Accommodating Marine New Technology Insertion and Design Changes Through Use of a Management Flight Simulator

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Synopsis

Several Navies have established policies and initiatives to manage assets and new technologies more efficiently and effectively and implement analytical decision tools and simulation models. In warship design, new technology, changes, ambiguity in expectations, and managing multiple stakeholders add to system and program complexity. Engineers, management and suppliers often work in isolation leading to inconsistencies in product information, tracking of design changes and challenges with decision-making. Despite the many disparate discipline-specific models, tools and techniques in addressing these challenges, product design and program failures are pervasive. Many defence projects have incurred significant cost overruns and delays, with the causes attributed to program pressure, changing requirements, immature technology, and under-estimation of risks. Traditional practices and measures are unable to predict the impact of new technology and design changes. Moreover, there is not a practical approach or tool to help integrate multiple disciplines to better understand system and program complexity and the impact of changes and new technology insertion. Understanding risks, potential changes and technologies through knowledge gain early in the design can help reduce costs and schedule delays. Using set-based design, application of engineering principles and an agile management approach can provide for a robust design that can better accommodate changes and new technology. Along with these principles, systems thinking, system dynamics, a decision support system, and techno-socio-economic and cultural factors are considered in development of a novel management flight simulator. This simulator is presented through application of a case study on an advanced marine integrated power system. The simulator represents a digital twin of the physical system and associated life cycle management curves. It links key discipline specific models through a digital thread that includes the intrinsic properties of the physical system and the intangible assets of knowledge, organizational integration, culture and work performance. Adaptive intelligence and augmentation are possible through recognition and response to system attribute and management behavioural patterns and trends, as visualized within the simulator. As part of the simulator, the decision support system allows for trade-off and what-if analysis where six-sigma attributes are managed. Along with a set-based design and agile approach, disruptive and sustaining technologies can be better managed with the help of the decision support system. The system dynamics sub-model provides visualization and control of design life cycle management curves as impacted by system state. In particular, key system, policy and process interactive levers can be adjusted to improve the behaviour of these curves. 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, vendor-furnished information maturity, design maturity, and work performance. Use of the simulator allows for critical thinking, adaptation to complexity, early knowledge gain, identification of problems early in design, integration of disciplines, and ultimately product and program success. The simulator provides a 'big picture' perspective and total solution not possible with the use of separate engineering and management models.

Keywords: Multi-Discipline; Integration; New technology; Simulation; Decision support; Knowledge management

1. Introduction

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 (Lombardi & Rudd, 2013, Parker, 2016).

Given these challenges, it is important that teams have collaborative analytical tools for predicting and resolving design change and new technology problems. In addressing this need, the current study proposes a novel approach and model by way of a management flight simulator. The strategy and use of the simulator are described through a technology roadmap methodology with application of a complex system case study.

Author's Biography
Raymond Jonkers is a Senior Systems Engineer. A Professional Engineer and Project Manager, he has 22 years experience as a Marine Systems Engineer in the Canadian Navy and 15 years in industry in various management roles. He has led several major equipment projects, engineering changes, a wide range of technology studies, concept development work, and design evaluation.

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2. The Need for an Analytical Decision Support Tool

The need for optimization and analytical decision management tools is supported by project 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 (Behdinan, Ruben & Liu, 2011).

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 (Chalfant, 2015). 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.

The integration of a DSS and key models within a management flight simulator forms a digital twin for adaptive intelligence where teams can develop strategies in response to design changes and new technology insertion. While digital twins have gained traction in the manufacturing industry, they have not been developed for system design and program management. The digital twin simulator in the current study includes system normalized technical and quality measures, visualization of levels and trends in attributes for set-based design, and a system dynamics (SD) model for program management. The simulator brings together multiple disciplines on a common platform using a common language to help understand the different perspectives involved in trade-off solutions.

3. Ontology of New Technologies

Innovation studies have shown that not all technologies are equal in terms of their impact and that a dynamic relationship exists between types of technology and military doctrine (Te Haico & Smit, 2010). The different types of technology, their readiness level and operational relevance are factors considered in deciding whether to adopt them. New technology may be described as sustaining technology, which is aimed at improving system performance, or as disruptive technology which can have a disruptive effect on both the existing physical system and the program.

4. Integrating Models Within the Management Flight Simulator

In the current study, key models are integrated within a management flight simulator using systems thinking, system dynamics and aspects of control system theory. The linking of these models is achieved through a digital thread or knowledge graph of transformational variables, as depicted in Figure 1.

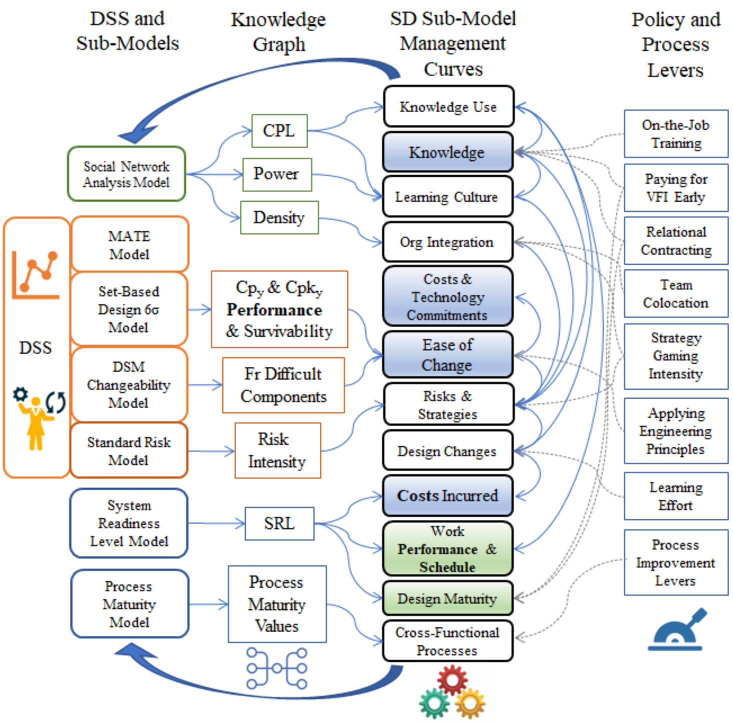

Figure 1. Management Flight Simulator Elements and Linkages

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The simulator and its DSS incorporate the design attributes of performance, survivability and operational capability. The extension of these attributes using a Multi-Attribute Tradespace Exploration (MATE) model provides a new value space that is of importance in the design of defence systems.

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 (MIT, 2017). While MATE is typically used in concept design, it is brought forward into the design cycle in the current study as a reference for component changes and their associated attribute levels.

The DSS includes a SRM, Design Structure Matrices (DSM) and a component changeability dynamic chart. The DSS is supported by a SD model that captures several lifecycle management curves. Other key supporting models include a Systems Readiness Level (SRL) model, Social Network Analysis (SNA) model and a Process Maturity Model (PMM). Each of these integrated models has an important function that addresses the challenges and techno-socio-economic-cultural factors in design change and new technology management.

5. Influencing Key Design Lifecycle Management Curves

The lifecycle management curves depicted in Figure 2 are adapted in the current study (Blanchard & Fabrycky, 1998). These are viewed as rudimentary management curves for product and project success.

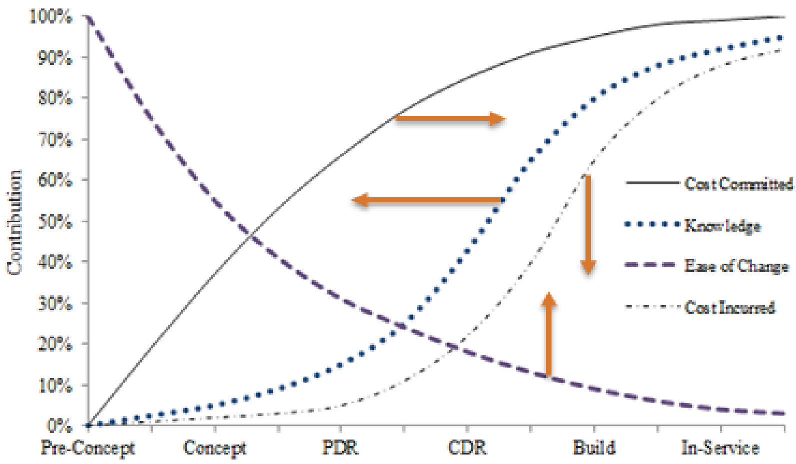

Figure 2. Influencing System Lifecycle Management Curves

Through the application of key system, policy and process levers within the simulator, the knowledge curve may be advanced, ease-of-change curve pushed up, commitments delayed, and incurred costs reduced. It is proposed that this will reduce cost overruns, schedule delays, and better accommodate design changes, new technology, and procurement options throughout the design cycle. Use of the simulator in gaming what-if design change and new technology insertion scenarios can increase knowledge and situational awareness for collective and adaptive intelligence, informed decision-making and a learning culture.

6. System Dynamics and Causal Relationships

Systems dynamics is used to analyze the behaviour in organizational or social systems over time through describing and evaluating causal relationships. One of the earliest uses of systems dynamics for defence programs was conducted by Ingalls Shipbuilding to help validate causes for delays and disruptions in the program (Cantwell, Sarkani & Mazzuchi, 2013).

In SD model development, causal loop diagrams (CLD) are defined using influencing factors, flows and stocks. Feedback loops can be either positive reinforcing (R) loops or negative balancing (B) loops. The behaviour of a stock level (S) or management curve may be described by the integral of inflows minus the outflows, and an initial stock level (S_{to}) as follows:

$$S = \int_{t_0}^{t} (Inflows - Outflows)\, dt + S_{t_0} \qquad (1)$$

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7. Causal Loop Diagrams to Describe Lifecycle Management Curves

Causal loop diagrams are used in the current study to describe the behaviour of management curves in response to technical, organizational and program factors including design changes and new technology insertion. In addition to the typical four management curves, other curves relevant to the current study include design change management, design maturity and work performance.

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 (Morkos, Shankar & Summers, 2012). The cost of making design changes significantly increases throughout the design cycle. This can be 10 times the cost at the critical design stage, increasing up to 100 times at the start of production (Smith. Hargroves & Desha, 2007). In the current study, the average cost per change is adjusted to reflect the effect of time in the design cycle. In addition to this adjustment, a cost correction factor (CCF) is applied to account for the influence of the system readiness level (SRL). The design change and costs incurred CLD, and their influencing factors are depicted in Figure 3.

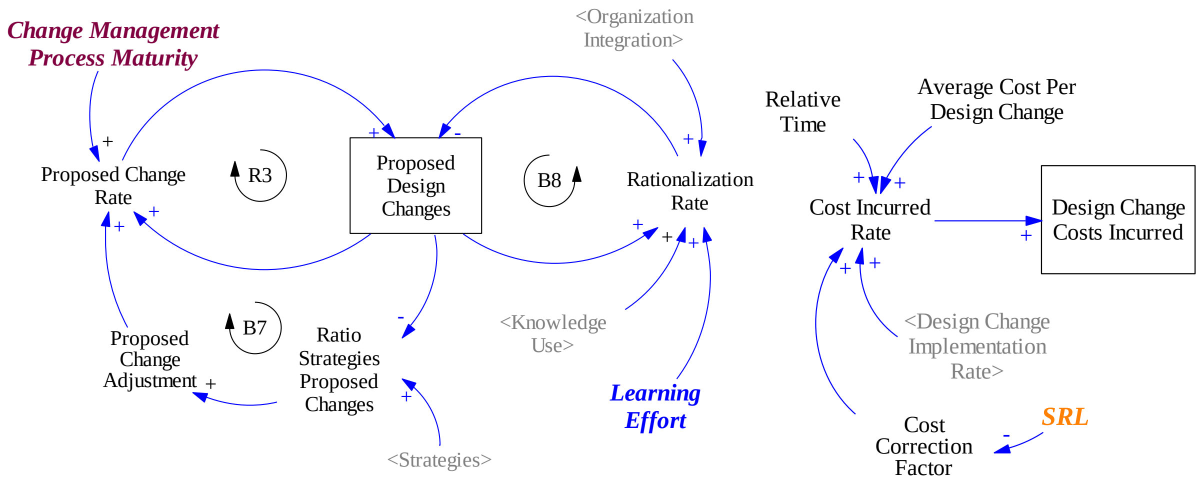

Figure 3. Proposed Design Changes and Costs Incurred CLD

It has been reported that 85 percent of technology and product costs are committed prior to detailed design when little is known on the impact of design changes (Kennedy, Sobek & Kennedy, 2013). At this stage, there is limited knowledge in system components and interdependences. Through set-based design, these commitments may be delayed allowing for new technology insertion, procurement options and a different spend plan. Factors that affect ease-of-change in a system can include the design attribute variance measures of C_{py} and C_{pky}. Other factors include the application of engineering principles. Working toward modularity and loose coupling of system components has been known to reduce costs and increase flexibility in design (Sanchez & Mahoney, 1996). As depicted in Figure 4, ease of change in a physical system can help decrease the rate of commitments.

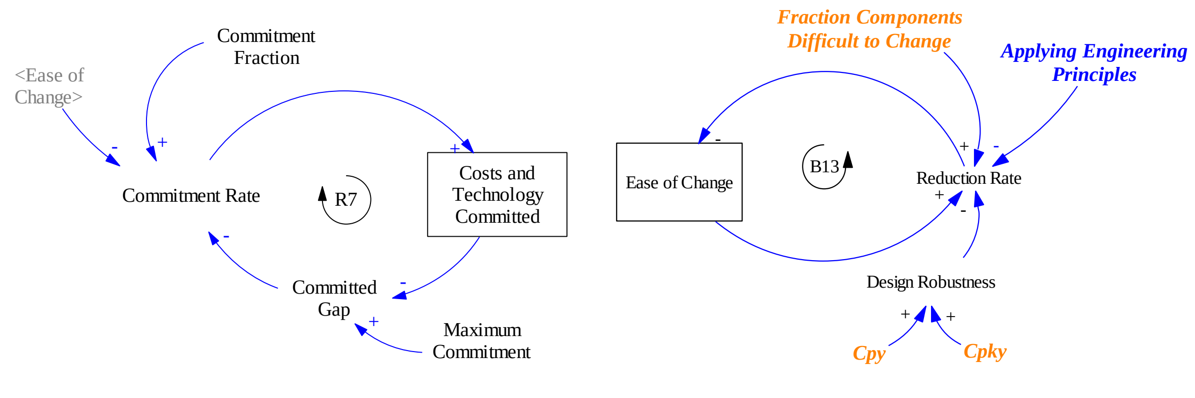

Figure 4. Commitments and Ease of Change CLD

In the NASA review of past project challenges, it was noted that knowledge is lost at project lifecycle phase boundaries, resulting in increased development cost and risk of delayed discovery of design problems (Bayes,

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2009). 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 (Chalfant, 2015).

As depicted in Figure 5, the knowledge CLD includes several factors that affect the generation and transfer of knowledge across the organization and lifecycle phase boundaries.

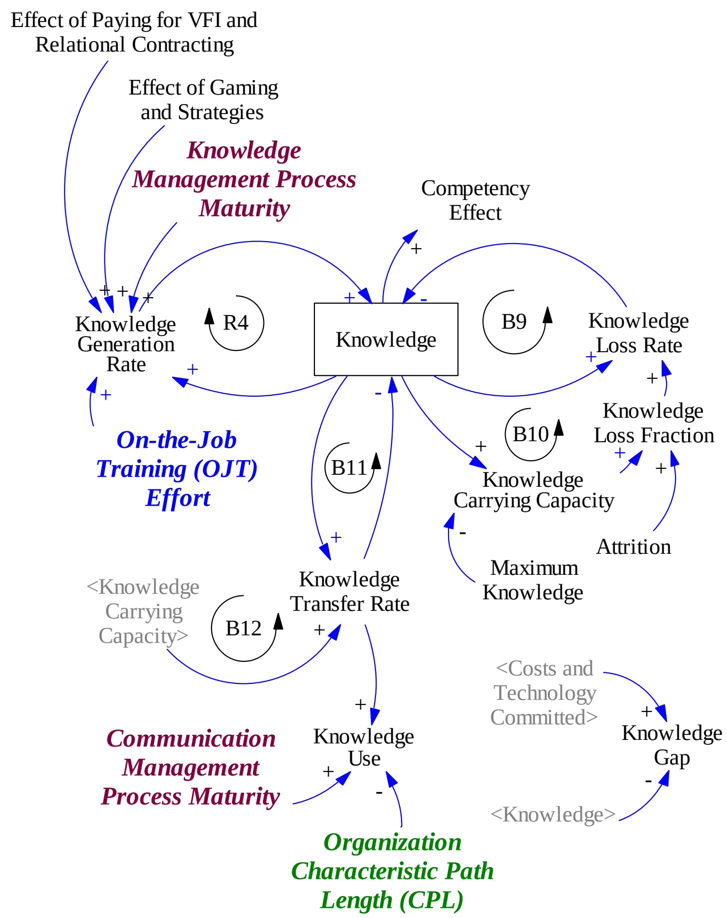

Figure 5. Knowledge CLD

In the current study, assessing design maturity includes several program management and systems engineering measures. As depicted in Figure 6, the design maturity rate is influenced by vendor furnished information (VFI) maturity, schedule performance index (SPI), SRL, and level of proven design used in the project. These factors represent an integrated set of project management and systems engineering measures that define design maturity.

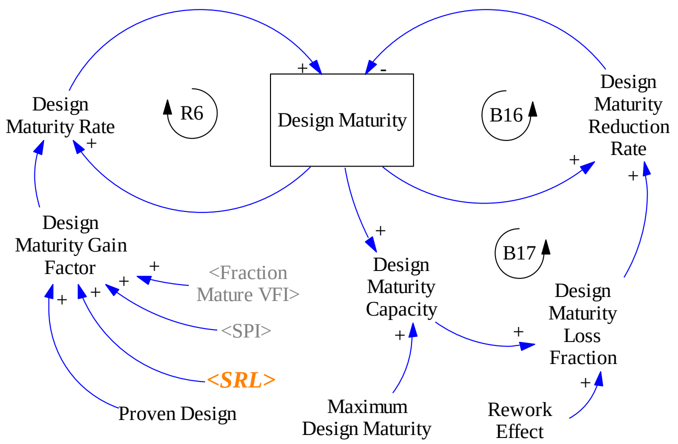

Figure 6. Design Maturity CLD

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The work performance CLD depicted in Figure 7 provides a different perspective on schedule performance.

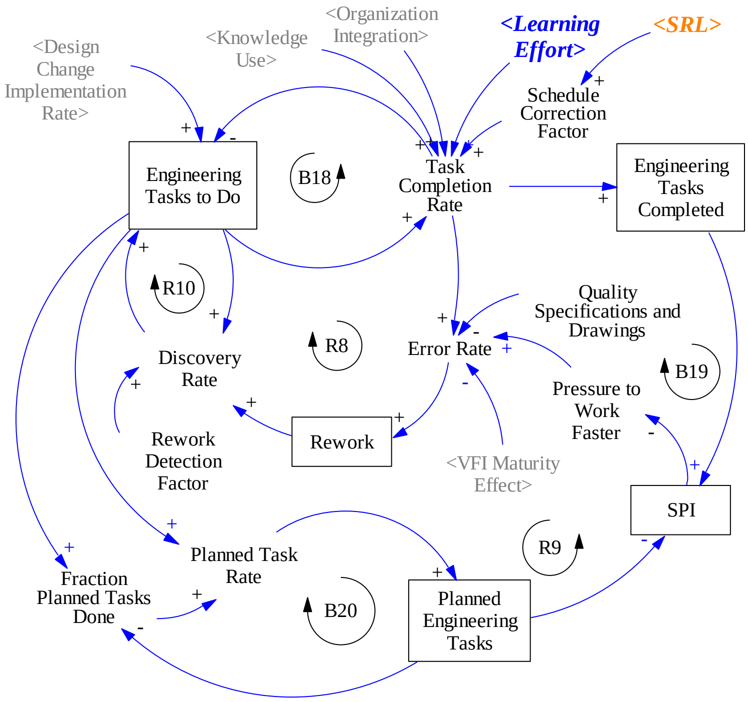

Figure 7. Work and Schedule Performance CLD

8. Case Study

The simulator is based on a future advanced marine integrated power system (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, a high-energy storage system (HESS), and a zonal electrical distribution (ZED) architecture.

9. Design Change and New Technology Roadmap Governance

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 8.

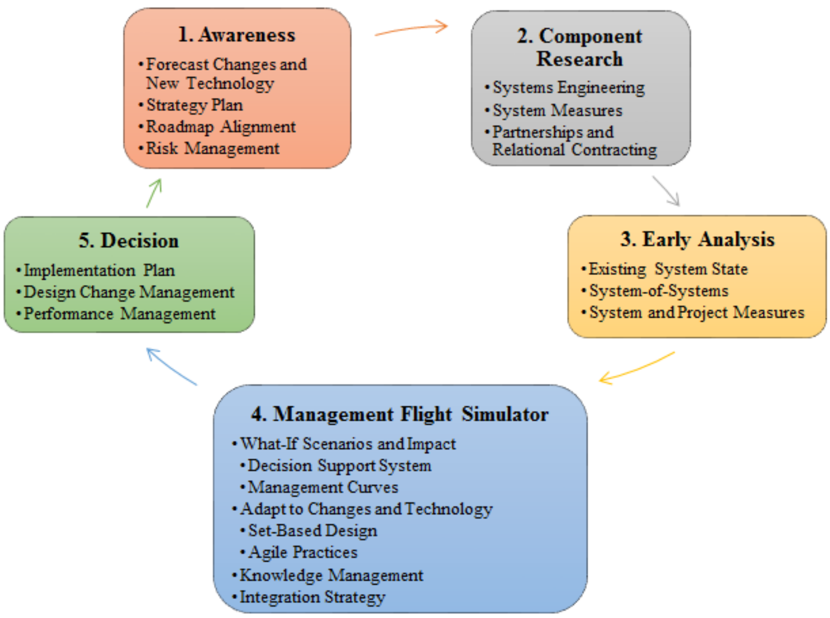

Figure 8. Design Change and New Technology Roadmap Governance

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9.1 Awareness of New Technology and Risks

The Gartner's Hype Cycle provides an indication of how new technologies emerge over time (Fenn & Blosch, 2018). This cycle can be customized for emerging naval technologies and combined with technology maturity and supportability curves, as depicted in Figure 9. Candidate new technologies may be mapped to naval operational capability roadmaps as well as strategic objectives.

Risk is inherent in all projects, but it is especially prevalent in those that deal with new technologies and rapidly changing industries (Smith & Merritt, 2002). During the awareness stage, potential design changes and new technology can be captured within the SRM.

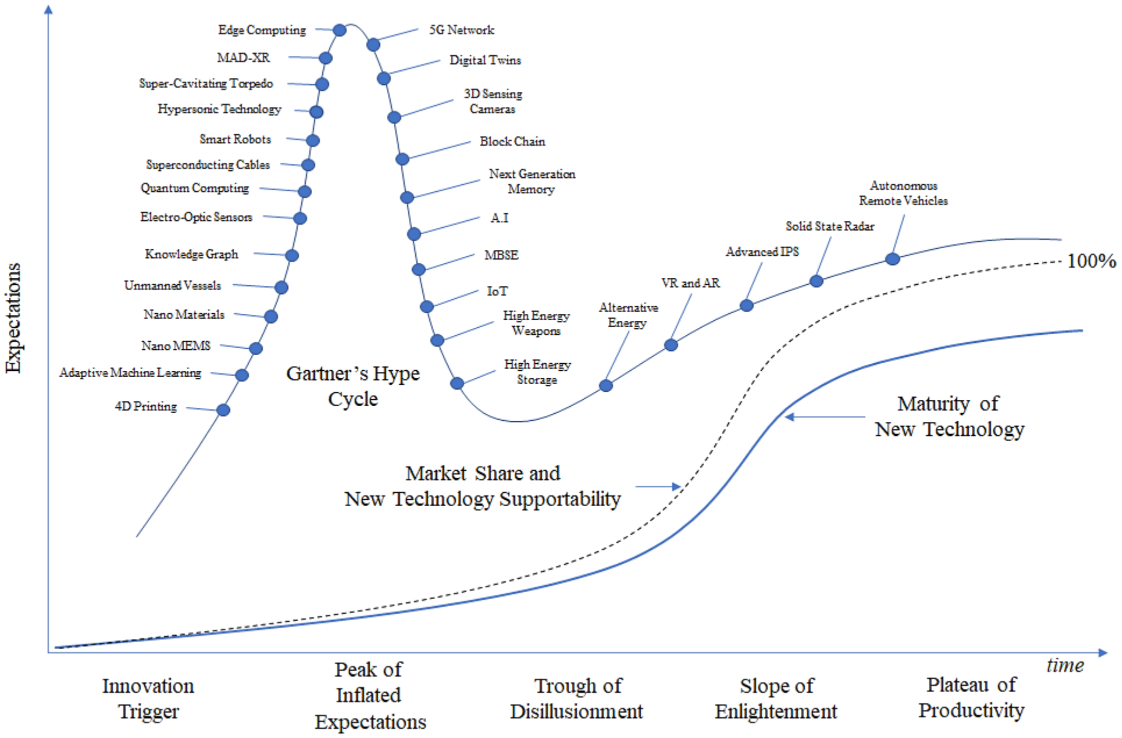

Figure 9. Notional Emerging Marine New Technology Hype Cycle and Technology Maturity

9.2 Component Research

In the component research stage, the design change or new technology under consideration is analyzed 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 important early in the design for capturing component information.

9.3 Early Analysis

It has been a challenge to properly quantify and model the emergent behaviour of complex systems and the coupling of system components (Simpson & Martins, 2011). Both the TRL and DSM can help to understand the complexity and coupling of system components. The current study also includes a component changeability dynamic chart that is based on linkages between the DSM, technical risks and change propagation trees.

The fraction of system components that are difficult to change at a point in the design can be based on those residing in the top right quadrant of the changeability chart in Figure 10. Understanding changeability, interfaces and dependencies early in the design allows for decisions in applying engineering principles to key components. These principles include standardization, modularity and loose coupling of components.

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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 (Sauser, 2008). The current study adopts SRL as a more comprehensive technical risk management metric. To estimate SRL, its value is calculated through the product of normalized Integration Readiness Level (IRL) and TRL matrices.

$$[SRL]_{nx1} = [IRL]_{nxn}\, X\, [TRL]_{nx1} \tag{2}$$

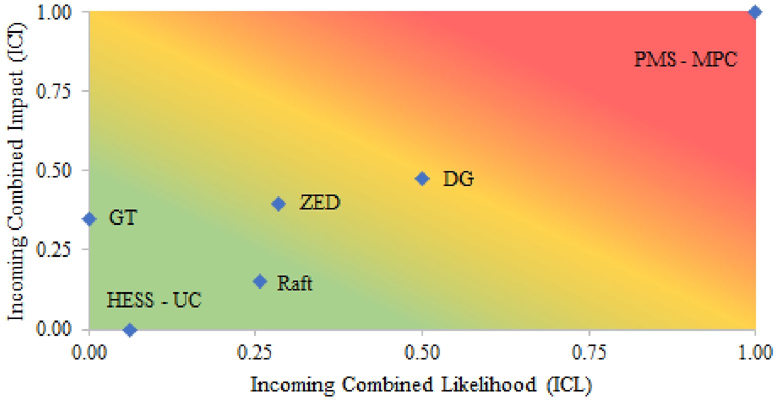

Figure 10. IPS Component Changeability Dynamic Chart

The ship design process has been known to be ad-hoc where attributes are not properly managed (Pinto, 2016). While there have been advancements in design space exploration and multidisciplinary optimization in design in several industries, most marine design efforts today still rely on a manual point-design approach (McCoy, 2015). In point design, teams inefficiently move from one alternative to the next in search of a solution.

In set-based design, requirements and system design attributes are represented as ranges instead of point values where there can be explicit views of trade-off values prior to decision making. Set-based design has been reported as effective in improving design robustness and in reducing rework (Kennedy, Sobek & Kennedy, 2013). The current study adopts a set-based design approach through use of the DSS and understanding the state of new component and existing system attributes.

With the performance trajectory of new technology components understood, the current state of the existing system and its performance envelope is examined. As depicted in Figure 11, the non-dimensional range over time of an existing system attribute can be monitored for a window to accept a corresponding new technology attribute value that is on the right trajectory. This should be balanced with the fact that the cost factor for change dramatically increases over the course of the design lifecycle. At the same time, pushing existing system attribute levels above the lower threshold can help achieve a robust design and flexibility in accepting changes.

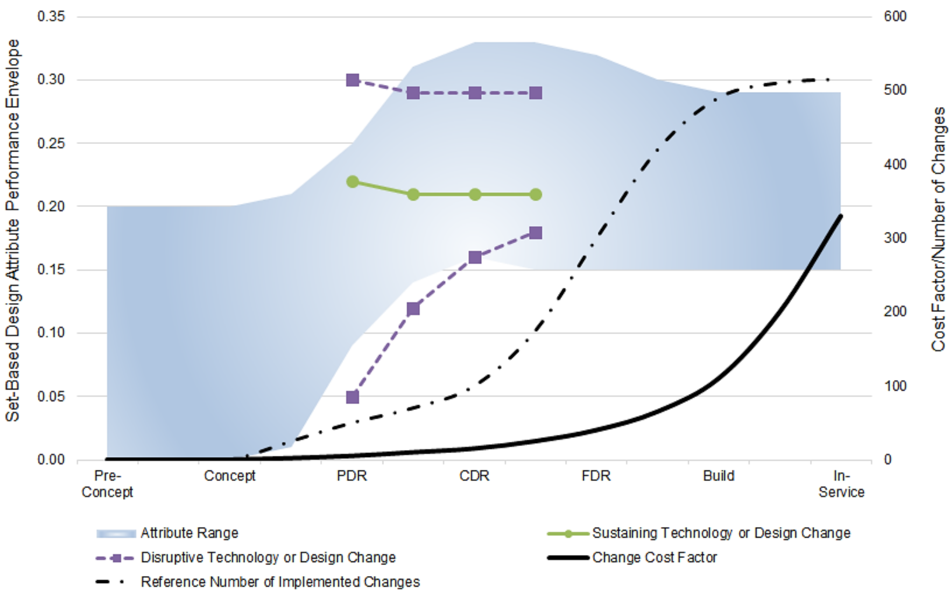

Figure 11. Technology Insertion, Design Changes and Cost Considerations

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9.4 The Management Flight Simulator

With increased complexity and change, traditional management tools have failed to solve persistent problems (Sterman, 2000, Walworth, 2016). This can lead to late awareness or warning of problems and poor program performance. The management flight simulator provides for early knowledge and can enhance traditional management tools for product and project success. Moreover, the simulator can help predict the impact of changes and new technology on an existing system design.

The simulator consists of the models depicted in Figure 12. The simulator predicts the state of the physical system and its impact on management curves where teams can respond with design change strategies using interactive controls. Design changes and new technology insertion are represented as disturbances to the system. To improve ability of the system to respond to these disturbances, a feed forward feature is incorporated where the impact of changes and new technology can be played out through what-if scenarios early in the design cycle.

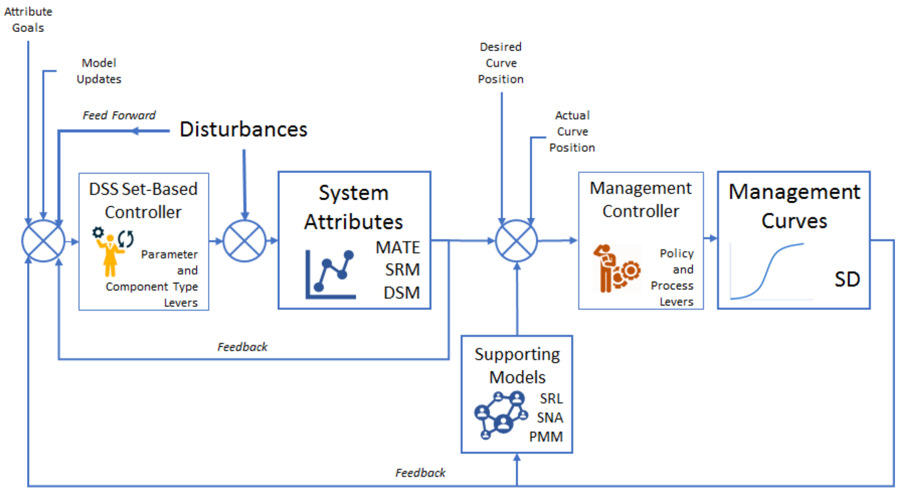

Figure 12. Management Flight Simulator Control System Perspective

9.5 Decision-Making

The Navy makes decisions with less knowledge compared to commercial design and typically proceeds with significant risks, unclear expectations and high cost uncertainty. Furthermore, the Navy does not devote sufficient time to engage stakeholders early in the program to evaluate and balance requirements and costs (GAO, 2009). This includes engaging subcontractors and suppliers early in the design as part of relational contracting where information, learning and building trust can be established. This also includes participation of engineering and program management multi-disciplinary teams in gaming design changes and building early knowledge.

The effectiveness of teams in decision-making is enhanced through the gaming of design change solutions within the DSS. The outputs from the DSS and supporting models form inputs into the SD model. The SNA model is based on Inflow® software; Microsoft® Excel software is used for developing the DSS, PMM and SRL models where information is transformed through a digital thread for use in the SD model.

Through use of the simulator and understanding the performance trajectory of new technology and the existing system attribute envelope, decisions can be made in terms of changes and technology insertion. With acceptance of these changes, the performance of the overall system and program is monitored. The performance of system attributes is monitored using the DSS dashboard depicted in Figure 13. The variance of attributes over time is monitored using the process capability measures of C_{py} and C_{pky}.

$$C_{py} = \frac{USL-LSL}{6\sigma}\ ,\ C_{pky} = \min\left(\left(\frac{USL-avg}{3\sigma}\right),\left(\frac{avg-LSL}{3\sigma}\right)\right) \tag{3}$$

Where LSL and USL represent the lower and upper attribute specification limits respectively and σ represents the standard deviation. The higher the C_{py} value; the better as it represents how well attributes fit within their limits. The complimentary C_{pky} measure represents the position of attributes, the higher this value; the better.

The DSS dashboard includes interactive controls for adjusting system performance parameters and component types in response to potential design change and new technology risks. These controls and their underlying physical laws influence a hierarchy of system and program attributes. Both performance and survivability attributes are

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aggregated up through an analytical hierarchy process (AHP) into mission and operational capability effectiveness attributes. The hierarchy of attributes and their weightings address the different interests of stakeholders involved in the decision-making process.

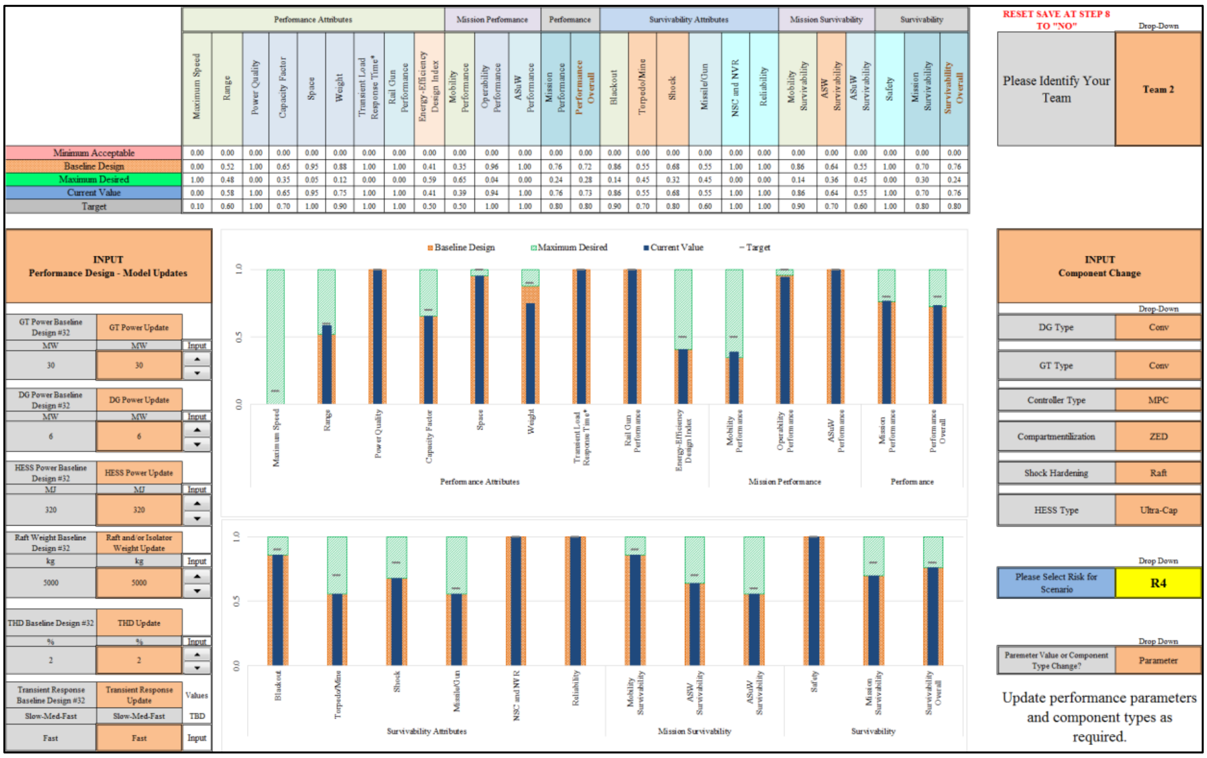

Figure 13. Decision Support System Attribute Dashboard

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 (Rebentisch, 2017). Understanding the risks associated with potential changes and new technology provides for early knowledge in the design cycle. The simulator monitors both technical and program risks within the SRM.

The performance of the program is typically monitored through use of earned value management (EVM) cost and schedule measures. It has been noted that these traditional project management metrics are viewed as lagging in nature and unable to show incremental design maturity. It was also noted that monitoring complex projects is difficult using traditional measures and don't take into account the techno-socio-cultural factors (Walworth, 2016).

System dynamics modeling is a well-established modeling approach for project management and can include these factors as well as an understanding of the adverse consequences in decision-making. The simulator and its SD model provide for a different perspective on program performance that is more predictive in nature. These measures can challenge, enhance and validate typical EVM measures. The SD management curves are unique in that they address the techno-socio-economic and cultural factors not captured in traditional performance management systems.

10. Results

Three design change scenarios are applied to the simulator with predicted curves and aggregated end month results compared to baseline references and expected behaviour. Results can be verified for convergence against the actual number of design changes, costs incurred, commitments, VFI maturity and traditional EVM measures.

In response, key SD model control levers in Table 1 are adjusted to optimal settings at the end of the month for improving the position of the management curves. These levers may be calibrated through a comparison between predicted and actual management curve values.

With adjustment to just a few key levers, the typical four management curves are positively influenced with a cascading positive effect on other management curves. The key levers selected are based on a sensitivity analysis conducted within the simulator. Management curve dynamics and influencing factors are captured within the SD model using Vensim® software.

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Table 1. Adjustment of SD Model Levers for Optimal Performance

Lever	Adjusted Value
On-Job-Training (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

As depicted in Figure 14, the position of the four typical management curves is improved through these adjusted levers with corresponding predicted end month values. With increased gaming of change scenarios, the knowledge curve is advanced. With adjustment to the engineering principles lever, the ease-of-change curve may be moved up. The favourable shift in the knowledge and ease-of-change curves leads to postponed commitments. Along with a robust design, postponement of commitments can allow for knowledge gain, flexibility in procurement options and just-in-time technology. With early and increased knowledge use, design changes and potential new technology are better rationalized leading to fewer changes and reduced costs.

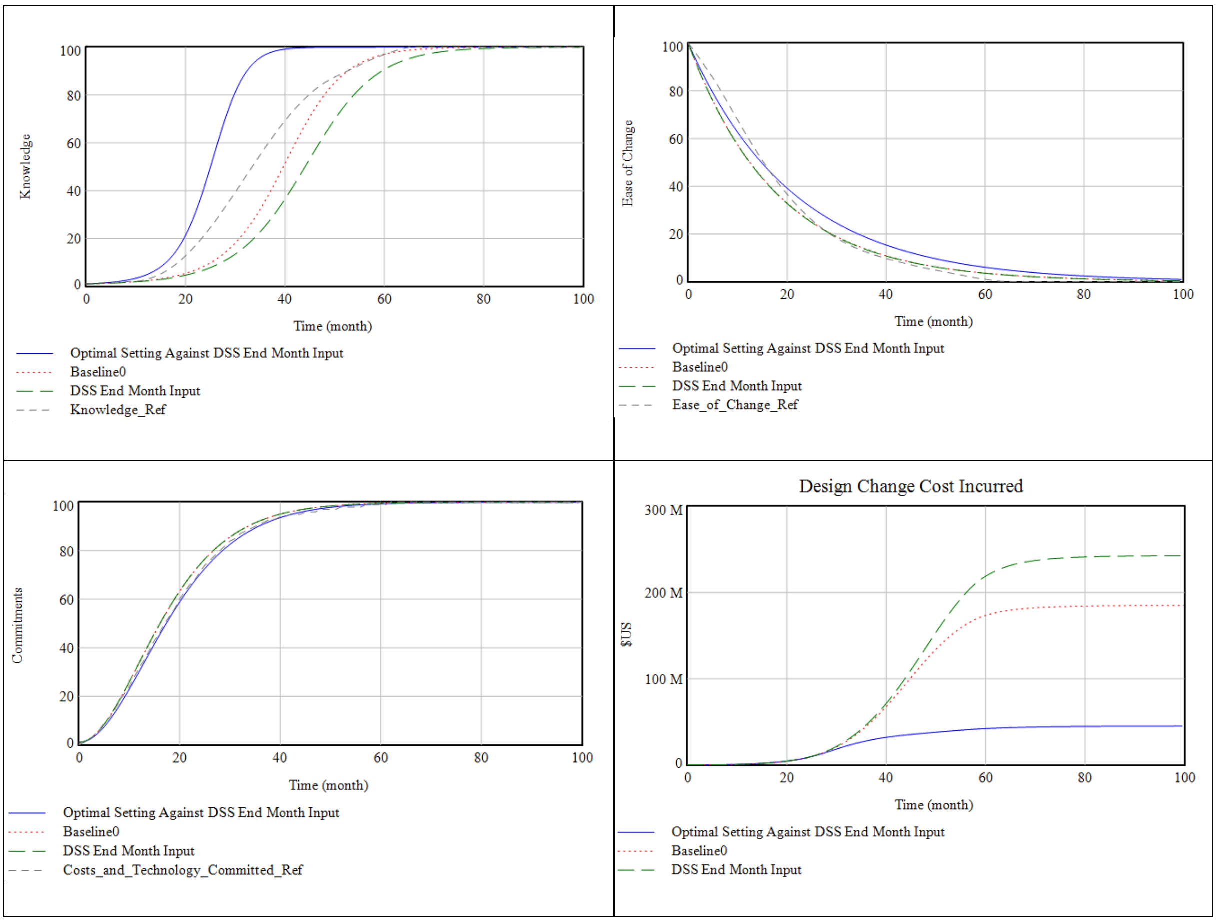

Figure 14. Improved Position of the Four Typical Management Curves

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The improved position of these management curves has a positive cascading effect on several other related SD model entities and curves. As depicted in Figure 15, schedule performance and design maturity have been improved. With an increase in knowledge use and VFI maturity early in the design cycle, the task completion rate is increased leading to an increase in SPI, reduced rework, and an increase in Design Maturity.

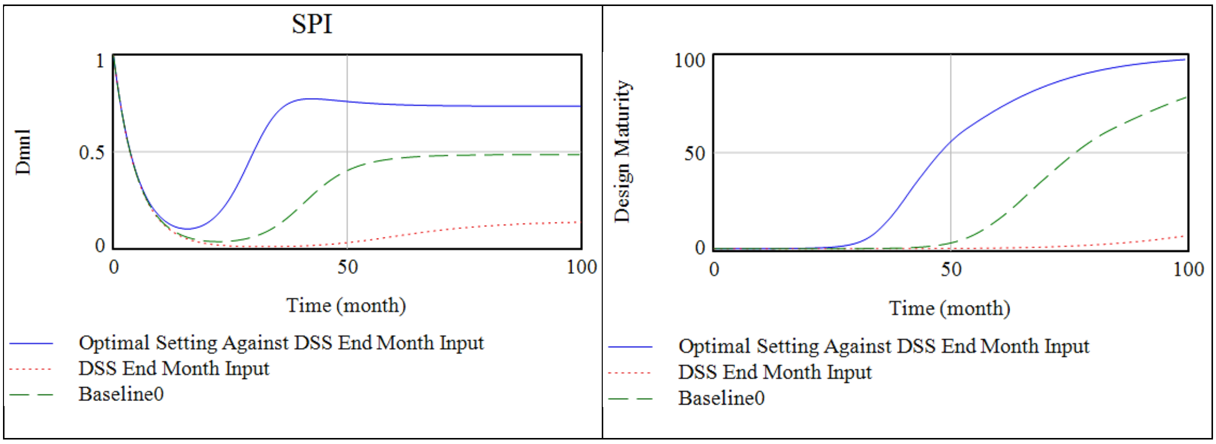

Figure 15. SPI and Design Maturity Increased Through Adjusted Levers

With selected levers applied and predicted improvement to management curves, it will take time for these levers to take hold and for the simulator and system to react. This is where the cycle continues following both the simulator control system and the technology roadmap governance approach.

11. Conclusions

This study presented a management flight simulator as a practical and innovative approach to bring systems engineering and program management disciplines together for complex product and project success. It can help visualize and understand the causal relationships and design attributes affecting decision-making. The simulator can help predict the impact of design changes and new technology insertion on both the existing physical system and program management curves. Through the gaming of design change scenarios and adjustment to only a few key policy levers, management curves and program performance can be positively influenced.

The simulator provides intelligence augmentation through a multi-experience dynamic user interface for what-if design change and technology adoption strategies. This can improve collaboration, learning, knowledge, and team effectiveness. Together with the simulator, the technology roadmap governance approach can reduce project cost overruns and schedule delays. The value in using the simulator was validated using an IPS case study, design change scenarios, verification of SD model behaviour, interviews and surveys with industry.

Acknowledgements

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