committed

(019) CpKy=0.38
Units: Dmnl
Cpky from DSS

(020) Cpy=0.57
Units: Dmnl
Cpy from DSS

(021) Culture Adj=1
Units: 1/Culture

(022) Culture Eating Strategy Effect = WITH LOOKUP (Culture Adj*Learning Culture/100, ([(0,0.9)-(1,2)],(0,2),(1,1)))
Units: Dmnl
Culture Eats Strategy Reference Peter Drucker

(023) Culture Gap=Maximum Learning Culture-Learning Culture
Units: Culture

(024) Cumulative Implemented Changes= INTEG (Change Implementation Rate,1)
Units: Implemented Changes
Cumulative Implemented Changes as affected by the implementation rate of Proposed Changes

(025) Cumulative Proposed Changes= INTEG (Proposed Change Rate,1)
Units: Proposed Changes
Cumulative Proposed Changes

(026) Design Change Cost Incurred= INTEG (Costing Changes,1)
Units: $US
Costs from Implemented Changes

(027) Design Cycle Cost Factor = WITH LOOKUP (Relative Time,([(0,0)-(100,80)],(0,1),(100,80)))
Units: Dmnl
Design Cycle effect on design change costs as per literature

(028) Design Maturity= INTEG (Design Maturity Rate-Design Maturity Loss,1)
Units: Design Maturity
Design Maturity level as affected by SRL and VFI Maturity rate

(029) Design Maturity Loss=Design Maturity*Design Maturity Loss Fraction
Units: Design Maturity/month
Rate of Design Maturity Loss balancing gain

(030) Design Maturity Loss Fraction=Effect Design Maturity Capacity*Rework Effect
Units: 1/month
Design Maturity Loss Fraction as affected by Rework Effect and Design Maturity Capacity

(031) Design Maturity Rate=Design Maturity*Gain Design Maturity
Units: Design Maturity/month

(032) Discovery Rate=Engineering Tasks To Do*Rework Detection Fraction
Units: Tasks/month
Capability to detect rework balanced with work to do

(033) Ease of Change= INTEG (-Ease of Change Depletion,100)
Units: Ease of Change
Ease of Change curve in ability to change system components

(034) Ease of Change Adj=0.01
Units: 1/Ease of Change

(035) Ease of Change Depletion=Ease of Change*Ease of Change Fraction/(Effect of Components Difficult to Change*Effect of Applying Engineering Principles)
Units: Ease of Change/month

(036) Ease of Change Fraction = WITH LOOKUP (CpKy*Cpy,([(0.1,0)-(4,0.2)],(0.1,0.04),(4,0.02)))
Units: 1/month
Ease of Change Fraction as affected by Cpy and Cpky scaled with lookup

(037) Effect Design Maturity Capacity=Lookup Effect Design Maturity(Design Maturity/Maximum Design Maturity Level)
Units: Dmnl

(038) Effect Ease of Change on Strategies=Ease of Change*Ease of Change Adj
Units: Dmnl
Effect of system changeability on generating strategies

(039) Effect of Applying Engineering Principles = WITH LOOKUP (Applying Engineering Principles,([(0,0)-(1,2)],(0,1),(1,1.5)))

Units: Dmnl
The more applied principles, the flexible and easier to change the system

(040) Effect of Components Difficult to Change = WITH LOOKUP (Fraction Components Difficult to Change,([(0,0)-(1,1)],(0,1),(1,0.01)))
Units: Dmnl
Effect of ICI and ICL upper fraction of number of components difficult to change

(041) Effect of Gaming and Strategies = WITH LOOKUP (Strategies*Effect Strategy Adj, ([(0,0)-(50,1)],(0,0),(35,1)))
Units: Dmnl
Strategies into Knowledge adjustment

(042) Effect of Knowledge Capacity=
Lookup Effect of Knowledge Capacity(Knowledge/Normal Knowledge Level)
Units: Dmnl
Effect Knowledge to Normal Knowledge of 100 percent providing S curve

(043) Effect of Knowledge Management Program=Knowledge Program Adj*Knowledge
Units: 1/month

(044) Effect of Strategies=Lookup Effect of Risk Strategy Capacity(Active Risks/(Strategies*Strategy Variety))
Units: Dmnl
Normalized effect of ratio risks to strategies in resolving risks

(045) Effect of Strategy Capacity=Lookup Effect of Strategy Capacity(Strategies/Limit on Number of Strategies)
Units: Dmnl
Effect of capacity to develop strategies

(046) Effect Paying for VFI and Relational Contracting = WITH LOOKUP (Paying for VFI+Relational Contracting Effort,([(0.4,0.9)-(1.2,2)],(0.4,0.95),(0.6,1),(1.2,1.5)))
Units: Dmnl
Effect of paying for VFI and relational contracting on knowledge gain

(047) Effect Strategy Adj=1.5
Units: 1/Strategies
Effect of strategies on knowledge

(048) Engineering Tasks Done= INTEG (Task Completion Rate,1)
Units: Tasks
Tasks completed

(049) Engineering Tasks To Do= INTEG (Discovery Rate-Task Completion Rate+Change Tasks,Initial Tasks To Do)

Units: Tasks
Number of Tasks to do

(050) Error Rate=Task Completion Rate*Pressure to Work Faster*max(1-VFI Maturity/100,0.001)*max(1-Quality of Drawings and Specifications,0.001)*VFI Maturity Effect
Units: Tasks/month
Error rate affecting amount of rework

(051) FINAL TIME = 100
Units: month
The final time for the simulation.

(052) Fraction Components Difficult to Change=0.33
Units: Dmnl
From ICL and ICI as per DSM changeability chart within MCDM IAF DSS

(053) Fraction Mature VFI=VFI Maturity/(VFI Required+VFI Maturity)
Units: Dmnl
Fraction mature VFI to required immature VFI

(054) Fraction Work Done=Planned Work/(Engineering Tasks To Do+Planned Work)
Units: Dmnl

(055) Gain Design Maturity=SRL*Fraction Mature VFI*SPI*Proven Design Factor
Units: 1/month
Gain for reinforcing Design Maturity

(056) Gaming Adjustment=Lookup Effect Ratio Risks Strategy(Ratio Risk Strategy)
Units: Dmnl
Adjustment to number of Gaming scenarios for generating strategies

(057) Gaming Intensity=1.1
Units: Dmnl
Intensity of gaming of scenarios for generating strategies

(058) Implementation Rate = WITH LOOKUP (Relative Time,([(0,0)-(100,2)],(0,0),(14.9847,0.201754),(21.7125,0.350877),(36.0856,1.22807),(43.4251,1.58772),(48.6239,1.66667),(52.5994,1.5614),(56.2691,1.35965),(60.5505,0.789474),(66.6667,0.394737),(73.7003,0.175439),(77.0642,0.131579),(79.8165,0.105263),(85.6269,0.0526316),(100,0)))
Units: Implemented Changes/Proposed Changes/month
Rate of implementing changes per month

(059) Initial Tasks To Do=1000
Units: Tasks

Initial number of tasks to do

(060) INITIAL TIME = 0
Units: month
The initial time for the simulation.

(061) Integration Management Process Maturity=0.8
Units: Dmnl

(062) Knowledge= INTEG (Knowledge Generation-Knowledge Loss-Knowledge Transfer,1)
Units: Knowledge

(063) Knowledge Commitment Adj=Costs and Technology Committed*Knowledge Commitment Ratio
Units: Knowledge
Committed technology and costs adjusted if required

(064) Knowledge Commitment Ratio=1
Units: Knowledge/Commitments

(065) Knowledge Gain Fraction=Effect of Gaming and Strategies*On the Job Training Effort*Knowledge Management Process Maturity*Effect Paying for VFI and Relational Contracting
Units: 1/month
Effect of strategies and relational contracting in creating tacit knowledge and VFI for creating explicit knowledge

(066) Knowledge Gap=max((Knowledge Commitment Adj-Knowledge),0)
Units: Knowledge
Knowledge Gap from knowledge attained minus committed costs_technology

(067) Knowledge Generation=Knowledge Gain Fraction*Knowledge
Units: Knowledge/month
Knowledge generated from gaming of scenarios and OJT

(068) Knowledge Loss=Knowledge Loss Fraction*Knowledge
Units: Knowledge/month
Knowledge Loss per month

(069) Knowledge Loss Fraction=Normal Knowledge Loss Fraction*Effect of Knowledge Capacity
Units: 1/month
Knowledge Loss Fraction as affected by Normal Loss Fraction

(070) Knowledge Management Process Maturity=0.8
Units: Dmnl

KM Process Maturity assessed through a process maturity model

(071) Knowledge Program Adj=1/100
Units: 1/Knowledge/month

(072) Knowledge Transfer= Knowledge*Transfer Rate
Units: Knowledge/month
Knowledge Transfer outflow

(073) Knowledge Use=Communication Management Process Maturity*(2.2-Organization Characteristic Path Length)*Knowledge Transfer/100
Units: Knowledge/month
Knowledge Use per month from transferred knowledge

(074) Learning Culture= INTEG (Learning Culture Rate,1)
Units: Culture
Level of Learning Culture

(075) Learning Culture Rate=Effect of Knowledge Management Program*Power Std Dev and Ability to Question Effect*(2-Organization Characteristic Path Length)*Culture Gap
Units: Culture/month
Learning Culture Rate with key variables of Knowledge program and questioning ability

(076) Learning Effort=4
Units: Dmnl

(077) Learning From Liaising with Vendors=Fraction Mature VFI*Relational Contracting Effort
Units: Dmnl
As VFI matures with liaison with vendors maturing is reinforced

(078) Limit on Number of Strategies=1000
Units: Strategies
Constraining factor on team capacity to develop strategies

(079) Lookup Effect Design Maturity([(0,0)-(1,3)],(0,0),(0.16208,1.48684),(0.360856,2.25),(0.620795,2.76316),(1,3))
Units: Dmnl

(080) Lookup Effect of Knowledge Capacity([(0,0)-(1,1)],(0,0),(1,1))
Units: Dmnl
Lookup for ratio Knowledge to Normal Knowledge Level

(081) Lookup Effect of Risk Strategy Capacity([(0,0)-(10,10)],(0,0.01),(3,1))
Units: Dmnl

(082) Lookup Effect of Strategy Capacity([(0,0)-(1,3)],(0,0),(1,3))
Units: Dmnl
Effect of number of strategies and limiting factor

(083) Lookup Effect Ratio Risks Strategy([(0,0)-(1,1)],(0,0),(0.5,0.5),(1,1))
Units: Dmnl
Lookup effect of ratio of Active Risks to Strategies

(084) Maximum Commitment=100
Units: Commitments
Goal 100 percent for cost commitments

(085) Maximum Design Maturity Level=100
Units: Design Maturity

(086) Maximum Learning Culture=100
Units: Culture

(087) Month=1
Units: month

(088) "Normal Fraction Non-Converging"=0.3*Organization Integration
Units: Dmnl
Normal fraction of non-converging strategies as affected by
Organization Integration and ability to discover them

(089) Normal Knowledge Level=100
Units: Knowledge
Capacity of knowledge in organization assumed at 100 percent

(090) Normal Knowledge Loss Fraction=Attrition*Knowledge Gain Fraction
Units: 1/month

(091) Normal Transfer Rate=Knowledge Gain Fraction-Normal Knowledge Loss Fraction
Units: 1/month
Knowledge Transfer rate dependent on knowledge gain and loss

(092) On the Job Training Effort=1.25
Units: 1/month
OJT Effort per month

(093) Organization Characteristic Path Length=1.36
Units: Dmnl
The organization CPL for Knowledge Transfer is proposed from a Social Network
Analysis SNA

(094) Organization Density=0.64
Units: Dmnl
Organization Density from Social Network Analysis

(095) Organization Integration=Gaming Intensity*Organization Density*Team Colocation*Integration Management Process Maturity
Units: Dmnl
Effect of Organization Integration per month on generating strategies

(096) Paying for VFI=0.4
Units: Dmnl
Effort in Paying for VFI to increase maturity level

(097) Planned Work= INTEG (Planned Work Rate,1)
Units: Tasks

(098) Planned Work Effort=5
Units: month

(099) Planned Work Rate=Engineering Tasks To Do*Fraction Work Done/Planned Work Effort
Units: Tasks/month

(100) Power Std Dev and Ability to Question Effect=1-SNA Power Std Dev
Units: Dmnl
1-Std Dev in SNA Power amongst teams as indication of teams to question and have a voice

(101) Pressure to Work Faster=max(1-SPI,0.01)
Units: Dmnl
Pressure to work faster dependent on work progress

(102) Proposal Change Approval Rate = WITH LOOKUP (Relative Time,([(0,0)-(100,40)],(0,0),(25.3823,2.10526),(33.6391,3.50877),(39.4495,5.96491),(44.3425,9.12281),(50.1176,11.6726),(55.9633,8.24561),(62.3853,5.61404),(70.948,3.33333),(82.263,1.22807),(100,0)))
Units: 1/month
Proposed changes approvals per month

(103) Proposed Change Rate=Proposed Changes*Proposal Change Approval Rate
Units: Proposed Changes/month
Proposed Changes level per month

(104) Proposed Changes= INTEG (Conversion to Changes-Rationalization Rate,12)
Units: Proposed Changes

Proposed Changes based on strategies and knowledge use to balance change growth

(105) Proven Design Factor=1
Units: 1/month

(106) Quality of Drawings and Specifications=0.95
Units: Dmnl
Quality of drawings and technical specifications

(107) Ratio Risk Strategy=Risk Strategy Adj*Active Risks/Strategies
Units: Dmnl
Ratio of Active Risks to Strategies

(108) Rationalization Rate=Organization Integration*Proposed Changes*Knowledge Use*Learning Effort*Strategy to Knowledge Use Ratio
Units: Proposed Changes/month
Rationalization and reduction of changes through knowledge use

(109) Relational Contracting Effort=0.7
Units: Dmnl
Relational contracting effort, building trust and learning with external contractors

(110) Relative Time=Time/Month
Units: Dmnl

(111) Rework= INTEG (max((Error Rate+Discovery Rate),0),1)
Units: Tasks
Number of tasks requiring rework

(112) Rework Detection Fraction=0.005
Units: 1/month
Fraction rework detected

(113) Rework Effect=Gain Design Maturity/3
Units: 1/month
Rework Effect balancing Gain Design Maturity

(114) Risk Generation=Active Risks*Risk Intensity
Units: Active Risks/month
Reinforcing effect of Active Risk Growth

(115) Risk Intensity=0.22
Units: 1/month
Intensity of Active Risks per month

(116) Risk Management Process Maturity=0.8

Units: Dmnl

(117) Risk Mitigation=Risk Management Process Maturity*Effect of Strategies*Active Risks/Average Risk Resolution Time
Units: Active Risks/month
Balancing effect in reduction of active risks

(118) Risk Strategy Adj=1
Units: Strategies/Active Risks

(119) SAVEPER = TIME STEP
Units: month [0,?]
The frequency with which output is stored.

(120) Schedule Correction Factor=SRL
Units: Dmnl

(121) SNA Power Std Dev= 0.17
Units: Dmnl

(122) SPI=Engineering Tasks Done/Planned Work
Units: Dmnl
Earned work completed to planned work

(123) SRL= 0.45
Units: Dmnl
System Readiness Level from the MCDM IAF DSS

(124) Strategic Management Process Maturity=0.8
Units: month

(125) Strategies= INTEG (Strategy Generation-Strategy Reduction,1)
Units: Strategies
Number of Strategies

(126) Strategies Proposed Changes Adjustment=Strategy Effect(Strategy Proposed Change Ratio)
Units: Dmnl
Strategies to Proposed Changes Adjustment as per Strategy Effect Lookup

(127) Strategy Development Rate=1
Units: month

(128) Strategy Effect([(0,0)-(55,5)],(0,0),(12.2783,0.328948),(24.5566,1.27193),(55,5))
Units: Dmnl
Number Strategies to Proposed Changes Lever

(129) Strategy Generation=Strategies*Gaming Adjustment*Organization Integration*Effect Ease of Change on Strategies/Strategy Devlopment Rate
Units: Strategies/month
Strategy Generation balanced by ratio of risks to strategies

(130) Strategy Proposed Change Adj=1.2
Units: Proposed Changes/Strategies

(131) Strategy Proposed Change Ratio=Strategy Proposed Change Adj*Strategies/Proposed Changes
Units: Dmnl

(132) Strategy Reduction=Culture Eating Strategy Effect*Adjusted Fraction of Non-Converging Strategies*Strategies/Strategic Management Process Maturity
Units: Strategies/month
Reduction of strategies

(133) Strategy to Knowledge Use Ratio=0.6
Units: 1/Knowledge

(134) Strategy Variety=0.4
Units: Active Risks/Strategies
Variety of Strategies in addressing risks

(135) Supply and VFI Process Maturity=0.8
Units: Dmnl

(136) Task Completion Rate=Knowledge Use*Organization Integration*Engineering Tasks To Do*Learning Effort*Schedule Correction Factor*Tasks to Knowledge Use Ratio
Units: Tasks/month
Tasks depletion rate

(137) Tasks to Knowledge Use Ratio=1
Units: 1/Knowledge

(138) Team Colocation=0.8
Units: Dmnl

(139) TIME STEP = 0.0625
Units: month [0,?]
The time step for the simulation.

(140) Time to Resolve VFI=0.8
Units: month
time to resolve and reduce Required VFI and increase maturity

(141) Transfer Rate=Effect of Knowledge Capacity*Normal Transfer Rate
Units: 1/month
Transfer rate dependent on effect of Knowledge level and capacity of 100%

(142) VFI Acquisition Rate=Supply and VFI Process Maturity*VFI Required*Learning From Liaising with Vendors*Paying for VFI/Time to Resolve VFI
Units: VFI/month
rate of maturing VFI

(143) VFI Maturity= INTEG (VFI Acquisition Rate,1)
Units: VFI
Level of mature VFI

(144) VFI Maturity Effect=2
Units: 1/VFI

(145) VFI Required= INTEG (-VFI Acquisition Rate,99)
Units: VFI
VFI Required level

Appendix E – INCOSE IW2020 Survey Histograms and Respondent Results

Histograms for the INCOSE IW2020 response to survey questions follow:

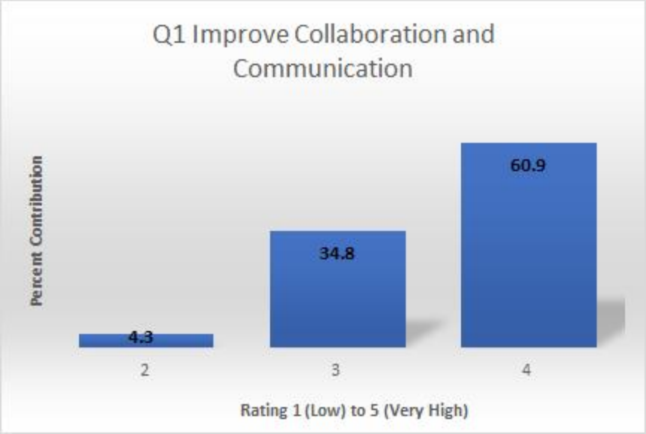


Figure E-1. Histogram Q1 Improve Collaboration and Communication

For Q1, 95.7 percent of responses included ratings from 3 to 4, with a negatively skewed distribution and the majority of responses at a rating of 4.

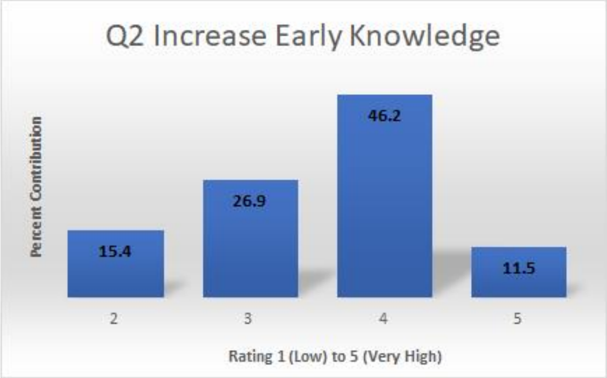


Figure E-2. Histogram Q2 Increase Early Knowledge

For Q2, 84.6 percent of responses included ratings from 3 to 5, with a high contribution toward a rating of 4.

Figure E-3. Histogram Q3 Risk Management

For Q3, all responses included ratings from 3 to 4, with a significant portion at a rating of 4.

Figure E-4. Histogram Q4 Promote Learning and Systems Engineering Tools

For Q4, 75.0 percent of responses included ratings from 3 to 5, with the majority around ratings of 3 and 4.

Figure E-5. Histogram Q5 Perspectives for Managing Complexity

For Q5, all responses included ratings from 3 to 5, with a normal distribution around a mean of 4.11 and a mode of 4.0.

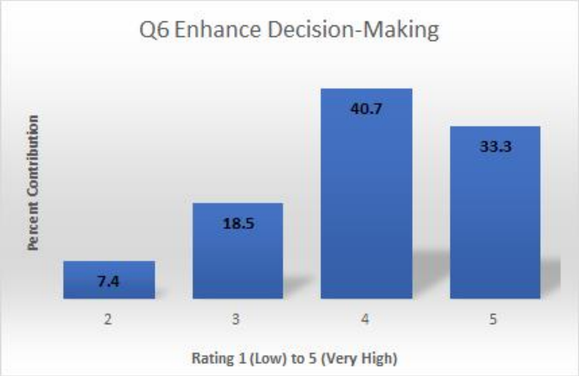


Figure E-6. Histogram Q6 Enhance Decision-Making

For Q6, 92.6 percent of responses included ratings from 3 to 5, with a negatively skewed distribution.

Figure E-7. Histogram Q7 Improve Product Quality

For Q7, 85.2 percent of responses included ratings from 3 to 4, with the majority at a rating of 4.

Figure E-8. Histogram Q8 Improve Project Performance

For Q8, all responses included ratings from 3 to 5, with the majority at a rating of 4.

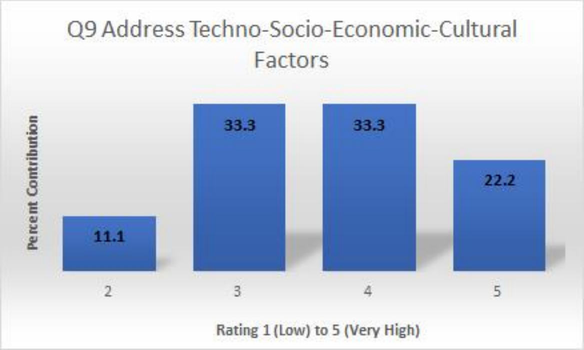


Figure E-9. Histogram Q9 Address Techno-Socio-Economic and Cultural Factors

For Q9, 88.9 percent of responses included ratings from 3 to 5, with a normal distribution and a majority of responses around a rating of 3 and 4.

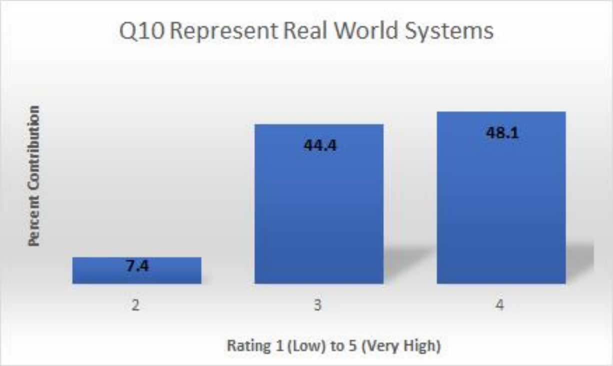


Figure E-10. Histogram Q10 Represent Real World Systems

For Q10, 92.6 percent of responses included ratings from 3 to 4, with a negatively skewed distribution.

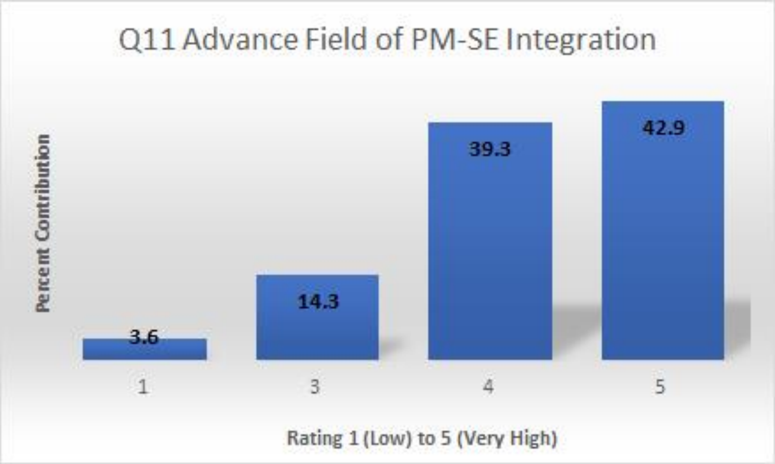


Figure E-11. Histogram Q11 Advance Field of PM-SE Integration

For Q11, 96.4 percent of responses included ratings from 3 to 5, with a negatively skewed distribution.

The histograms for the two groups of questions are provided in Figures 18 and 19.

Figure E-12. Group 1 Knowledge Management Histogram

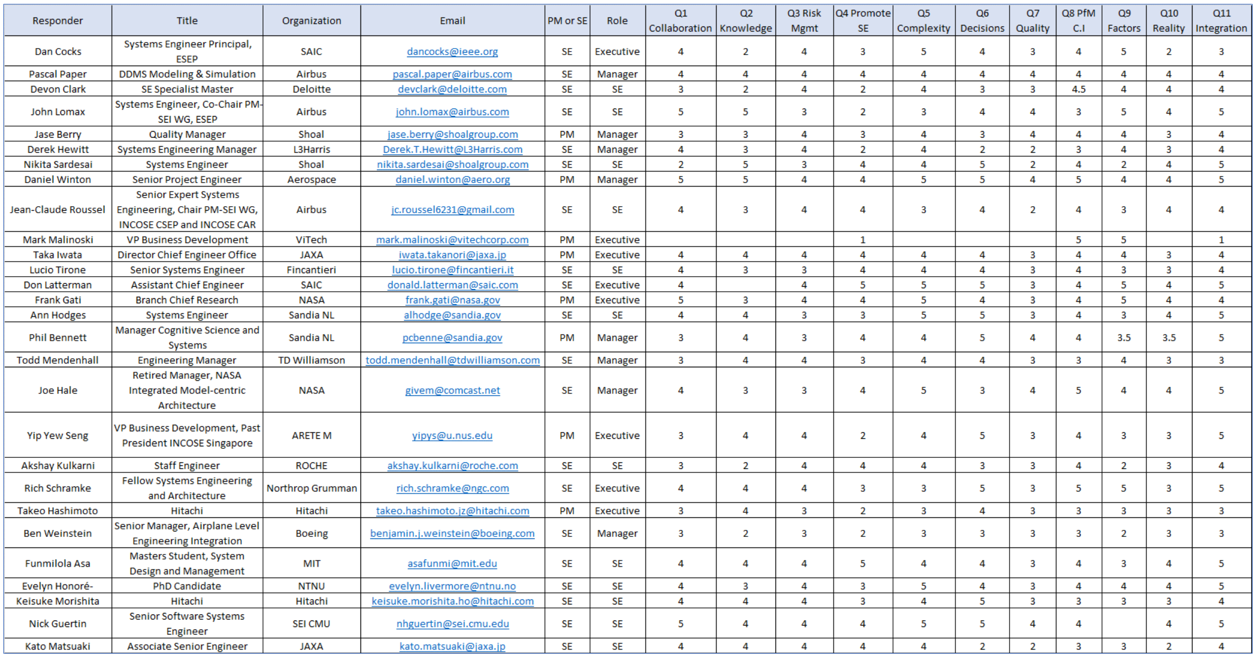
For Group 1, 85.1 percent of responses relate to ratings from 3 to 5 with a negatively skewed distribution.

Figure E-13. Group 2 Risk and Strategy Management Histogram

For Group 2, 97.5 percent of responses relate to ratings from 3 to 5, with most responses at a rating of 4.

Table E-1 provides a summary of responses to the IW2020 survey, individual responses follow.

Table E-1. IW2020 Survey Individual Responses.



Responder	Title	Organization	Email	PM or SE	Role	Q1 Collaboration	Q2 Knowledge	Q3 Risk Mgmt	Q4 Promote SE	Q5 Complexity	Q6 Decisions	Q7 Quality	Q8 PfM C.I	Q9 Factors	Q10 Reality	Q11 Integration
Dan Cocks	Systems Engineer Principal, ESEP	SAIC	dancocks@ieee.org	SE	Executive	4	2	4	3	5	4	3	4	5	2	3
Pascal Paper	DDMS Modeling & Simulation	Airbus	pascal.paper@airbus.com	SE	Manager	4	4	4	4	4	4	4	4	4	4	4
Devon Clark	SE Specialist Master	Deloitte	devclark@deloitte.com	SE	SE	3	2	4	2	4	3	3	4.5	4	4	4
John Lomax	Systems Engineer, Co-Chair PM-SEI WG, ESEP	Airbus	john.lomax@airbus.com	SE	SE	5	5	3	2	3	4	4	3	5	4	5
Jase Berry	Quality Manager	Shoal	jase.berry@shoalgroup.com	PM	Manager	3	3	4	3	4	3	4	4	4	3	4
Derek Hewitt	Systems Engineering Manager	L3Harris	Derek.T.Hewitt@L3Harris.com	SE	Manager	4	3	4	2	4	2	2	3	4	3	4
Nikita Sardesai	Systems Engineer	Shoal	nikita.sardesai@shoalgroup.com	SE	SE	2	5	3	4	4	5	2	4	2	4	5
Daniel Winton	Senior Project Engineer	Aerospace	daniel.winton@aero.org	PM	Manager	5	5	4	4	5	5	4	5	4	4	5
Jean-Claude Roussel	Senior Expert Systems Engineering, Chair PM-SEI WG, INCOSE CSEP and INCOSE CAR	Airbus	jc.roussel6231@gmail.com	SE	SE	4	3	4	4	3	4	2	4	3	4	4
Mark Malinoski	VP Business Development	ViTech	mark.malinoski@vitechcorp.com	PM	Executive				1				5	5		1
Taka Iwata	Director Chief Engineer Office	JAXA	iwata.takanori@jaxa.jp	PM	Executive	4	4	4	4	4	4	3	4	4	3	4
Lucio Tirone	Senior Systems Engineer	Fincantieri	lucio.tirone@fincantieri.it	SE	SE	4	3	3	4	4	4	3	4	3	3	4
Don Latterman	Assistant Chief Engineer	SAIC	donald.latterman@saic.com	SE	Executive	4		4	5	5	5	3	4	5	4	5
Frank Gati	Branch Chief Research	NASA	frank.gati@nasa.gov	PM	Executive	5	3	4	4	5	4	3	4	5	4	4
Ann Hodges	Systems Engineer	Sandia NL	alhodge@sandia.gov	SE	SE	4	4	3	3	5	5	3	4	3	4	5
Phil Bennett	Manager Cognitive Science and Systems	Sandia NL	pcbenne@sandia.gov	PM	Manager	3	4	3	4	4	5	4	4	3.5	3.5	5
Todd Mendenhall	Engineering Manager	TD Williamson	todd.mendenhall@tdwilliamson.com	SE	Manager	3	4	4	3	4	4	3	3	4	3	3
Joe Hale	Retired Manager, NASA Integrated Model-centric Architecture	NASA	givem@comcast.net	SE	Manager	4	3	3	4	5	3	4	5	4	4	5
Yip Yew Seng	VP Business Development, Past President INCOSE Singapore	ARETE M	yipys@u.nus.edu	PM	Executive	3	4	4	2	4	5	3	4	3	3	5
Akshay Kulkarni	Staff Engineer	ROCHE	akshay.kulkarni@roche.com	SE	SE	3	2	4	4	4	3	3	4	2	3	4
Rich Schramke	Fellow Systems Engineering and Architecture	Northrop Grumman	rich.schramke@ngc.com	SE	Executive	4	4	4	3	3	5	3	5	5	3	5
Takeo Hashimoto	Hitachi	Hitachi	takeo.hashimoto.jz@hitachi.com	PM	Executive	3	4	3	2	3	4	3	3	3	3	3
Ben Weinstein	Senior Manager, Airplane Level Engineering Integration	Boeing	benjamin.j.weinstein@boeing.com	SE	Manager	3	2	3	2	3	3	3	3	2	3	3
Funmilola Asa	Masters Student, System Design and Management	MIT	asafunmi@mit.edu	SE	SE	4	4	4	5	4	4	3	4	3	4	5
Evelyn Honoré-	PhD Candidate	NTNU	evelyn.livermore@ntnu.no	SE	SE	4	3	4	3	5	4	3	4	4	4	5
Keisuke Morishita	Hitachi	Hitachi	keisuke.morishita.ho@hitachi.com	SE	SE	4	4	4	3	4	5	3	3	3	3	4
Nick Guertin	Senior Software Systems Engineer	SEI CMU	nhguertin@sei.cmu.edu	SE	SE	5	4	4	4	5	5	4	4		4	5
Kato Matsuaki	Associate Senior Engineer	JAXA	kato.matsuaki@jaxa.jp	SE	SE	4	4	4	4	4	2	2	3	3	2	4

Tue 28, Jan 13:00-14:00

Survey Question and Answer Session:
A Model(s)-Based Approach to PM-SE Integration

Chair: Kamran Eftekhari Shahroudi Co-Presenter: Raymond Jonkers, PhD Candidate

How do you rate (*Circle Low 1 to Very High 5*) the potential of the Management Flight Simulator to:

1. improve Communication and Collaboration?
   1 | 2 | 3 | [✓ 4] | 5
2. increase early Knowledge, Learning and provide Mental Models?
   1 | [✓ 2] | 3 | 4 | 5
3. proactively address risks and promote a Risk Management culture?
   1 | 2 | 3 | [✓ 4] | 5
4. promote learning and application of Systems Engineering and its models?
   1 | 2 | [✓ 3] | 4 | 5
5. provide different Perspectives for addressing Complexity?
   1 | 2 | 3 | 4 | [✓ 5]
6. enhance Tradeoff Analysis and Optimize design change Decisions?
   1 | 2 | 3 | [✓ 4] | 5
7. increase Product Quality?
   1 | 2 | [✓ 3] | 4 | 5
8. improve Project Performance and foster Continuous Improvement?
   1 | 2 | 3 | [✓ 4] | 5
9. address techno-socio-economic and cultural factors?
   1 | 2 | 3 | 4 | [✓ 5]
10. represent real world systems, predict and analyze behavior?
    1 | [✓ 2] | 3 | 4 | 5
11. advance the field of Systems Engineering and Project Management Integration?
    1 | 2 | [✓ 3] | 4 | 5

Responder's Name: DAN COCKS
Organization: SAIC
Email: dancocks@ieee.org

Additional Feedback: VERY HARD TO APPRECIATE WITH SUCH A QUICK OVERVIEW. PRESENTATION SHOWED LOTS OF SWITCHES, BUT LITTLE INSIGHT TO APPRECIATE IMPACTS. "TRUST ME. IT'S ALL GOOD UNDER THE HOOD" WITH LINKED MODELS MAKES THIS HARD TO RAPIDLY ASSESS.

After Session Contact: ray.jonkers@merlantec.ca

Tue 28, Jan 13:00-14:00

Survey Question and Answer Session:
A Model(s)-Based Approach to PM-SE Integration

Chair: Kamran Eftekhari Shahroudi Co-Presenter: Raymond Jonkers, PhD Candidate

How do you rate (*Circle Low 1 to Very High 5*) the potential of the Management Flight Simulator to:

1. improve Communication and Collaboration?
   1 2 3 [✓ 4] 5
2. increase early Knowledge, Learning and provide Mental Models?
   1 2 3 [✓ 4] 5
3. proactively address risks and promote a Risk Management culture?
   1 2 3 [✓ 4] 5
4. promote learning and application of Systems Engineering and its models?
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10. represent real world systems, predict and analyze behavior?
    1 2 3 [✓ 4] 5
11. advance the field of Systems Engineering and Project Management Integration?
    1 2 3 [✓ 4] 5

Responder's Name: PAPER Pascal
Organization: AIRBUS / DDMS
Email: pascal.paper@airbus.com
Additional Feedback:

After Session Contact: ray.jonkers@merlantec.ca

Tue 28, Jan 13:00-14:00

Survey Question and Answer Session:
A Model(s)-Based Approach to PM-SE Integration

Chair: Kamran Eftekhari Shahroudi   Co-Presenter: Raymond Jonkers, PhD Candidate

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1. improve Communication and Collaboration?
   1 | 2 | [✓ 3] | 4 | 5
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   1 | 2 | [✓ 3] | 4 | 5
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   1 | 2 | 3 | [✓ 4 | 5]
9. address techno-socio-economic and cultural factors?
   1 | 2 | 3 | [✓ 4] | 5
10. represent real world systems, predict and analyze behavior?
    1 | 2 | 3 | [✓ 4] | 5
11. advance the field of Systems Engineering and Project Management Integration?
    1 | 2 | 3 | [✓ 4] | 5

Responder's Name: Devon Clark
Organization: Deloitte
Email: devclark@deloitte.com

Additional Feedback:
The reason that some of my ratings are on the lower side is because it ~~was not~~ seemed ~~clear~~ to me ~~two~~ that there was a lot of user feel to how to represent changes by adjusting levers. As it stands, to understand how levers will affect outcomes to know which to adjust, you need to understand the intricacies + interconnections of the model. As a result, there will be incentives for teams to status a certain way/.

After Session Contact: ray.jonkers@merlantec.ca

so the "use" by lower level teams may not be appropriate

Tue 28, Jan 13:00-14:00

Survey Question and Answer Session:
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Chair: Kamran Eftekhari Shahroudi Co-Presenter: Raymond Jonkers, PhD Candidate

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   1 | 2 | 3 | 4 | [✓ 5]
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   1 | 2 | [✓ 3] | 4 | 5
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   1 | 2 | [✓ 3] | 4 | 5
6. enhance Tradeoff Analysis and Optimize design change Decisions?
   1 | 2 | 3 | [✓ 4] | 5
7. increase Product Quality?
   1 | 2 | 3 | [✓ 4] | 5
8. improve Project Performance and foster Continuous Improvement?
   1 | 2 | [✓ 3] | 4 | 5
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   1 | 2 | 3 | 4 | [✓ 5]
10. represent real world systems, predict and analyze behavior?
    1 | 2 | 3 | [✓ 4] | 5
11. advance the field of Systems Engineering and Project Management Integration?
    1 | 2 | 3 | 4 | [✓ 5]

Responder's Name: John Lomax
Organization: AIRBUS
Email: john.lomax@airbus.com

Additional Feedback:

Fantastic. Good Job. A+

After Session Contact: ray.jonkers@merlantec.ca

Tue 28, Jan 13:00-14:00

Survey Question and Answer Session:
A Model(s)-Based Approach to PM-SE Integration

Chair: Kamran Eftekhari Shahroudi Co-Presenter: Raymond Jonkers, PhD Candidate

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   1 2 3 [✓ 4] 5
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   1 2 3 [✓ 4] 5
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   1 2 3 [✓ 4] 5
10. represent real world systems, predict and analyze behavior?
    1 2 [✓ 3] 4 5
11. advance the field of Systems Engineering and Project Management Integration?
    1 2 3 [✓ 4] 5

Responder's Name: Jase Berry
Organization: Shaw
Email: jase.berry@shawgroup.com
Additional Feedback:
Representing fluffy areas such as "Knowledge maturity" in a numeric metric is a challenging task!
Great see you are working towards this and actively seeking feedback.

After Session Contact: ray.jonkers@merlantec.ca

Tue 28, Jan 13:00-14:00

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Chair: Kamran Eftekhari Shahroudi
Co-Presenter: Raymond Jonkers, PhD Candidate

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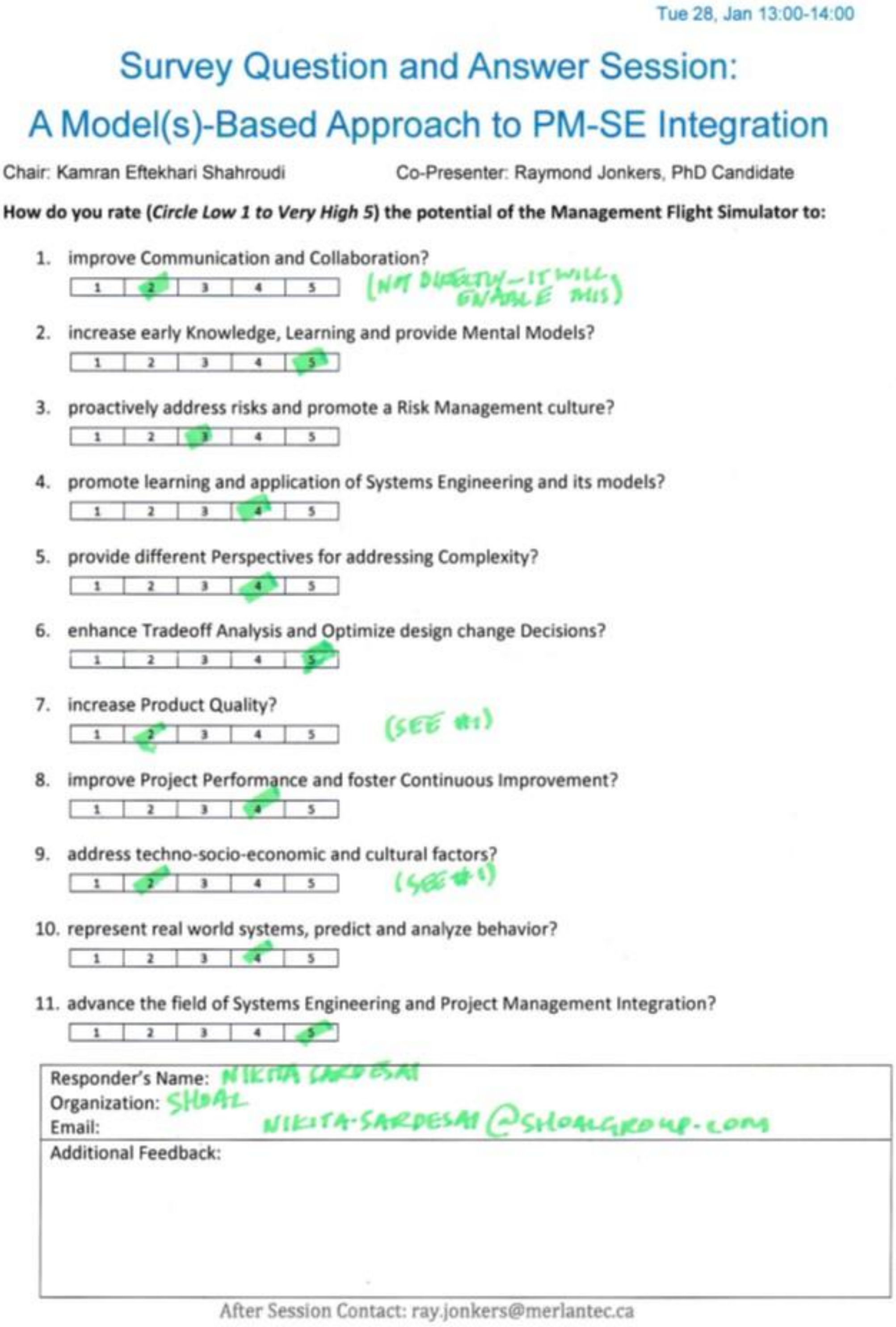
10. represent real world systems, predict and analyze behavior?
    1 2 [✓ 3] 4 5
11. advance the field of Systems Engineering and Project Management Integration?
    1 2 3 [✓ 4] 5

Responder's Name: Derek Hewitt
Organization:
Email: Derek.T.Hewitt@L3Harris.com

Additional Feedback:
Very complex tool with a lot of variables. Difficult to understand in such a short period of time. I have a hard time truly seeing most of the real world applications for a project. But I do like the potential to show many complex aspects of a project + how they are connected.

After Session Contact: ray.jonkers@merlantec.ca



Tue 28, Jan 13:00-14:00

Survey Question and Answer Session:
A Model(s)-Based Approach to PM-SE Integration

Chair: Kamran Eftekhari Shahroudi
Co-Presenter: Raymond Jonkers, PhD Candidate

How do you rate (*Circle Low 1 to Very High 5*) the potential of the Management Flight Simulator to:

1. improve Communication and Collaboration?
   1 [✓ 2] 3 4 5 (NOT DIRECTLY – IT WILL ENABLE THIS)
2. increase early Knowledge, Learning and provide Mental Models?
   1 2 3 4 [✓ 5]
3. proactively address risks and promote a Risk Management culture?
   1 2 [✓ 3] 4 5
4. promote learning and application of Systems Engineering and its models?
   1 2 3 [✓ 4] 5
5. provide different Perspectives for addressing Complexity?
   1 2 3 [✓ 4] 5
6. enhance Tradeoff Analysis and Optimize design change Decisions?
   1 2 3 4 [✓ 5]
7. increase Product Quality?
   1 [✓ 2] 3 4 5 (SEE #1)
8. improve Project Performance and foster Continuous Improvement?
   1 2 3 [✓ 4] 5
9. address techno-socio-economic and cultural factors?
   1 [✓ 2] 3 4 5 (SEE #1)
10. represent real world systems, predict and analyze behavior?
    1 2 3 [✓ 4] 5
11. advance the field of Systems Engineering and Project Management Integration?
    1 2 3 4 [✓ 5]

Responder's Name: NIKITA SARDESAI
Organization: SHOAL
Email: NIKITA.SARDESAI@SHOALGROUP.COM

Additional Feedback:

After Session Contact: ray.jonkers@merlantec.ca

Tue 28, Jan 13:00-14:00

Survey Question and Answer Session:
A Model(s)-Based Approach to PM-SE Integration

Chair: Kamran Eftekhari Shahroudi   Co-Presenter: Raymond Jonkers, PhD Candidate

How do you rate (*Circle Low 1*

1. improve Communicatic
   1 2 3

   1 5

2. increase early Knowled
   1 2 3

   2 5

3. proactively address risk
   1 2 3

   3 4

4. promote learning and a
   1 2 3

   4 4

5. provide different Persp
   1 2 3 4

   5 5

6. enhance Tradeoff Analy
   1 2 3 4

   6 5

7. increase Product Qualit
   1 2 3 4

   7 4

8. improve Project Perforn
   1 2 3 4

   8 5

9. address techno-socio-ec
   1 2 3 4

   9 4

10. represent real world sys
    1 2 3 4

    10 4

11. advance the field of Syst
    1 2 3 4

    11 5

Responder's Name:
Organization:
Additional Feedback:

daniel.b.winton
@aero.org

After

Tue 28, Jan 13:00-14:00

Survey Question and Answer Session:

A Model(s)-Based Approach to PM-SE Integration

Chair: Kamran Eftekhari Shahroudi Co-Presenter: Raymond Jonkers, PhD Candidate

How do you rate (*Circle Low 1 to Very High 5*) the potential of the Management Flight Simulator to:

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   1 2 [✓ 3] 4 5
10. represent real world systems, predict and analyze behavior?
    1 2 3 [✓ 4] 5
11. advance the field of Systems Engineering and Project Management Integration?
    1 2 3 [✓ 4] 5

Responder's Name: Jean Claude ROUSSEL
Organization: AIRBUS
Email: jc.roussel6231@gmail.com
Additional Feedback:

After Session Contact: ray.jonkers@merlantec.ca

Tue 28, Jan 13:00-14:00

Survey Question and Answer Session:
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Chair: Kamran Eftekhari Shahroudi Co-Presenter: Raymond Jonkers, PhD Candidate

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   1 2 3 4 5
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   1 2 3 4 5
4. promote learning and application of Systems Engineering and its models?
   [✓ 1] 2 3 4 5
5. provide different Perspectives for addressing Complexity?
   1 2 3 4 5
6. enhance Tradeoff Analysis and Optimize design change Decisions?
   1 2 3 4 5
7. increase Product Quality?
   1 2 3 4 5
8. improve Project Performance and foster Continuous Improvement?
   1 2 3 4 [✓ 5]
9. address techno-socio-economic and cultural factors?
   1 2 3 4 [✓ 5]
10. represent real world systems, predict and analyze behavior?
    1 2 3 4 5
11. advance the field of Systems Engineering and Project Management Integration?
    [✓ 1] 2 3 4 5 NOT YET, BUT POTENTIAL IS HIGH

Responder's Name: MARK MALINOSKI
Organization: VITECH
Email: MARK.MALINOSKI@VITECHCORP.COM

Additional Feedback:
- FANTASTICALLY IMPORTANT WORK
- I'M GETTING TRIPPED UP BY WHAT MANNER OF MBSE/SE IS IN CONTEXT. THERE EXISTS MUCH MORE INTEGRATED MBSE THAT MIGHT NEED CONSIDERATION (I STRUGGLED TO COMPLETE THE SURVEY AS A RESULT)

After Session Contact: ray.jonkers@merlantec.ca

Tue 28, Jan 13:00-14:00

Survey Question and Answer Session:
A Model(s)-Based Approach to PM-SE Integration

Chair: Kamran Eftekhari Shahroudi
Co-Presenter: Raymond Jonkers, PhD Candidate

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11. advance the field of Systems Engineering and Project Management Integration?
    1 | 2 | 3 | [✓ 4] | 5

Responder's Name: Taka(nori) Iwata
Organization: Japan Aerospace Exploration Agency (JAXA)
Email: iwata.takanori@jaxa.jp

Additional Feedback:

After Session Contact: ray.jonkers@merlantec.ca

Tue 28, Jan 13:00-14:00

Survey Question and Answer Session: A Model(s)-Based Approach to PM-SE Integration

Chair: Kamran Eftekhari Shahroudi Co-Presenter: Raymond Jonkers, PhD Candidate

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11. advance the field of Systems Engineering and Project Management Integration?
    1 2 3 [✓ 4] 5

Responder's Name: LUCIO TIRONE
Organization: FINCANTIERI
Email: lucio.tirone@fincantieri.it

Additional Feedback:

After Session Contact: ray.jonkers@merlantec.ca

Tue 28, Jan 13:00-14:00

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11. advance the field of Systems Engineering and Project Management Integration?
    1 | 2 | 3 | 4 | [✓ 5]

Responder's Name: Don Latterman
Organization: SAIC
Email: Donald.Latterman@SAIC.com

Additional Feedback:

After Session Contact: ray.jonkers@merlantec.ca

Tue 28, Jan 13:00-14:00

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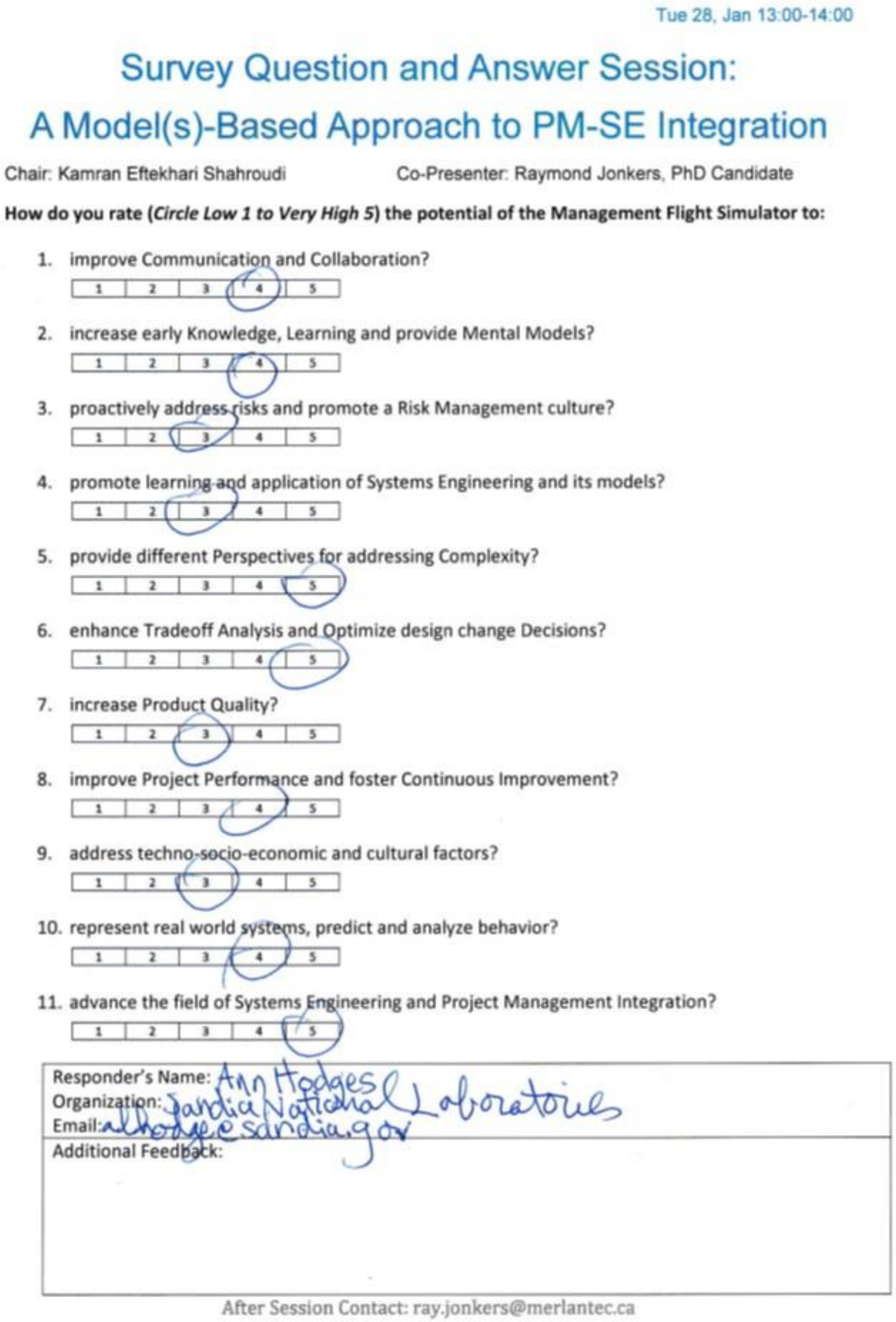
11. advance the field of Systems Engineering and Project Management Integration?
    1 2 3 [✓ 4] 5

Responder's Name: FRANK GATI
Organization: NASA GRC
Email: FRANK.GATI@NASA.GOV

Additional Feedback:

After Session Contact: ray.jonkers@merlantec.ca



Tue 28, Jan 13:00-14:00

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Responder's Name: Ann Hodges
Organization: Sandia National Laboratories
Email: alhodge@sandia.gov
Additional Feedback:

After Session Contact: ray.jonkers@merlantec.ca

Tue 28, Jan 13:00-14:00

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A Model(s)-Based Approach to PM-SE Integration

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Co-Presenter: Raymond Jonkers, PhD Candidate

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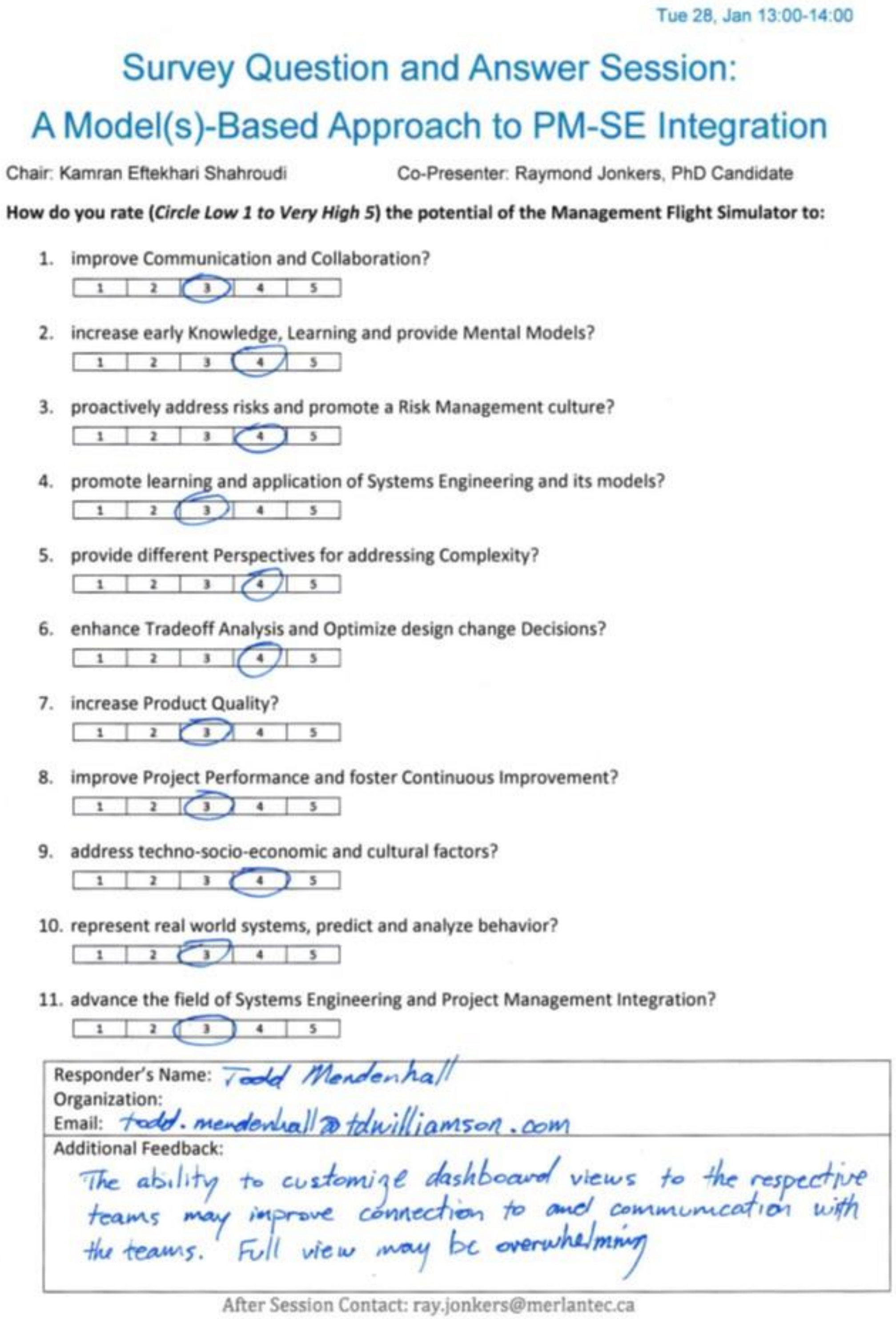
   1 | 2 | [✓ 3] | [✓ 4] | 5
11. advance the field of Systems Engineering and Project Management Integration?
   1 | 2 | 3 | 4 | [✓ 5]

Responder's Name: PHIL BENNETT
Organization: SANDIA NATL LABS
Email: pcbenne@sandia.gov

Additional Feedback:

UNFORTUNATELY SMALL PROJECTION IN ROOM => DIFFICULT TO SEE
SHORT TIME => DIFFICULT TO ASSESS.
WILLING TO GIVE THIS AGAIN VIA WEB OR ONSITE ?

After Session Contact: ray.jonkers@merlantec.ca



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11. advance the field of Systems Engineering and Project Management Integration?
    1 2 [✓ 3] 4 5

Responder's Name: Todd Mendenhall
Organization:
Email: todd.mendenhall@tdwilliamson.com

Additional Feedback:
The ability to customize dashboard views to the respective teams may improve connection to and communication with the teams. Full view may be overwhelming

After Session Contact: ray.jonkers@merlantec.ca

Tue 28, Jan 13:00-14:00

Survey Question and Answer Session:
A Model(s)-Based Approach to PM-SE Integration

Chair: Kamran Eftekhari Shahroudi
Co-Presenter: Raymond Jonkers, PhD Candidate

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Responder's Name: Joe HALE
Organization: Retired NASA
Email: givem@comcast.net

Additional Feedback:

After Session Contact: ray.jonkers@merlantec.ca

Tue 28, Jan 13:00-14:00

Survey Question and Answer Session:
A Model(s)-Based Approach to PM-SE Integration

Chair: Kamran Eftekhari Shahroudi Co-Presenter: Raymond Jonkers, PhD Candidate

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Responder's Name: Yip Yew Seng
Organization: INCOSE Singapore Chapter
Email: yipys@u.nus.edu

Additional Feedback:

After Session Contact: ray.jonkers@merlantec.ca

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Responder's Name: AKSHAY KULKARNI
Organization: ROCHE
Email: akshay.kulkarni@roche.com

Additional Feedback:
Will be good to try some data crunching with a project following Agile or Scaled Agile? just a thought.

After Session Contact: ray.jonkers@merlantec.ca

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Responder's Name: Rich Schramke
Organization: Northrop Grumman
Email: rich.schramke@ngc.com

Additional Feedback: On dashboard, would be good to see before + after changes were made. Looked pretty highly aligned with waterfall methodology (?) How well would this work (models especially) with an agile program?

After Session Contact: ray.jonkers@merlantec.ca

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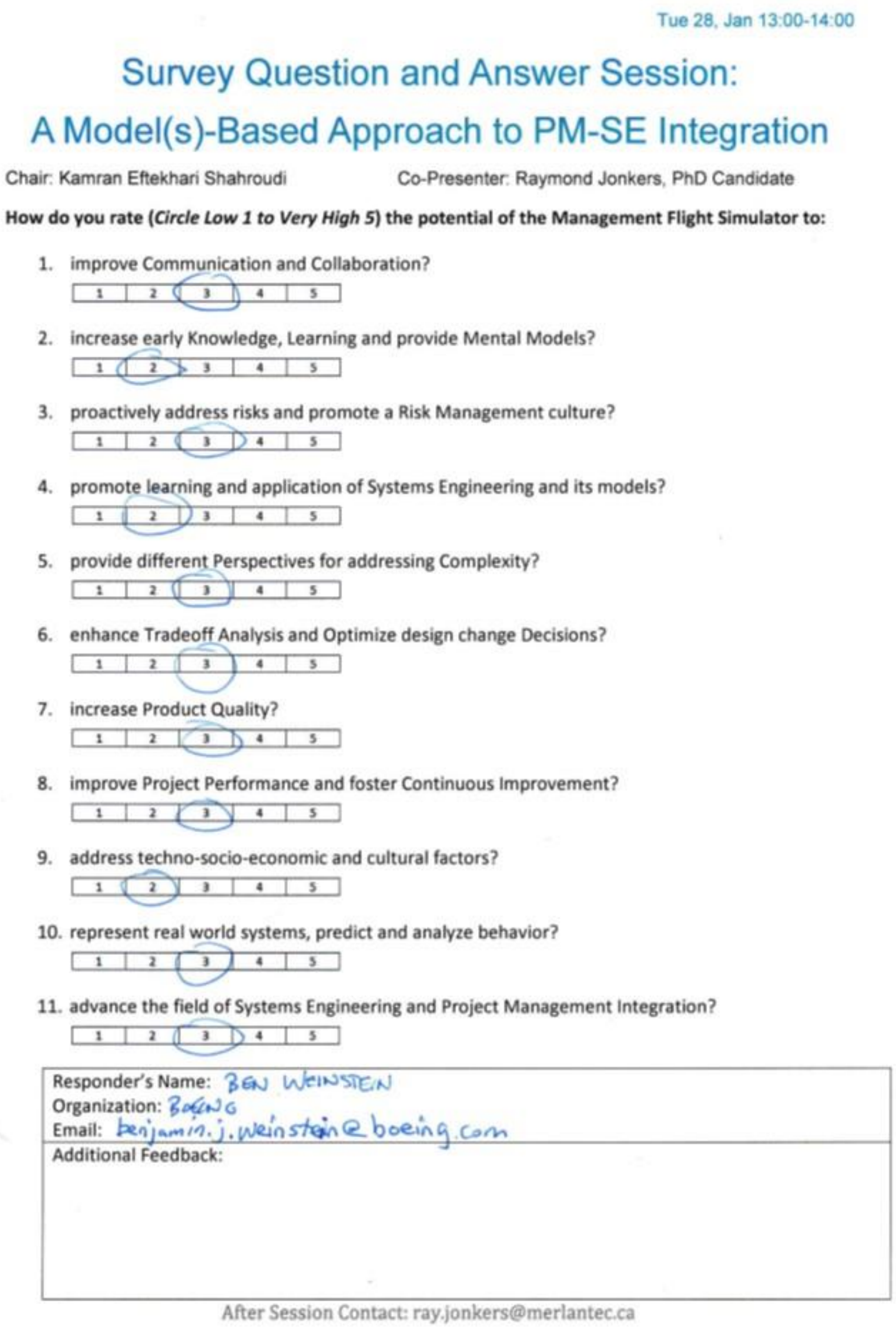
Responder's Name: Takeo Hashimoto
Organization: Hitachi
Email: takeo.hashimoto.jz@hitachi.com

Additional Feedback:

After Session Contact: ray.jonkers@merlantec.ca



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Responder's Name: BEN WEINSTEIN
Organization: BOEING
Email: benjamin.j.weinstein@boeing.com

Additional Feedback:

After Session Contact: ray.jonkers@merlantec.ca

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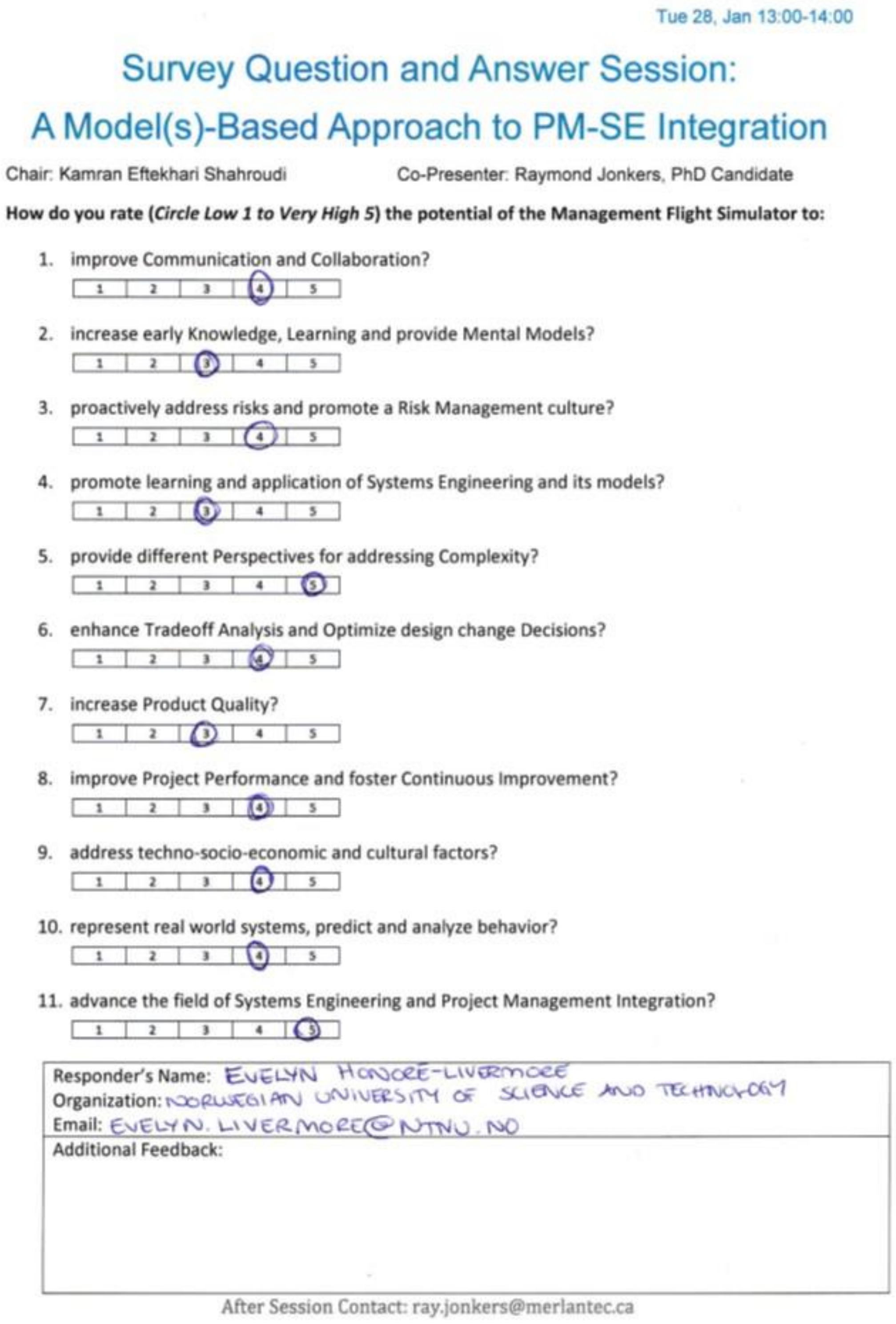
Responder's Name: Funmilola Asa
Organization: MIT (Masters student in System Design & Mgt)
Email: asafunmi@mit.edu

Additional Feedback: The management flight simulator is a great idea for attempting to bridge the gap between SE & PM. Feels like a great way to feed into management reports but skills level required to actually use tool may be atleast one step below management due to significant details.

After Session Contact: ray.jonkers@merlantec.ca



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Responder's Name: EVELYN HONORE-LIVERMORE
Organization: NORWEGIAN UNIVERSITY OF SCIENCE AND TECHNOLOGY
Email: EVELYN.LIVERMORE@NTNU.NO

Additional Feedback:

After Session Contact: ray.jonkers@merlantec.ca

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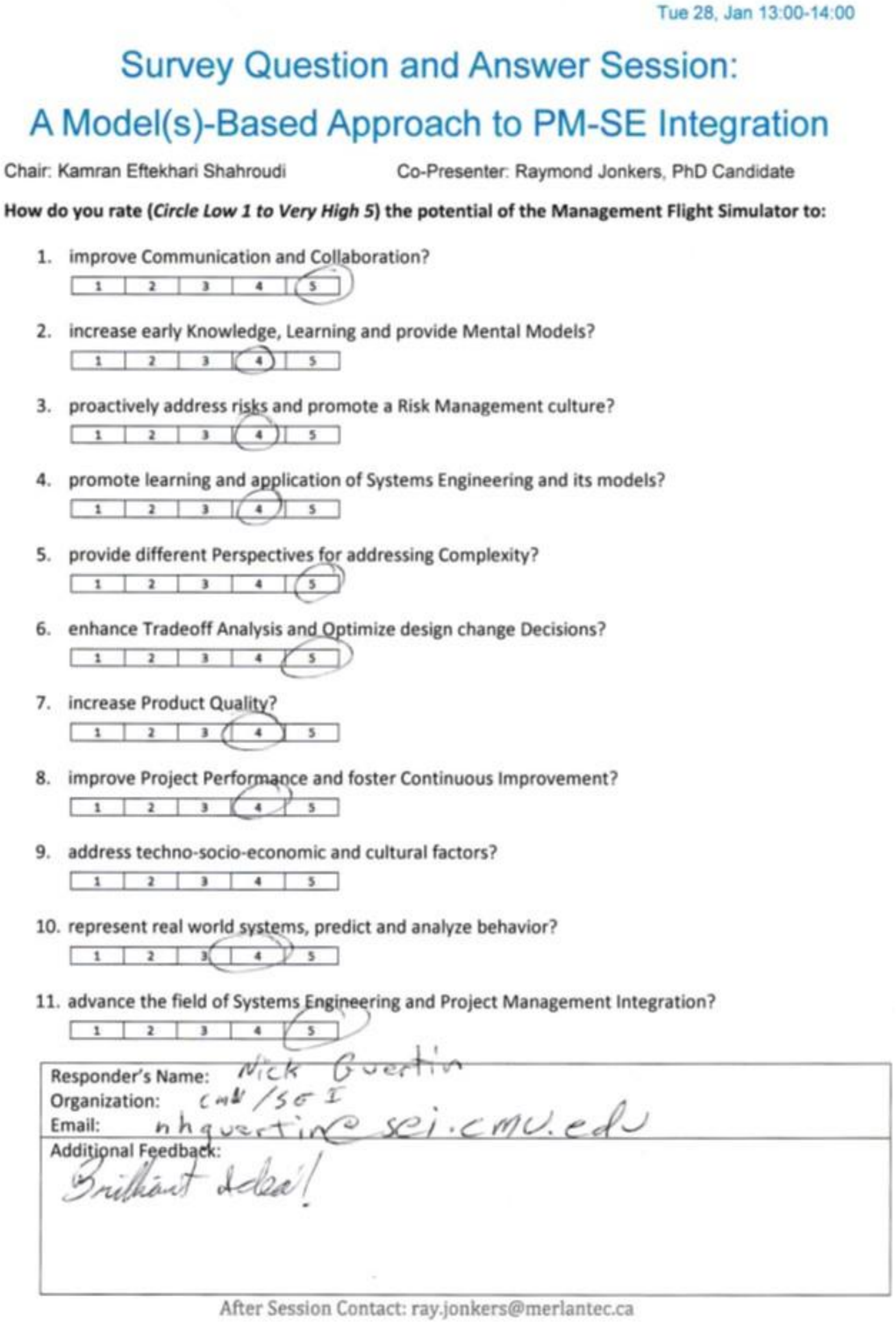
Responder's Name: Keisuke Morishita
Organization: JCOSE/Hitachi
Email: keisuke.morishita.ho@hitachi.com

Additional Feedback:
I'd like to know about relationship with a system model based SysML.

After Session Contact: ray.jonkers@merlantec.ca



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Responder's Name: Nick Guertin
Organization: CMU/SEI
Email: nhguertin@sei.cmu.edu

Additional Feedback:
Brilliant Idea!

After Session Contact: ray.jonkers@merlantec.ca

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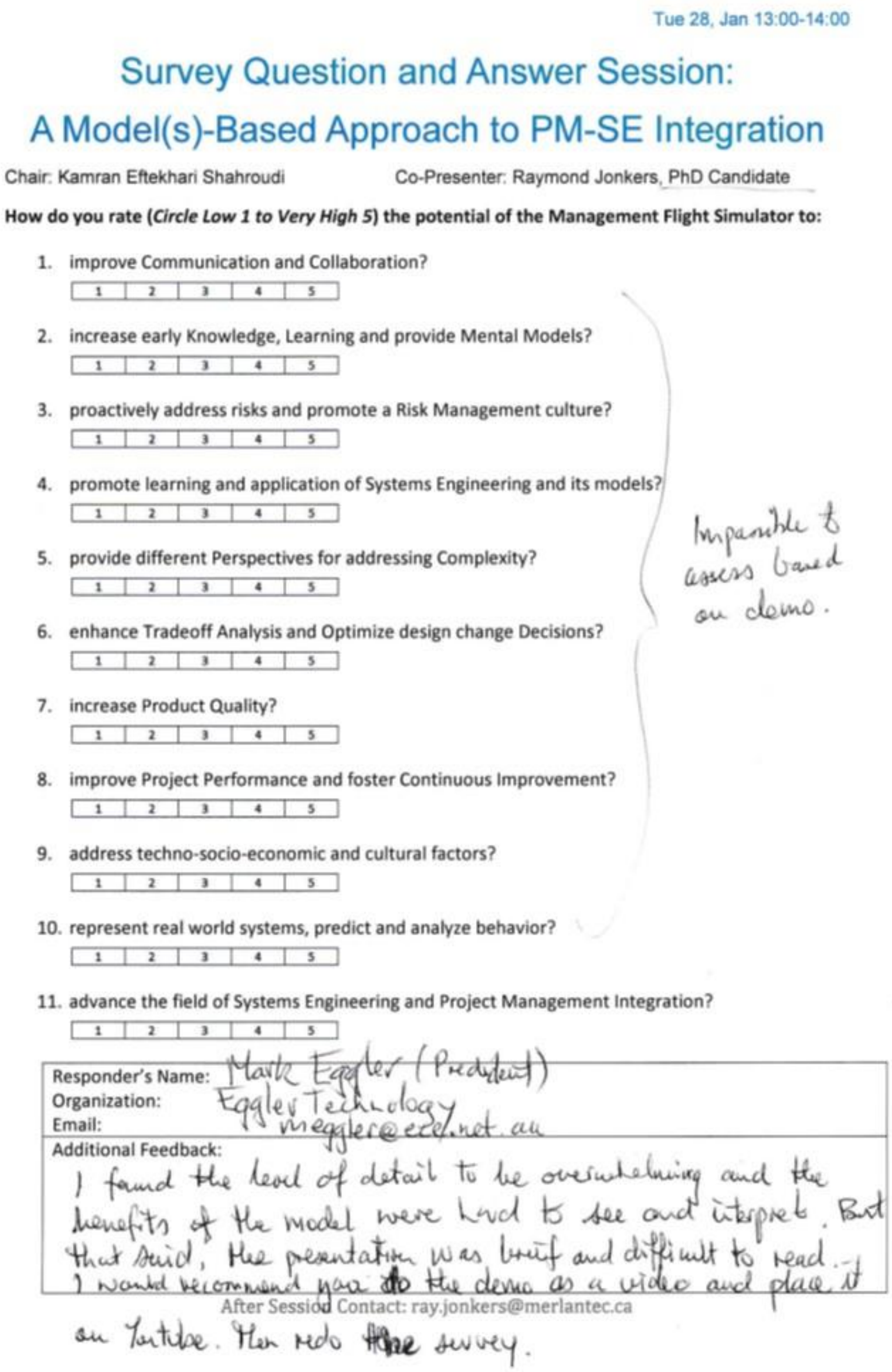
Responder's Name: Matsuki Kato
Organization: JAXA
Email: kato. matsuki @ jaxa. JP

Additional Feedback:

I think it is needed to validate ~~this model~~ in real world.
Is there any plan or idea to feedback from real world

After Session Contact: ray.jonkers@merlantec.ca



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Impossible to assess based on demo.

11. advance the field of Systems Engineering and Project Management Integration?

1	2	3	4	5

Responder's Name: Mark Eggler (President)
Organization: Eggler Technology
Email: meggler@ecel.net.au
Additional Feedback:
I found the level of detail to be overwhelming and the benefits of the model were hard to see and interpret. But that said, the presentation was brief and difficult to read. I would recommend you do the demo as a video and place it on Youtube. Then redo the survey.

After Session Contact: ray.jonkers@merlantec.ca