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MBSE METHODOLOGY AND ANALYSIS TOOL TO IMPLEMENT MBSE POST MILESTONE C

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THESIS

MBSE METHODOLOGY AND ANALYSIS TOOL TO IMPLEMENT MBSE POST MILESTONE C

by

James Beaufait

September 2018

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13. ABSTRACT (maximum 200 words)

This thesis proposes a model-based systems engineering (MBSE) methodology to be implemented post Milestone C, develops a Microsoft Excel MBSE analysis tool which provides a recommendation to implement MBSE, and provides a case study for implementing MBSE post Milestone C on a Department of Defense (DoD) acquisition program. The purpose of the MBSE methodology is to identify how MBSE should be implemented post Milestone C to address the systemic challenges which are faced by DoD acquisition programs post Milestone C. The Excel MBSE analysis tool provides a set of questions which provide metrics to the program office to determine the benefit of implementing MBSE post Milestone C into their program. The thesis then details, through a case study, how the Excel MBSE analysis tool can be used to decide whether to implement MBSE. Prior research on the systemic challenges within DoD acquisition programs as well as the use of MBSE during post Milestone C activities were leveraged in developing the proposed MBSE methodology and Excel MBSE analysis tool.

The thesis makes a recommendation to implement MBSE post Milestone C to mitigate schedule, cost, and risk uncertainties. This is done through digitally linking various models, such as a manufacturing model and a logistics model to an integrated master schedule (IMS). Based on the metrics and cost, the Excel MBSE analysis tool provides a recommendation on which models should be implemented.

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MBSE METHODOLOGY AND ANALYSIS TOOL TO IMPLEMENT MBSE POST MILESTONE C

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Submitted in partial fulfillment of the
requirements for the degree of

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from the

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ABSTRACT

This thesis proposes a model-based systems engineering (MBSE) methodology to be implemented post Milestone C, develops a Microsoft Excel MBSE analysis tool which provides a recommendation to implement MBSE, and provides a case study for implementing MBSE post Milestone C on a Department of Defense (DoD) acquisition program. The purpose of the MBSE methodology is to identify how MBSE should be implemented post Milestone C to address the systemic challenges which are faced by DoD acquisition programs post Milestone C. The Excel MBSE analysis tool provides a set of questions which provide metrics to the program office to determine the benefit of implementing MBSE post Milestone C into their program. The thesis then details, through a case study, how the Excel MBSE analysis tool can be used to decide whether to implement MBSE. Prior research on the systemic challenges within DoD acquisition programs as well as the use of MBSE during post Milestone C activities were leveraged in developing the proposed MBSE methodology and Excel MBSE analysis tool.

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LIST OF ACRONYMS AND ABBREVIATIONS

CAD	computer-aided design
COTS	commercial-off-the-shelf
DoD	Department of Defense
EDM	engineering development unit
ESGN	Electrostatically Supported Gyro Navigator
FOG	fiber optic gyroscope
FRP	full rate production
GAO	Government Accountability Office
IMS	Integrated Master Schedule
INS	inertial navigation system
IMU	inertial measurement unit
INCOSE	International Council on Systems Engineering
JSF	Joint Strike Fighter
LOTB	life-of-type-buy
LRIP	low rate initial production
MBSE	model-based systems engineering
MDAP	major defense acquisition program
O&S	operations and support
OEE	overall equipment effectiveness
PCD	printable circuit card
PSM	product support manager
ROI	return-on-investment
SysML	System Modeling Language
TDP	technical data package
UML	Unified Modeling Language

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EXECUTIVE SUMMARY

The growing complexity of Department of Defense (DoD) weapon systems has driven the DoD to seek out new systems engineering processes (Hart 2015). Model-based systems engineering (MBSE) is a modern approach to systems engineering which the DoD is implementing, with some success, within the DoD weapon system acquisition process (Pavalkis 2014). The focus of the MBSE implementation within the DoD has been during development as this is where the biggest benefit the program will realize due to implementing MBSE. With many DoD weapons system programs that are post development and post Milestone C, it is important to understand the benefit of implementing MBSE post Milestone C and to what extent the program office should implement MBSE. Based on the research contained in this thesis, there is a benefit to implementing MBSE post Milestone C. That benefit is highly dependent upon the program needs and execution. The extent to which the program office implements MBSE is also highly dependent upon program needs and execution. This research investigates the necessary questions that programs need to answer to be able to determine whether MBSE will be beneficial to their program and the extent that the program office implements MBSE. The following research questions guides the research of this thesis:

1. How can DoD programs benefit from implementing MBSE during post Milestone C activities?
2. What criteria should the program office use to determine whether to implement MBSE post Milestone C?
3. What are the major decisions that the program office needs to make post Milestone C?
4. What challenges exist with implementing MBSE post Milestone C?
5. What resource requirements exist to initiate a MBSE approach post Milestone C?

The research identifies several challenges that programs encounter post Milestone C. The decomposition of the post Milestone C challenges identified four categories as shown in Figure ES-1. The program office answers questions for each category to identify whether to implement MBSE to mitigate the risk of occurrence. The decomposition of each category identifies the root causes that drive the risk. The

decomposition of the root causes identifies the necessary questions that programs need to answer to determine whether the program office implements MBSE into their program from a technical viewpoint. These questions are the foundation of an Excel MBSE analysis tool, developed as part of this research that provides a score to each root cause. The higher the score, the more benefit the program will receive from implementing MBSE. The Excel MBSE analysis tool implements a cost model to determine the return-on-investment (ROI) and to recommend whether the program office implements MBSE from a programmatic viewpoint.

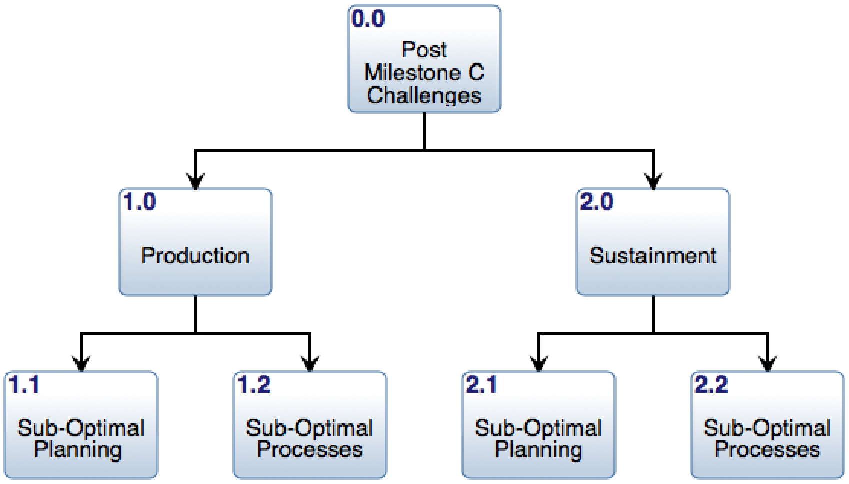

Figure ES-1. Decomposition of Post Milestone C Challenges.

As MBSE is tailorable, this research identifies a recommended MBSE methodology to use post Milestone C. The MBSE methodology employs a MBSE architecture as shown in Figure ES-2. The key aspects to this architecture for production and sustainment are:

- the manufacturing model that captures the time and resources it takes for build and assembly as well identifying the risk;
- the supply chain model that captures the time it takes to place a part into stock from the time the program office places an order as well as identifying the risk;

- the maintenance model that captures the failure and repair data as well as the identifies the risk; and
- the obsolescence model that captures the time when stock will reach zero, when the vendors will no longer provide support to the parts, and the associated risks.

The systems, hardware, software, simulation, and test models are applicable to sustainment programs that are going through an obsolescence refresh that requires development. This research does not thoroughly discuss these models as there is a significant amount of research that addresses how to implement MBSE during development. The Microsoft Excel MBSE analysis tool along with the MBSE methodology provides a program office with the necessary information to make the decisions on whether to implement MBSE, and if so, how to implement MBSE.

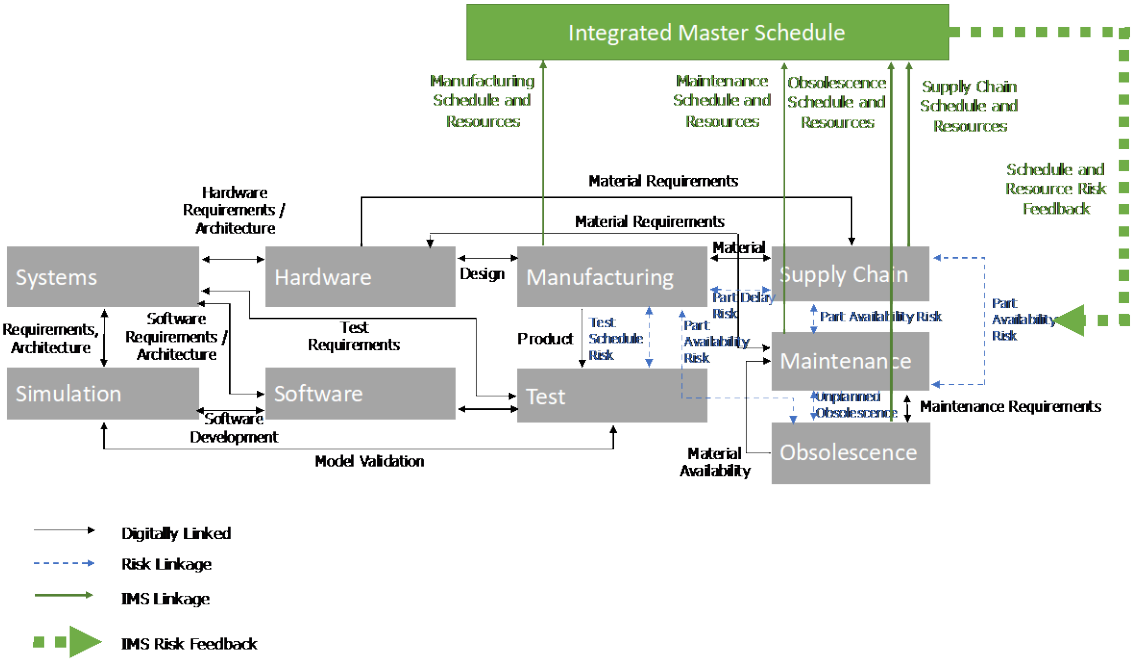

Figure ES-2. Recommended MBSE Architecture.

To provide evidence of the applicability of the Excel MBSE analysis tool and the MBSE methodology, this research conducts a case study of two inertial navigation systems (INS) programs. Each program is a subsystem within the same weapons system and each program started its development in the early 2000s. One program used a MBSE approach and the other did not. The program that did not use a MBSE approach suffered significant program challenges and delays, while the program that used a MBSE approach achieved its program objectives on cost and on schedule. The results of the case study provide evidence that the Excel MBSE analysis toolset correctly determines which programs will benefit from implementing MBSE. The results of the case study also provide evidence that the MBSE methodology will mitigate the challenges experienced during post Milestone C activities.

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Pavalkis, Saulius. 2014. "Model Based Management of Configurations of Complex Systems: Common Submarine Combat System." *Modeling Community* (blog). April 4, 2014. https://blog.nomagic.com/model-based-management-of-configurations-of-complex-systems-common-submarine-combat-system/.

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I. INTRODUCTION

The purpose of this thesis is to determine the feasibility of implementing model-based systems engineering (MBSE) after a program has reached Milestone C, identify a MBSE methodology, and develop an Excel MBSE analysis tool to tailor the implementation of MBSE. While many articles and textbooks identify how to implement MBSE from the beginning of a program, there are gaps in how to implement MBSE into a mature program and how to tailor the implementation of MBSE to create a tangible program benefit with respect to technical, cost, or schedule. This research partially fills those gaps. The benefit of this research, the resulting MBSE methodology, and the Microsoft Excel MBSE analysis tool provides the program office a basis to make the decision on whether the program office implements MBSE into their programs and provides an Excel MBSE analysis tool to guide their methodology.

A. BACKGROUND

The Department of Defense (DoD) has demonstrated the difficulty of managing acquisition programs, specifically weapon system programs. In a 2007 Government Accountability Office (GAO) report, only 11 out of 72 major defense programs were on time, on budget, and meeting performance criteria (Charette 2008). Recently, a 2017 GAO report identifies 43 out of 86 weapon system programs experienced cost growth, totaling $74.82 billion, between 2016 and 2017 as shown in Figure 1 (Oakley 2017). The other 43 programs experienced a reduction in overall cost by $20.17 billion for a total increase in the DoD’s portfolio of $54.65 billion (Oakley 2017). The article by Charrette estimates that the DoD pays $21 million per hour for the acquisition of these weapon systems with an average program schedule delay of 21 months (Charette 2008). These schedule delays often drive up costs that lead to a decrease in the capability promised to the stakeholders. It is possible with properly implemented processes and tools, the program office could have avoided a significant majority of these schedule delays and cost overruns.

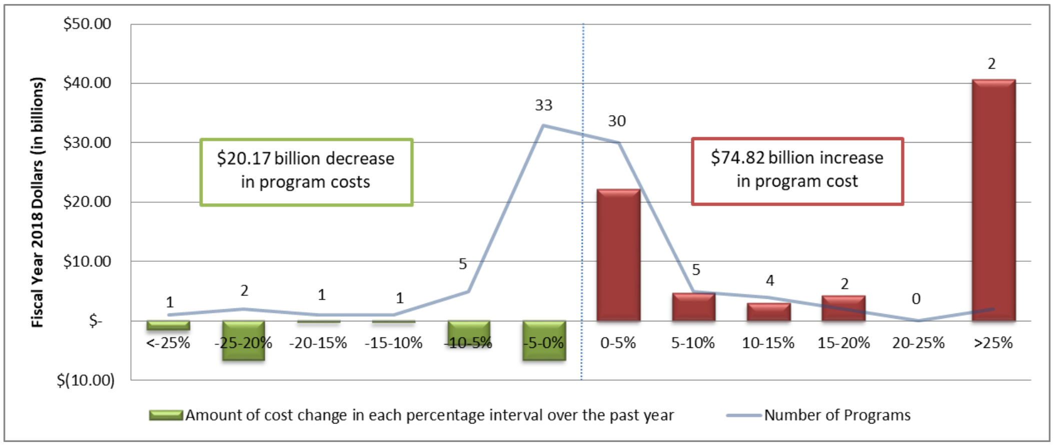

Figure 1. DoD Weapon System Program Cost Increases and Decreases from 2016 to 2017. Adapted from Oakley (2017).

While the majority of the schedule delays and cost overruns are incurred due to decisions made during development, the majority of the cost is incurred post Milestone C. Figure 2 identifies the cost growth, by acquisition phase, in the DoD's 2017 portfolio, that shows most of the cost growth occurs during production (Oakley 2017). As shown in Figure 3, the DoD Instruction 5000.02 identifies Milestone C is the transitional point between the Engineering and Manufacturing Development phase and the Productions and Deployment phase. Each phase of the acquisition life cycle has its own unique challenges that the program office must consider. The needs of the tools to meet these challenges are often unique to the phase and the program office needs to choose the correct tools and tailor them appropriately. Ideally, the tools selected are applicable across all phases.

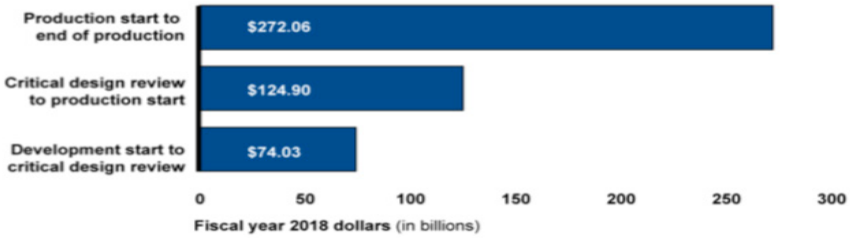

Figure 2. DoD's 2017 Portfolio Cost Growth by Acquisition Phase. Source: Oakley (2017).

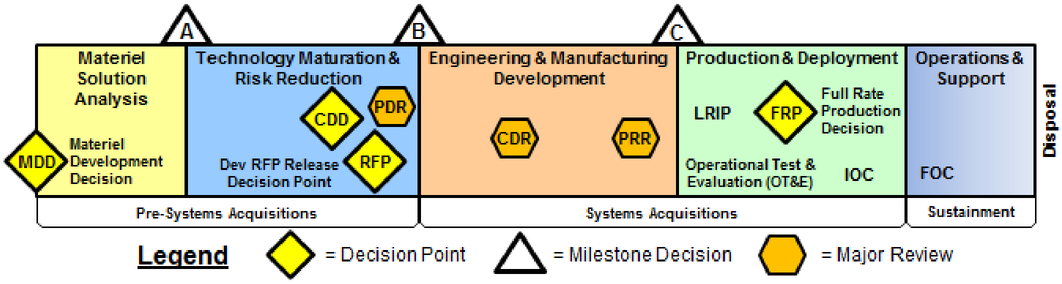

Figure 3. DoD 5000.02 Acquisition Life Cycle.
Source: Department of Defense (2017).

During the Production and Deployment phase, the program office defines the requirements, developed a design, verified the design the design against the requirements, and established production processes. During the low rate initial production (LRIP), the program is ensuring the consistent production of the end item to the approved technical data package (TDP) and within the cost estimates. Production processes become refined during this period. The challenges that generally occur during LRIP are determining the correct number of units to produce and concurrent development.

When development schedules slip, programs will begin production before the TDP is complete. This occurs when the program manager believes that the design is stable and the risk caused by the design uncertainty is manageable. When this occurs, production starts concurrently with development. When the program office does not coordinate design, test, and production activities, concurrent development can, and often does, create delays and adds additional cost to production due to design changes after the production facility has staged parts, implemented work instructions, and developed processes. If the program office does not produce enough LRIPs, this can lead to delays during full rate production (FRP) as production processes and the supply chain may not have been satisfactorily stressed. Upon entering FRP, the focus is on identifying efficiencies in the processes. Challenges that occur during this phase are parts obsolescence, part defects, and design issues. Both parts obsolescence and part defects can lead to schedule delays and additional cost if not properly planned. The largest cost increase and schedule driver is if the parts cause an additional round of qualifications.

Once the program office deploys a product, the sustainment is for the operational life. Depending on the product, sustainment can range from obsolescence refreshes to consuming the product. Products can range in useful life of less than a year to 40 years or more. The challenges during the deployment phase are identifying when obsolescence will occur, additional development required due to an unanticipated obsolescence issue, identifying preventative maintenance, and optimizing logistics. Major defense acquisition programs (MDAP) with an operational life of several years to several decades usually have an obsolescence refresh program with incremental subsystem updates. These obsolescence refreshes are development programs that follow the DoD 5000.02 acquisition life cycle. The one major difference is these MDAPs generally enter the life cycle post Milestone B.

Model-based systems engineering is a set of processes and tools that systems engineers can utilize to assist in the execution and planning of a program throughout all phases of the program. According to Dr. Warren Vanemen, "Model-based systems engineering is the formalized application of modeling to support system design and analysis, throughout all phases of the system life cycle, through the collection of related processes, methods (languages), and tools to support the discipline of systems engineering in a model-based or model-driven context" (Vaneman 2016, 1). The increased complexity of systems has driven the need for MBSE. At the core of MBSE is ensuring integration across all stakeholders by transferring truth from documents to models. This philosophy is not new. The IPC-2581 format is, "a generic standard for printed circuit board and assembly manufacturing description data and transfer technology" (IPC-2581 Consortium 2018). The IPC-2581 consortium developed IPC-2581 to replace the Gerber file format. The use of IPC-2581 files reduces the risk of misinterpretation of the design drawings between the design engineer and the production engineer and allows the production of the PCB in accordance to the design engineers' intention on the initial production run. The user can generate documents from the models. The advantages to MBSE are that it allows systems engineers to focus on the problem instead of the document, there is less ambiguity in a model, the structure is more consistent, and the models capture dependencies better as the use of IPC-2581 files and computer-aided design has demonstrated in (CAD) (International Council on Systems Engineering 2012).

B. PROBLEM STATEMENT

The weapon systems today are increasingly more complex. Components are continually becoming smaller and there is a desire to fit more functionality into a single item that drives more complexity and components into a single item. An example is a cell phone today that has added Wi-Fi, GPS, fingerprint scanners, cameras, and touchscreens into a single device. Fifteen years ago, those functions were separate items. Data has become more readily available and users can share data quicker. Computing power has increased, allowing computers to process the available data quicker. Due to all of this, systems have become more interconnected internally and externally and often reach across different DoD entities. This drives the need for a better understanding of the interfaces and tradeoffs between the requirements of each function to optimize the system. Not only are the weapon systems becoming more complex, but also at the same time, the DoD workforce is downsizing. To manage these more complex systems with fewer people, it is imperative that the program office implement the correct processes and tools so they can meet their program needs. The DoD is implementing MBSE throughout DoD acquisitions as a tool to maximize efficiencies in weapon system development and during the Production and Deployment phase.

This research addresses the problem statement: The most expensive phase of a DoD acquisition program is post Milestone C, and the complexities of the modern systems as well as the reduced workforce make it a challenge to go through production, deployment, and sustainment on time and on budget.

C. RESEARCH QUESTIONS

Due to the potential, MBSE has shown in the development phase, the program office needs to conduct an assessment to determine the effectiveness of MBSE if the program office is to implement MBSE post Milestone C. This thesis addresses the following research questions with the assumption that the program office did not implement MBSE prior to Milestone C:

1. How can DoD programs benefit from implementing MBSE during post Milestone C activities?
2. What criteria should the program office use to determine whether to implement MBSE post Milestone C?
3. What are the major decisions that the program office needs to make post Milestone C?
4. What challenges exist with implementing MBSE post Milestone C?
5. What resource requirements exist to initiate a MBSE approach post Milestone C?

D. OBJECTIVE

The objective of this thesis is to determine if MBSE can be effective post Milestone C and if so, describe how by developing a MBSE methodology and an Excel MBSE analysis tool to implement the correct scope for MBSE. Every program is unique and the processes and tools implemented on each program need to be tailorable. The assumption of this research is that not every program office has a MBSE background or the time to obtain a full understanding of what MBSE is and how to implement it. For these reasons, providing a MBSE methodology and an Excel MBSE analysis tool to determine when MBSE is beneficial and why it is beneficial is critical.

E. APPROACH

The approach taken to answer the research questions is to:

1. Conduct a literature review to identify the challenges that exist in a post Milestone C program and identify MBSE methodology and tools that can be a benefit to those identified challenges.
2. Based on the findings from the literature review, describe how MBSE can mitigate those challenges by developing a MBSE methodology and an Excel MBSE analysis tool that provides the program office a methodology to implement MBSE to meet their needs.

The MBSE methodology and Excel MBSE analysis tool traces the findings identified in the literature review through a decision matrix and provide a recommendation based on the input factors. This research implements a case study of the MBSE methodology and the Excel MBSE analysis tool to ensure that the MBSE methodology and the Excel MBSE analysis tool are driving the program office to an acceptable solution.

F. SCOPE OF STUDY

The focus of the research and the case study is on the required decisions that the program office need to make post Milestone C and providing a MBSE methodology and an Excel MBSE analysis tool to help guide those decisions. This research focuses on the decisions common weapon system acquisitions need to make. The research in this thesis does not identify every decision that is possible. Unique challenges and decisions are outside the scope of the research.

G. ORGANIZATION

Chapter II of this thesis contains the results of a literature review that identifies challenges that programs are experiencing in the post Milestone C phase as well as the MBSE processes and tools that can provide a benefit to those challenges. Chapter III of this thesis identifies and provides recommended MBSE methodology and an Excel MBSE analysis tool for general weapon system acquisition programs to mitigate the challenges that this research identified in the literature review. This thesis details a case study in Chapter IV that applies those MBSE methodology and Excel MBSE analysis tool to actual DoD programs. Chapter V provides the recommendations and conclusions of the research.

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II. LITERATURE REVIEW

This chapter contains the literature review on the challenges of a DoD acquisition program post Milestone C followed by MBSE techniques that potentially are mitigations to those challenges. Model-based systems engineering is a tailorable process. To tailor the process, it is important to be able to understand the inherent challenges within the current processes and determine the applicability of MBSE to mitigate those challenges. This thesis conducted research to determine the challenges within post Milestone C weapon system acquisition and current research applying MBSE to mitigate those challenges.

A. INTRODUCTION

Department of Defense weapon system acquisition requires the tailoring of tools and processes to meet program needs (Department of Defense 2007). To tailor any tool or process appropriately, it is crucial to identify and understand the problem. When the program office implements tools without first developing a methodology that addresses the program's needs, the program is not receiving the full benefit from the tool or process. To implement MBSE successfully into a program, the program office must first identify the problem and then understand the problem such that the program office implements the MBSE methodology in a way that creates a solution to the problem. This is especially true when the program office is deciding whether to implement MBSE post Milestone C as the program office must tailor the implementation of MBSE to address problems that are outside the intended use of MBSE.

A program encounters many risks during the DoD acquisition life cycle. Figure 4 highlights the DoD acquisition life cycle and their associated risks. To implement MBSE effectively post Milestone C, there must be an understanding of the risks associated with that phase of the program to tailor the MBSE methodology in accordance to the program needs. This literature review investigates the general risks that programs face post Milestone C. It also investigates how program offices use MBSE to create a solution to those general risks.

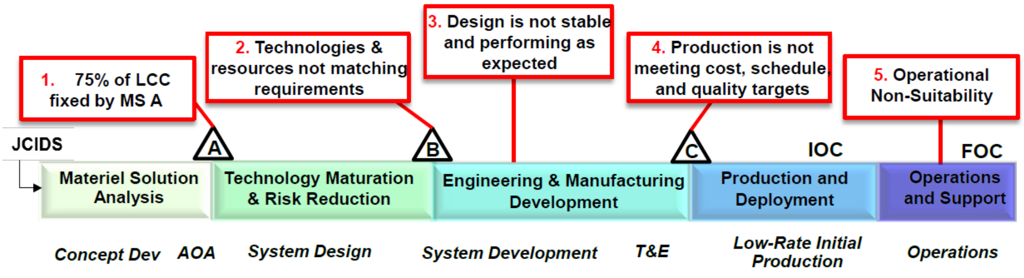


Figure 4. DoD Acquisition Life Cycle Risks.
Source: Zimmerman (2014).

B. PRODUCTION RISKS

The first phase of this literature review identified the risks associated with the Production and Deployment phase to understand the processes that the program offices are managing their programs. The second highest cost by DoD life cycle phase is the Production and Deployment phase and accounts for approximately 20% of total program life cycle cost incurred. The Production and Deployment phase is the first phase after exiting Milestone C and is the transition between development into production. Risks exist during the Production and Deployment phase that the program office must be able to understand and mitigate during post Milestone C activities.

This research identified the transition from development to production as a key transition point. W. J. Willoughby, Jr. wrote a DoD Directive about the challenges of transitioning from development to production for DoD weapon system acquisitions. The DoD Directive 4245.7, *Transition from Development to Production*, highlighted that the transition from development to production, “is not a discrete event, but is rather a process composed of three elements: design, test, and production” (Willoughby 1985, 1-1). Willoughby stated,

> Current DoD systems acquisition policies do not account for the fact that systems acquisition is concerned basically and primarily with an industrial process. Its structure, organization, and operation bear no similarity whatsoever to the systems acquisition process as it is described conventionally. It is a technical process focused on the design, test, and production of a product. It will either fail or falter if these processes are not performed in a disciplined manner, because the design, test, and

> production processes are a continuum of interrelated and interdependent disciplines. A failure to perform well in one area will result in failure to do well in all areas. When this happens, as it does all too often, a high-risk program results whose equipment is deployed later and at far greater cost than planned. (Willoughby 1985, 1-3)

A disconnect between design, test, and production can result in all facets of the program failing as a design that cannot be tested or produced efficiently drives schedule delays and increased cost (Willoughby 1985). For a program to be successful during post Milestone C, and specifically during the transition from development to production, the program office must use a disciplined approach to coordinate between the design, test, and production activities. While the program office needs to ensure that there is coordination across the design, test, and production activities, Willoughby argues that the DoD acquisition processes, including DoD Directive 5000.1 and DoD Instruction 5000.2, add layers of management that tends to “compartmentalize, matrixize, and polarize the major areas of the acquisition processes: design, test, and production” (Willoughby 1985, 1-2). To be successful, the program office “must manage the fundamentals of design, test, and production and let the management system describe itself” (Willoughby 1985, 1-2). While the DoD processes drive incoordination, the methodology that the program office implements needs to drive coordination and discipline especially while transition from development to production is occurring.

In 1985, the United States Government Accountability Office (U.S. GAO) issued a report, *Why Some Weapon Systems Encounter Production Problems While Others Do Not: Six Case Studies*, which details the challenges weapon systems face in transitioning from development into production. While this report is over 30 years old, based on my 12 years of experience in DoD weapon system acquisition, the findings are still accurate in 2018. The GAO report highlights five systemic problems in DoD weapon system production:

> - low [product] yield rate;
> - increasing time needed to procure [critical parts and materials];
> - late availability of needed production facilities and equipment;
> - difficulty in getting special tooling and test equipment to achieve the degree of accuracy required by component part specifications; and
> - re-designs. (Bowsher 1985)

According to the GAO, inadequate or late production planning is part of the cause of issues in transitioning from development to production. The factors that influence the transition from development to production success are technical performance concerns, program management and staff orientation, funding instability, and quantity instabilities as shown in Figure 5. These findings are consistent with the Willoughby DoD Directive as both highlight the need for coordination across the stakeholders. The fact that coordination is a key to success in transitioning from development to production leads credence to the belief that MBSE provides benefit to the program office as improved coordination is a stated benefit of MBSE (Hart 2015).

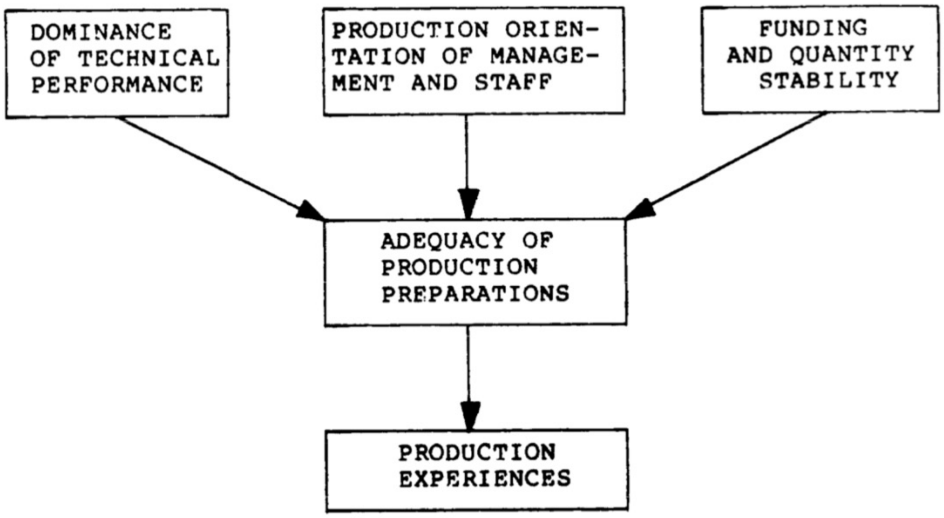


Figure 5. Influences of Production Experiences.
Source: Bowsher (1985).

When technical performance dominates the program, the focus is on ensuring that the programs are meeting performance requirements. When programs are compressed and underfunded in the late stages of development, the program office focuses efforts to complete development in place of the necessary production planning. When the program office must maintain production schedules, concurrent development and production will occur. Concurrent development and production is a risk that must be actively managed post Milestone C and requires coordination across all disciplines. The risk is a balance of design maturity, measurement of test stability, and certification of manufacturing processes (Willoughby 1985).

The makeup of the disciplines within the program office can drive the quality of the production planning, as production planning tends to begin late in development when the program office is mostly design focused. When the program office begins the planning of production late in development, the program office has not considered the producibility of the design. Once the design is post Milestone C, and the manufacturer has identified design issues that impact manufacturing, the program office needs to be able to assess the cost, schedule, and risk impacts due to performing a re-design and weigh them against the cost, schedule, and risk of maintaining the current design. To perform a re-design quickly, the program office needs tools in place that can provide cost, schedule, and risk data quickly. On advanced systems, designs can drive untried production processes due to the emerging technology used in the design. These untried production processes can cause significant production delays due to the amount of time it takes to deliver the required quantities. One modern technique to mitigate this risk is virtual training (Oldham 2017). Manufacturers can train the technicians virtually on the manufacturing processes and they can optimize the floor planning. When manufacturing issues occur, they can overwhelm production schedules and costs (Willoughby 1985). To mitigate the risk of schedule and cost impacts, the program office needs to be able to manage potential design related manufacturing issues proactively during post Milestone C activities.

Changes in production quantities in either direction can have a negative impact on the overall program. Generally, funding shortfalls drives a reduction in yearly quantities. A decrease in production quantities can drive inefficiencies and drive up the per unit costs. An increase in production quantities can exceed capacity and may require additional resources. These resources can be either people, equipment, or both. The program office needs tools in place to manage production quantities during post Milestone C activities proactively to optimize either the production throughput or knowingly making the decision to be less efficient based on program priorities.

Even when the program office properly plans for post Milestone C, there are still risks in manufacturing. Proper supply chain management is critical in achieving efficiencies during manufacturing to prevent either overstock or understock situations. According to Plex Systems, the following are the major risks of manufacturing:

- Schedule delays and increased cost due to no inventory, excess inventory, and carrying cost, caused by a lack of visibility into inventory and weak supply and demand planning.
- Increased costs due to paying expedite fees caused by poorly aligned planning processes. When the stock reaches zero, or when lead times are beyond the date of need, manufacturers often pay for an expedite fee to receive the material earlier.
- Poor product quality and timely shipments, caused by disconnected quality management and production scheduling processes
- Not meeting production goals due to a lack of control. This leads to poor overall equipment effectiveness (OEE). Overall equipment effectiveness is a metric used to determine the effectivity of a manufacturing process and is a product of availability, performance, and quality.
- Data quality that the manufacturer does not trust due to disparate data that requires manual aggregation and reconciliation.
- Inability to commit to delivery times and identify reasons for delays due to a lack of shop-floor-to-top-floor and planning synchronization between processes.
- Technical staff that spends too much time maintaining instead of innovating caused by manual data gathering and compilation, integration issues, and managing software updates.
- Inefficient, sub-optimal workforce performance due to error-prone and inefficient manual processes. (Plex Systems 2018)

The challenge for the program office for production post Milestone C is to ensure the success of production, independent of the decisions made during development. The program office must properly plan the program by considering the risks associated with production. The production team requires a flexible methodology post Milestone C to ensure success by optimizing resources and providing accurate estimations. Both the Bowsher report and the Willoughby DoD Directive highlight the challenges in coordinating across the different stakeholders throughout the DoD life cycle. The risks identified by Plex Systems require coordination between the program office and the vendors to mitigate as well as integration of manufacturing data. Due to MBSE being able to improve coordination across multiple disciplines and to integrate disparate data, it appears to be a viable option to mitigate production risks.

C. SUSTAINMENT RISKS

The second phase of this literature review identifies the risks associated with the Sustainment phase to understand the current processes that program offices are managing their programs by during this phase. According to a 2014 GAO report, *Weapon Systems Management: Product Support Managers' Perspectives on Factors Critical to Influencing Sustainment-Related Decisions*, the DoD spends billions of dollars each year on operating and support (O&S) costs for weapon systems (Russell 2014). The O&S costs historically have accounted for approximately 70% of the weapons systems life cycle costs. While the O&S costs are the largest percentage of overall life cycle cost, most of the risks during the O&S phase are a result of decisions made during development and production. As with production, the team responsible for managing sustainment must ensure program success independent of the decisions made in the previous phases.

The DoD has recognized a risk on sustainment due to a lack of adequate planning during development. To improve sustainment planning, the DoD created product support managers (PSM) to provide sustainment input during development. The PSM is to provide the sustainment input to the program manager and ensure that the program office is addressing sustainment concerns during development. The GAO reported that the following challenges hindered the PSM in the execution of their duties:

- Resource constraints drive the program managers to prioritize development and production over sustainment. This is due development and production cost and schedules defining program success. Another reason provided was due to program managers putting an emphasis on near-term goals as they cycle through positions every three to four years.
- Product support managers do not have decision authority during development. The program manager has the authority over all decisions made during development. Not all program managers understand the role of the PSMs and therefore do not utilize them correctly.
- Product support managers often do not have knowledge of how much sustainment funding they have until prior to the year of execution. (French 2017)

Sustainment planning has been difficult for the DoD for the reasons identified in the GAO report, *Weapon Systems Management: Product Support Managers' Perspectives on Factors Critical to Influencing Sustainment-Related Decisions*. The sustainment findings are similar to the findings GAO identified for transition from development to production. The program managers often focus on near term issues whether they are development or production goals, the management and staff do not always have the background to plan for the next life cycle phase, and funding uncertainties. The program office often discovers these issues during post Milestone C and usually during sustainment when they arise. It is imperative that the program office identifies these issues as early as possible during post Milestone C activities to be able to mitigate the schedule and cost impacts. As with the Production and Deployment phase, coordination among all stakeholders is critical to success. Model-based systems engineering has proven capable of improving coordination. Even on programs that properly plan sustainment activities, the program office must mitigate persisting sustainment risks post Milestone C.

According to a GAO report, *High-Risk Series: Progress on Many High-Risk Areas, While Substantial Efforts Needed on Others,* "the DoD has experienced weaknesses in the management of its supply chain" (Mihm 2017, 248). The GAO has labeled supply chain management as a high-risk item since 1990 with only moderate improvement since then. The first finding in the report highlighted inefficiencies and ineffectiveness in the inventory management policies and procedures. These policies and procedures lead to excess spares and not accurately forecasting demand. The second finding in the report highlighted the DoD's challenge in delivering items. This includes delivering items on time as well as the ability to track items. The third finding in the report highlights the weakness in maintaining visibility of supplies. The findings in this report are similar to the finding from Plex Systems on manufacturing challenges. The program office needs to manage the supply chain proactively to ensure there are no unattended delays in returning systems back to service and maintain the required operational availability. If the program office had better access to the schedule data from vendors as well as the inventory trends, the program office would be able to be more effective at supply chain management.

The F-35 Joint Strike Fighter (JSF) is an example of the issues identified by the GAO report, *High-Risk Series: Progress on Many High-Risk Areas, While Substantial Efforts Needed on Others* (Mihm 2017). The F-35 is the latest DoD weapon acquisition program that has seen significant cost and schedule overruns during development and production. The Marine Corp introduced their variant of the F-35 and deemed it combat ready on 31 July 2015 (Neuman 2015). According to the GAO report, *F-35 Aircraft Sustainment: DoD Needs to Address Challenges Affecting Readiness and Cost Transparency*, the repair capabilities are six years behind schedule and the availability of spare parts is causing 22% downtime with an average repair time of 172 days (Russell 2017). Since 2012, the projected sustainment costs of the F-35 have increased 24% to over $1 trillion over its 60-year life cycle (Russell 2017). Managers need to be able to identify and correct these issues as early as possible to limit the cost incurred by taxpayers.

One aspect of sustainment is obsolescence refresh. Obsolescence refresh occurs when the repair or procurement of subsystems, or components of a subsystem, are no longer viable. The refresh is a functional replacement of the obsolete component or subsystem. Obsolescence refreshes follow the traditional DoD acquisition life cycle, but generally enter post Milestone B. While the system is post Milestone C in sustainment, a subsystem can be performing development. This occurs when technology becomes outdated and the technology is no longer in production. For example, due to a lack of availability in magneto-optical disks, the program office needs to update their design with newer technology to provide available media. As newer DoD systems are using more commercial-off-the-shelf (COTS) products, more components are becoming obsolete by the time the program office fields the DoD system. This is due to technology moving faster than the DoD can field a system. For example, as Figure 6 shows, 70% of components are obsolete by the time the DoD fields a sonar system (Singh and Sandborn 2006). The program office needs to put the tools in place to better track and plan for obsolescence. When the program office does not properly plan obsolescence during post

Milestone C activities, the program office can either spend resources on unplanned repair capabilities or reduce the capability of the system by either fielding less systems or removing functionality. For the program office to avoid an unexpected obsolescence issue, there needs to be coordination between the vendors and the program office as well as inventory and maintenance trends. This allows the program office to identify when it expects stock to reach zero and to identify whether the vendor will have required parts available for procurement to replenish the stock.

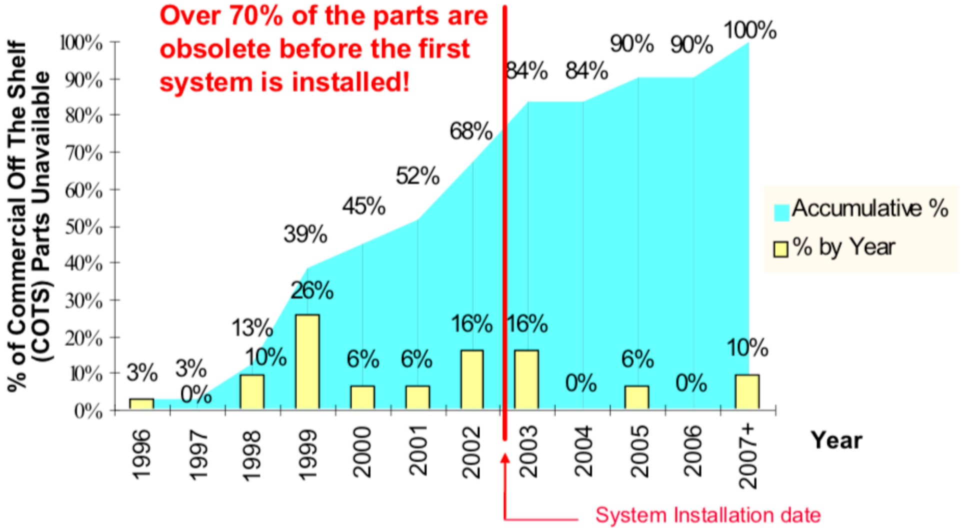


Figure 6. Percent of COTS Parts that Are Obsolete vs. First 10 Years of Life Cycle. Source: Singh and Sandborn (2006).

The challenge associated with an obsolescence refresh is to first identify the obsolescence and then execute development and production prior to the component or subsystem becoming obsolete. Numerous publications discuss the challenges associated with development that this research is not going to discuss in detail. The challenges are in understanding requirements, ensuring the correct allocation of requirements, minimizing changes in scope, creating accurate cost and schedule estimating, maintaining stable funding, and placing people with the right skills in the right places.

Sustainment is generally the longest DoD life cycle and accounts for the maintenance, logistics, and obsolescence refresh planning. The main challenges to sustainment are supply chain management and obsolescence planning. The root cause to both of those challenges is a lack of coordination that leads to the program office not understanding schedule. For supply chain management the program office does not know how long it takes to replace parts. That leads to the stock issues identified in the research. For obsolescence planning, the program office does not know when parts will go obsolete. This can cause significant cost, schedule, or capability impacts as discussed in this research. Based on my experience, DoD program offices plan conservatively. This means, for example, that the program office procures more spares than necessary and plans obsolescence refreshes earlier than required. This drives unnecessary cost onto the program. Model-based systems engineering, discussed later, has demonstrated the ability to capture requirements, processes, and integrate and link data across stakeholders and has the potential to mitigate these risks to sustainment.

D. HOW MBSE TECHNIQUES CAN HELP IN POST-MILESTONE C

The development of MBSE is to formalize the systems engineering process through modeling. The goal is to use a model-based process to improve rigor, communications, consistency, and to manage complexity through formal modeling languages and automation. Industry has many models in place that they are using, but the users did not integrate the models and the user based on individual needs creates the models based on documents. Model-based systems engineering formalizes and integrates those models to fulfill everyone's needs. Utilizing MBSE to understand the cost, schedule, and risks associated with the program and trade space within the program allows the program office to optimize the program based on needs. At lower levels, utilizing MBSE to capture manufacturing processes can help identify where process improvement or where the program office requires additional resources. Using MBSE to model the life cycle of components allows the program office to make informed decisions on sparing and obsolescence. Integrating all these models into a MBSE methodology provides disciplined coordination across all stakeholders.

Figure 7 highlights the model types that program often use and how the models integrate across a MBSE methodology. In this particular methodology, there are five major hubs represented by the blue bubbles. An Integrated Data Management Layer integrates the major hubs. The minor hubs, represented by gray circles, integrate between the major hubs. This is just an example of a MBSE methodology. There are various other methodologies; however, from a life cycle flow the types of models are similar. For a post Milestone C program, the focus is on the model types that occur to the right of the Engineering and Manufacturing Development event at the top of the figure.

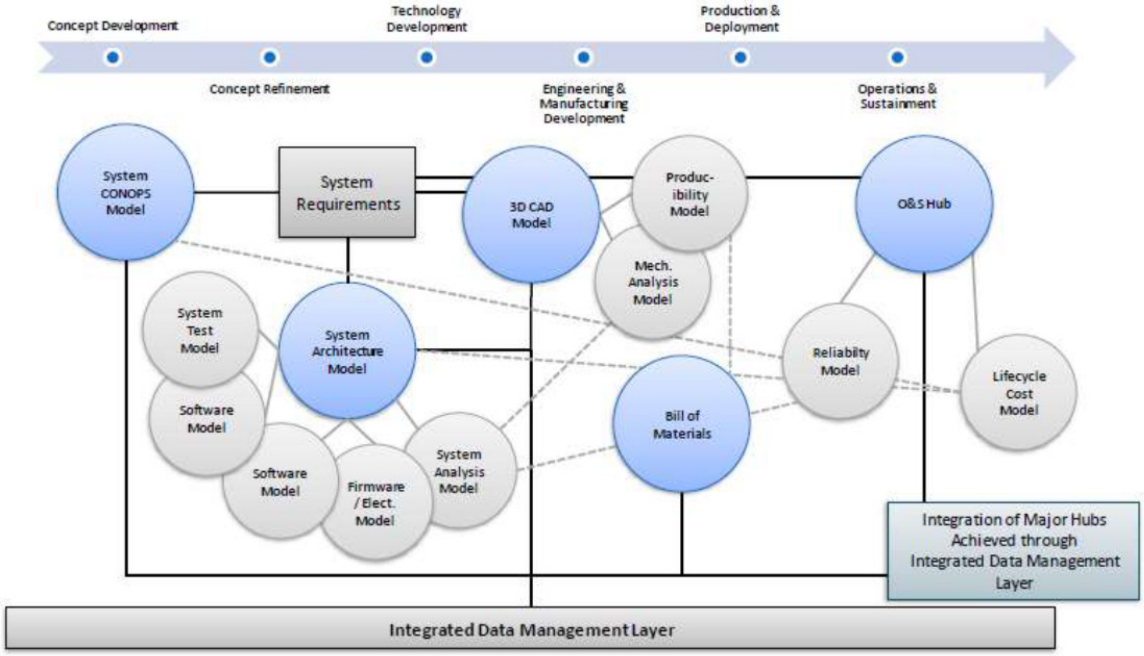


Figure 7. MBSE Methodology Example. Source: Hart (2015).

Model-based systems engineering tools and methods focus on requirements, design, verification, and validation. The intended use of MBSE was for development and not to implement them during post Milestone C activities; however, MBSE tools have been useful for post Milestone C activities. Research identified several articles where SysML is used to model discrete production lines. One paper written by Johan Van Noten details his experience with utilizing SysML for discrete production lines. Van Noten and his team utilized SysML to model the production line of a cupcake. The findings in the paper are that SysML is a useful modeling language. It does have drawbacks when using it for a discrete production line. There are scenarios that trivially occur in the context of a production line, but do not have an obvious solution in SysML (Van Noten 2017). Examples from the paper include, “describing implicit physical interactions, reflecting workpiece state, modeling complex workpieces, and avoiding UML validation issues” (Van Noten 2017, 161). The paper’s conclusion is, “systems engineers would benefit from enhancing the SysML language’s expressiveness and tailoring its complexity towards the systems domain” (Van Noten 2017, 162). In December 2017, the Object Management Group released a request for proposal for SysML v2.0 to improve the usability and expressiveness (Object Management Group 2017). This update should address some, if not all, of the issues that Van Noten describes. The paper proves that using a modeling language, such as SysML, can model post Milestone C processes, such as a production line, and it can be useful to make decisions.

Leon McGinnis of Georgia Tech and George Thiers of ModGeno wrote a PowerPoint titled, “Model-based Systems Engineering for Aerospace Manufacturing” (McGinnis, Leon, Thiers and George 2017). The PowerPoint discusses the digital thread for manufacturing. There are many links between different entities when dealing with production as shown in Figure 8. To implement MBSE, the program needs to link the models digitally, either the same as in Figure 8 or in a way the program office tailored. According to the PowerPoint, there is a need to move beyond just exchanging information. There is new material, new business models, faster times to market, changing product requirements, and changing technologies that require a production strategy that is different than a continuation of what programs have done in the past (McGinnis, Leon, Thiers and George 2017). There is a need to, “be able to specify and analyze the complete supply chain at levels of fidelity comparable to the specification and analysis of the product” (McGinnis, Leon, Thiers and George 2017, 12). We can use model-based systems engineering tools to accomplish this task because, “manufacturing systems are systems through which materials flow, and are transformed by processes, executed using resources, and organized in some way" (McGinnis, Leon, Thiers and George 2017, 16).

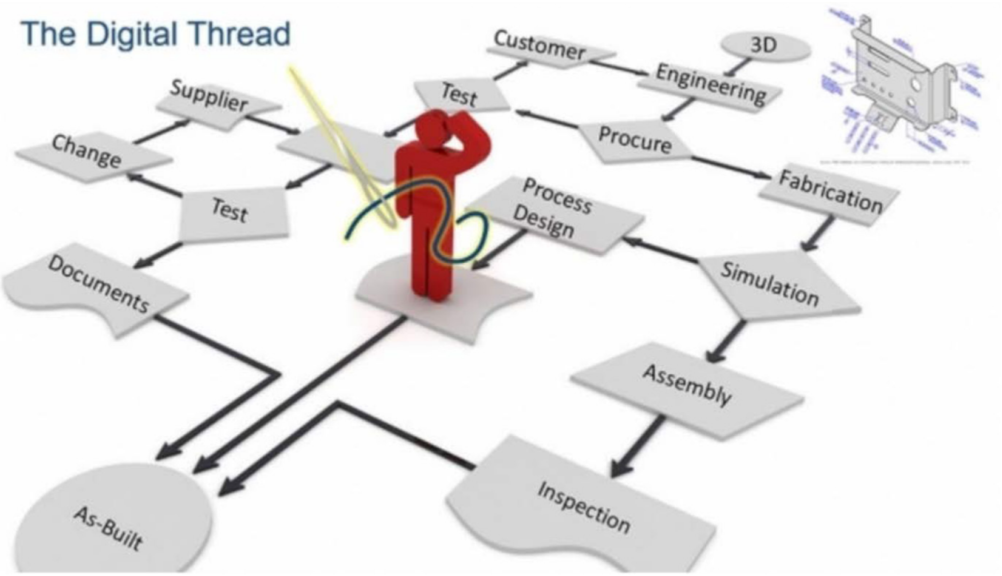


Figure 8. Manufacturing Digital Thread. Source: Leiva (2016).

The authors describe an MBSE framework for implementing a Discrete Event Logistics System as shown in Figure 9. The framework utilizes three layers to link the real system to a language layer. In-between the real system and the language layer is a system model that links to storage systems, production systems, transportation systems, and supply chain systems that link to the DELS reference model. This demonstrates that it is possible to link production and sustainment models together using existing languages and tools for use post Milestone C.

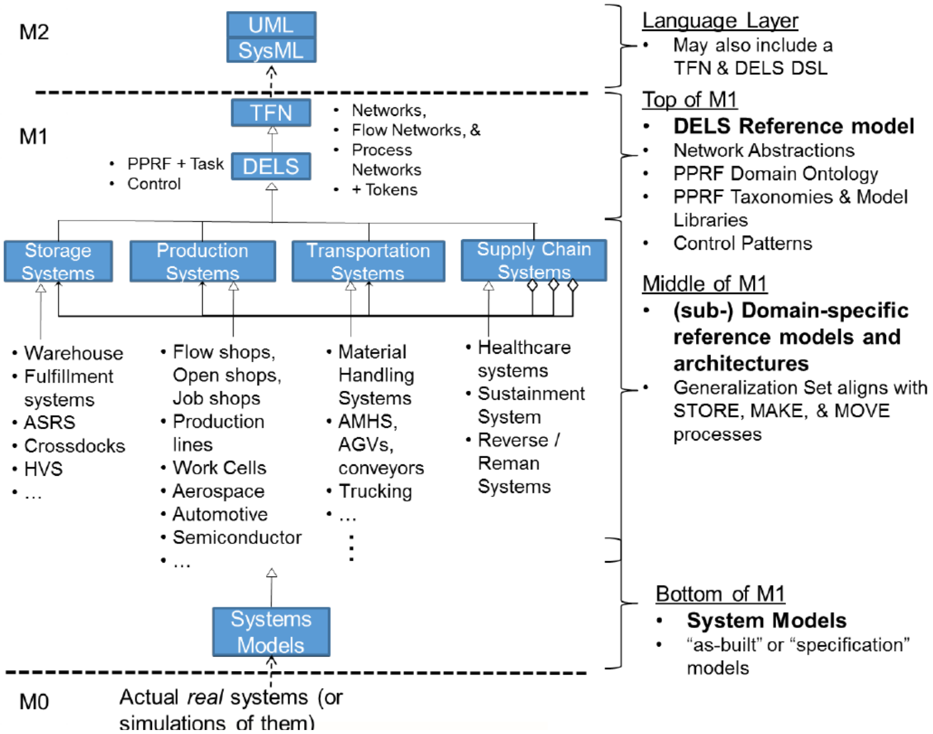


Figure 9. Discrete Event Logistics System.
Source: McGinnis and Thiers (2017).

E. SUMMARY

The program office can effectively tailor MBSE to help program planning and execution to mitigate risks associated with the post Milestone C activities. These risks make weapon system acquisition for the DoD challenging and the realization of these risks can overwhelm program schedule and cost. The program office makes many decisions for activities post Milestone C in advance during the development phase. These decisions do not always have the best interest of production and sustainment at hand. To mitigate these risks, it is important for the program office to implement tools and processes that provide confidence into the level of risk that their program contains. For the transition from development to production effort, the program office needs to ensure that there is a disciplined approach and coordination between the design, test, and production activities. Once the program enters full-rate production, the program office needs to be able to identify inefficiencies in the manufacturing processes, track the supply chain, and identify obsolescence. Once the program office deploys the system, the program office needs to be able to manage obsolescence, logistics, and track repairs.

In the conduct of the literature review, a significant gap in research is identified in implementing MBSE during post Milestone C activities. This research fills in some of that gap. The existing research related to sustainment risks was minimal. The existing research on sustainment consists mostly of GAO reports. It is beneficial to understand from an industry perspective what its risks are in supporting sustainment activities. Further research for the disposal phase of the DoD life cycle as well as the applicability of implementing MBSE for testing as no research was identified that existed already and this research did not pursue those activities is required.

III. IMPLEMENTATION OF MBSE POST MILESTONE C

The research in this section leverages the literature review conducted for post-Milestone C challenges as well as MBSE utilization post-Milestone C to identify opportunities for MBSE utilization post-Milestone C as well as the development of an Excel MBSE analysis tool. This section identifies the rationale for identifying how the program office can implement model that the program office can use to implement an MBSE approach to post Milestone C activities as well as the methodology of the Excel MBSE analysis tool. The Excel MBSE analysis tool provides a metric to the program office that identifies whether to recommend implementing MBSE. Chapter IV demonstrates a case study employing the MBSE methodology and Excel MBSE analysis tool described in this chapter.

A. INTRODUCTION

The benefit of utilizing MBSE is not in the generation of models. All program functions in all programs generate some sort of model to support their effort. These models only support a specific function, as the user did not implement the models in a way that is integrated. The benefit is realized when the models can be integrated across the different program functions. The typical implementation of MBSE normally starts with the definition of a problem and defining the stakeholder needs. The program can develop a functional problem space model to capture these stakeholder requirements. From the problem space model, the program can develop a black box system model to define system requirements. The program defines the system element requirements further by decomposing the black box system into functional and structural architectural models. The system model contains structural models, behavioral models, requirements, and parametric models that the program uses to represent the relationships among requirements, design, analysis, and verification elements. The program can link the system model to design, analysis, and testing models. This allows the traceability of lower level design requirements and design to the operational viewpoint to ensure mission effectiveness. As the industry and government move towards implementing

MBSE, program offices need to decide on whether MBSE is the right approach to implement into a mature program.

Post Milestone C programs have a unique set of issues and concerns not addressed by the typical implementation of MBSE. While the goal of MBSE in the traditional approach is to cross the systems engineering “Vee” early in system development, the goal is different upon entering production. Once the program reaches the production phase, the goal focuses away from requirements and design traceability to production schedule, cost, and risk traceability. The tools and methods that the program office implements need adjustments such that they can allow traceability to a schedule, such as an Integrated Master Schedule (IMS), a cost model, and a risk database. This does not imply that the programs should not use structural, behavioral, requirements, parametric, and/or process models, but it merely implies that the program uses them in such a way to trace to a schedule, cost, and capture risk. For example, the program should not develop structural models during production to change size and weight, but it may be beneficial to develop a structural model to identify opportunities to manufacture components either faster or more cost effectively. This allows the program office to perform schedule and cost tradeoffs to ensure the program stays within allocated budgets and schedules.

This research assumes that the program office has not implemented MBSE as part of the development efforts. As program offices generally utilize MBSE to influence design decisions, to implement it post Milestone C requires a different perspective on how the program office implements MBSE. To determine the effectiveness of implementing MBSE post Milestone C the return-on-investment (ROI) must be determined by the program office. While this research assumes that the program office has not implemented MBSE, this research does assume that the program uses industry standard models such as CAD and IPC-2581 files, but the program does not use them in a formalized way to influence system level trades and risk mitigation activities. The assumption is that the program office uses design models, such as CAD and IPC-2581 files, to provide a design to the manufacturer. To determine whether the program office implements MBSE, the program must first identify the problem, identify the model types, identify the decisions that the program office must make need, and identify the cost needs.

This research identified the common issues during production and sustainment for weapon system acquisition. A Microsoft Excel table captures the data. The research identifies whether a model could be beneficial to mitigate the risk from occurring. When the Excel MBSE analysis tool identifies a model to be beneficial, the Excel MBSE analysis tool captures the rationale for why it is beneficial. Upon capturing the rationale, the Excel MBSE analysis tool identifies questions that the program office needs to answer to determine whether the Excel MBSE analysis tool will recommend to implement that model a technical standpoint. The Excel MBSE analysis tool identifies generic model types that provide the risk mitigation. The goal of this research is not to identify the specific modeling language or modeling tool that the program office should use. The Excel MBSE analysis tool implements a cost model to trade off model development cost against cost of the risk. This provides the metrics for the program office to decide whether the program office should implement a MBSE approach.

B. CHALLENGES IMPLEMENTING MBSE POST MILESTONE C

There are a few key challenges in implementing MBSE post Milestone C. Whether to implement MBSE post Milestone C, the program office must determine if the ROI for implementing MBSE is worth pursuing in face of those challenges. Every program is unique and there are many variables in place for making the decision. A tool that one develops to assist in that decision-making process must be flexible.

The main challenge in implementing MBSE post Milestone C is the additional cost. The cost to implement MBSE can be significant. When a program reaches Milestone C, the planning and infrastructure is in place to support production and sustainment. The cost to implement MBSE post Milestone C can appear to be an unnecessary cost, as it does not add any direct value to the product the program is producing or sustaining. The value of implementing MBSE post Milestone C is in the reduction of risk and increasing confidence in cost and schedule. The program office needs to compare the overall risks to the cost to implement MBSE to provide the justification. The program office needs to determine if the additional cost is worth the amount of projected risk mitigation.

The second major challenge in implementing MBSE post Milestone C is the schedule. It takes time to develop the models and implement the methodology. In programs that would benefit the most from MBSE are likely the ones that are already facing schedule challenges. It can take a year or more to implement MBSE. The time it takes the program office to implement MBSE can reduce the effectiveness in implementing MBSE. For programs that are in production for only a year, it likely does not make sense to implement MBSE due to schedule. Programs that have production that lasts 10 years or more will receive the benefits of MBSE. Programs that are between five and 10 years need to weigh the pros and cons and make an informed decision.

The last major challenge in implementing MBSE post Milestone C is the lack of understanding of what MBSE is and how it can be useful. Based on experience in implementing MBSE, the major question to ask is, how are models going to help detect the unknown unknowns? To overcome this challenge, it is important to explain the logic in implementing models. The program office needs to understand that MBSE is not the creation and use of models or becoming model-centric instead of document-centric. It is important to implement MBSE to integrate across models and domains while utilizing automation to provide an integrated look at the data to drive faster decisions.

C. IMPLEMENTING MBSE DURING PRODUCTION

The key to managing production successfully is to understand the schedule, cost, and the tradeoffs between schedule and cost with design trade space throughout the entire life cycle of the program (Kokemuller 2018). To accomplish this, program offices develop a schedule that captures every critical step in the manufacturing process to build and deliver the end item as well as the resources associated with each step. If the resources are items, such as equipment, then the schedule needs to capture the procurement and setup time associated with that resource. This is not unique to the implementation of MBSE as it is true whether the program implements MBSE.

The need to understand how each step in the process influences the delivery of the end item is critical to be able to make informed decisions. Typically, the standard process is to develop an IMS the entire program (DoD 2007). The typical solution is a labor-intensive process where a person is required to make updates and track status on an IMS that can contain tens of thousands of lines. Implementing MBSE potentially can provide benefits to this problem. Figure 10 shows the recommended modeling architecture implementation. Implementing MBSE for post Milestone C activities should be IMS focused to track cost and schedule in a single view. The program develops an IMS such that it incorporates outputs from several other models. As shown in Figure 10, the various models provide input to the IMS. The IMS can highlight risks associated with schedule and resources. These risks provide a feedback into the models.

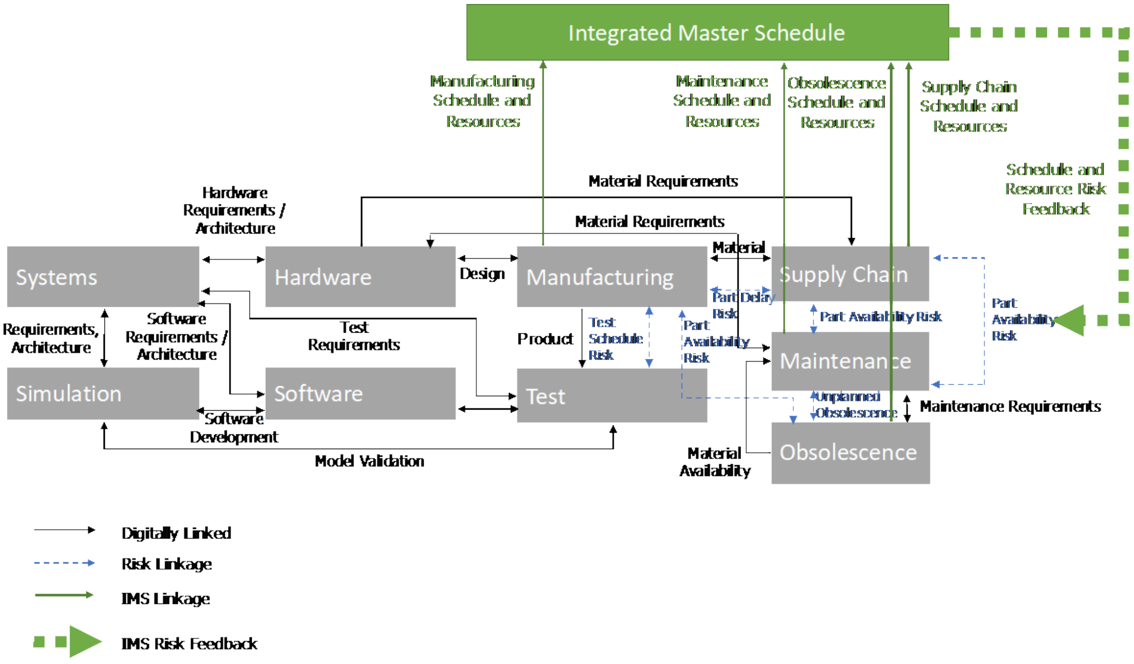


Figure 10. Integrated IMS Example.

Once the program develops the model, the program performs analysis within a reasonable timeframe to identify the sensitivities and bottlenecks. This provides the ability to apply appropriate risk mitigation resources to high sensitivity steps or to bottlenecks. Ideally, the program generates a schedule from the model. If the program office does not do this, or the program office cannot perform this function, then it is a labor-intensive process to generate a schedule from the model. As the program collects data from the production builds, the program uses the data to update the model to reflect the near real-time performance of the manufacturing process. When models do this, the program office has time and the ability to make informed decisions based on schedule and cost. It also has the potential to reduce labor hours associated with maintaining schedules manually. When the program develops other models, then the trades between schedule, cost, risk, and technical provide much more value.

This research developed a manufacturing model, as shown in Figure 11, to identify the bottom up schedule associated with the manufacturing process. Utilizing a modeling language such as SysML can capture processes, or a process modeling language (PML), can allow the manufacturer to perform trades of various processes and to identify potential bottlenecks. This provides the manufacturer the ability to optimize the process and identify where the program office needs to apply additional resources to mitigate low yields. In addition to modeling the process and allocating resources, the manufacturing model also includes the time it takes to setup the facility, and it uses any existing design models.

To be complete, the manufacturing model consists of a build and assembly model, a resource model, and a facility readiness model. The build and assembly model is implemented by an activity diagram that captures the work instructions and build processes. The purpose of this model is to capture the time and resources required to meet the allocated schedule to identify the risk to maintaining schedule and cost. This model interfaces with the hardware asset that provides the TDP and the test asset as the build and assembly provides the hardware that the program uses in testing. The resource model includes the personnel, budget, and schedule planned and available for production. The purpose of this model is to provide assets to the build and assembly model and provide constraints to the resources the build and assembly model utilizes. The facility readiness model consists of the production equipment, parts, test equipment, and special tooling required to complete the build and assembly. The purpose of this model is also to provide assets to the build and assembly model. It provides constraints to the availability of parts and production throughput to the build and assembly model. The facility readiness model interfaces with the supply chain model as the supply chain model provides parts that the program places in stock.

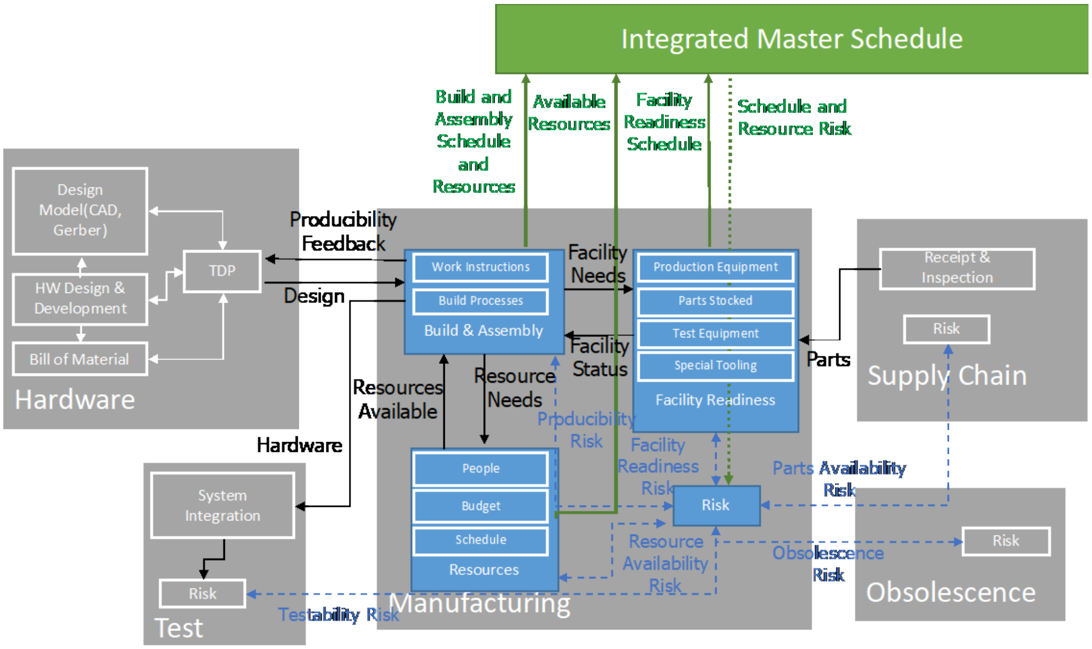


Figure 11. Manufacturing Model.

During the planning, the program office identifies and captures risks. The resource model identifies risks to obtaining the planned resources, the build and assembly model captures the risks associated with meeting build requirements, and the facility readiness model captures the risks associated with providing the necessary equipment, parts, and space required for production. The manufacturing risk model captures the risks from each of these models. Figure 11 identifies the high-level risks.

The outputs of the build and assembly model, resource model, and the facility readiness model are inputs to an IMS. As discussed before, ideally this is a digital connection that is an automated process; however, it can be a manual process. The build and assembly output is the time requirements for the build and assembly steps as well as the resources required to meet those time requirements. The outputs of the resource model are the available resources. The output of the facility readiness model is the time required to establish the facility to be ready to begin production as well as the time it takes to replace parts in stock. When program office integrates the timelines and resources into an IMS, it identifies where risk areas exist. The MBSE methodology then adds these risk areas to the maintenance risk model to update the models accordingly.

During production, there are times when re-designs need to occur. Several factors drive a re-design and the one that is avoidable is a re-design due to starting production prior to completing development and driving concurrent production and development. Several model types are beneficial to the program at this point. Developing a manufacturing model allows the program office to trade off any remaining design with its impact to production. Developing a system model, or parts of a system model, allows the program office to make trades within the design to understand the system level impacts of any design decision. The system model contains the requirements in a structure model, behavior model, and an interface model as well as the architecture. Utilizing the manufacturing model to identify the risks within the build and assembly and then linking those risks to the system model provides the program office insight into where the risks are on the program. To mitigate the manufacturing risks, the program office may choose to adjust parameters in the system model to provide flexibility to adjust the design to make manufacturing easier.

Using models that capture design, such as CAD or IPC-2581 files, can mitigate a lack of alignment between the designer and the manufacturer. This reduces the vagueness of the design and allows the manufacturer to understand the intent of the design. These models are generally common practice in industry. The key to MBSE is to link these models to the system model and influence program level trades to optimize program resources (Hart 2015). When requirements are too restrictive, it can be difficult for the manufacturer to produce. Often this occurs when discussing tolerances. The variability of the machines may be greater than the requirement itself. Developing a system model helps in identifying trade space for requirements. If the program office can relax requirements, the program office may decide to re-allocate requirements, update the design, and provide flexibility to the manufacturer to save production costs.

A lack of alignment between the purchaser and the supplier causes increasing yield times needed to procure parts and materials (Plex Systems 2018). The program office needs to understand schedule risk associated with their program and can accomplish this by developing a supply chain model, as shown in Figure 12. During production, the program can incur significant delays by late components from vendors that the program uses in the production of the end item. What often occurs is the discussion and agreements on lead times involve a point estimate, usually the most likely, for the delivery time and programs optimistically plan to the point estimate. What the program office needs to know is the distribution of delivery times as opposed to a point estimate. Utilizing a schedule that can implement variability into the delivery dates, the program office can run Monte Carlo simulations to identify schedule sensitivities. The variables of the Monte Carlo simulation consist of time, quantities, and resource availability. The outputs of the Monte Carlo simulation provide the probability density of the completion of the tasks. Developing this modeling approach forces the discussions between the purchaser and the supplier to identify the distribution in delivery times such that the program office can make risk-based decisions on schedules.

The supply chain model consists of a lead-time model, shipping model, and a receipt and inspection model. The supply chain model receives the bill of material from hardware and provides a time that the program will stock the material. This research implements all three models as an activity diagram. The lead-time model contains the material in the bill of material (BOM) and identifies the time it takes each material to be available at the supplier. The model uses distribution to capture the lead-time to be able to identify the confidence in the lead-time the program uses for planning. The shipping model provides the shipping times for each material. The model calculates the time from the moment a part is available until the moment the vendor delivers the part. The model considers the variability in shipping times based on the shipping region as well as the time of year. For example, the material shipped from Boston, MA in the winter should have risk of delivery delays due to snow. The receipt and inspection model considers the time it takes from the moment of receipt of delivery until the moment the program places the material in stock. The output of the supply chain model provides the time that the program projects to stock the material. The lead-time model, shipping model, and the receipt and inspection model provides an output to the IMS. For the lead-time model, this output is the time that parts become available from the supplier. The shipping model provides the time that the vendor delivers each piece of material once it becomes available at the supplier. The receipt and inspection model provides the time that the program stocks the material. As with the manufacturing model, the model captures the risk. Each model identifies the risk associated with the completion of its efforts and the IMS provides feedback to the risks.

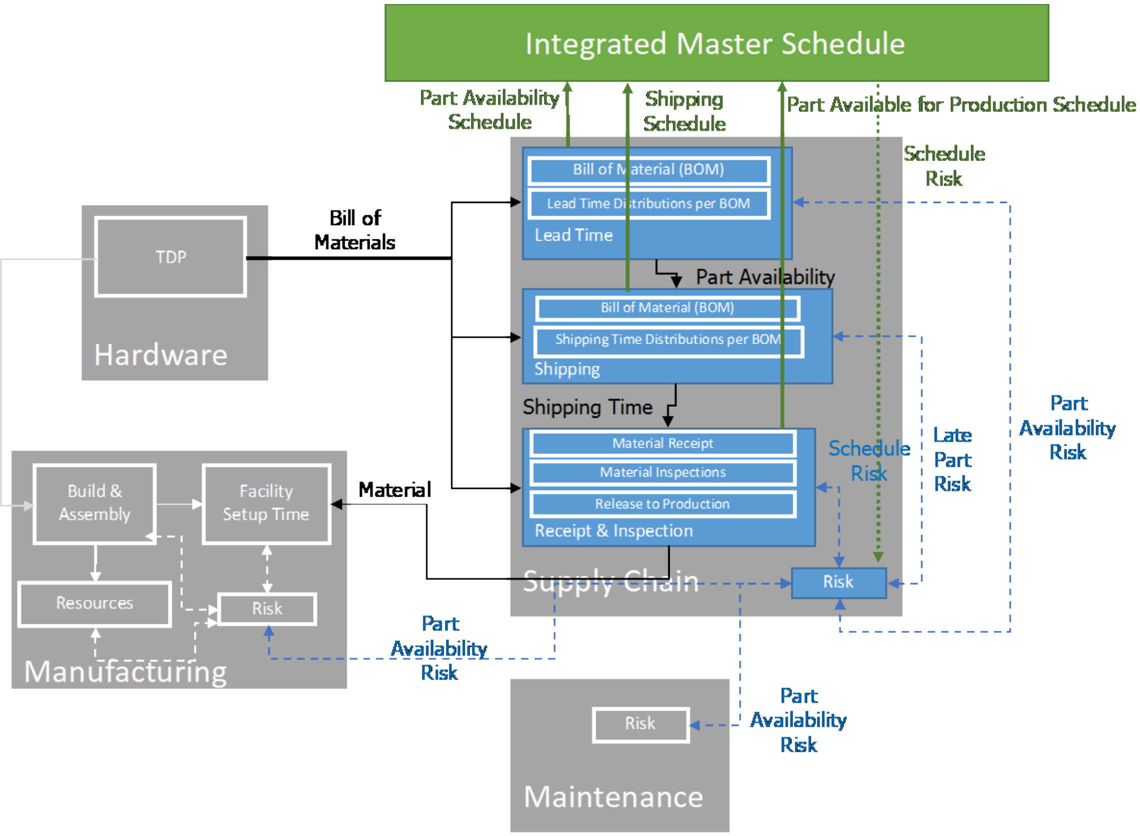


Figure 12. Supply Chain Model.

With the reliance of commercial-off-the-shelf (COTS) technology within the DoD, obsolescence becomes a major issue as COTS technology often has an 18-month life cycle while military systems have over a 20-year life cycle (Cole 2016). When production goes across several years, COTS products can, and often do, go obsolete. When products go obsolete, the program office identifies replacement parts. Sometimes it can be a simple replacement and sometimes it can be very difficult. An example of a difficult obsolescence refresh is the replacement of the navigator on the OHIO class submarines, discussed later. It is important for the program office to have an obsolescence model that identifies what components are at-risk of going obsolete during production, as shown in Figure 13. This helps to inform the program office on whether the program should utilize life-of-type-buys (LOTB) to mitigate the risk or if the program office should take other mitigations, such as adding time in the schedule to identify replacements. The model identifies schedule impacts and additional costs so that the program office can perform trades to optimize the resources and risk posture. Obsolescence can also drive concurrent development. In the case of concurrent development caused by obsolescence, the same models identified previously are applicable.

The obsolescence model consists of a provisioning model, a stock model, and an industry trend model. The MBSE methodology implements the provisioning model as an asset diagram that receives the maintenance requirements and based on projected failures, repair costs, and cost of spares provides the quantities of parts required over the life cycle that the program office needs to procure. This MBSE methodology implements the stock model as an activity diagram that uses the output of the provisioning model and determines when stock will reach zero based on current failure rates and trends to allow the program office the ability to make decisions on whether to buy more stock or perform a refresh. This MBSE methodology implements the industry trend model as an activity diagram that provides current industry trend data for part availability and projects when each component will be obsolete. This MBSE methodology categorizes the trend data by part type and by manufacturer. Different parts have different life cycles and different manufacturers may have different life cycles. The MBSE methodology uses the data to provide the stock model information to influence when to procure new stock. The stock model and the industry trend data provide an output to the IMS. The stock model provides the time when stock will reach zero and any planned stock procurements. The industry trend model provides when each component will go obsolete. The IMS identifies the risks associated with the dates when stock reaches zero and the dates of when the components will go obsolete. Each model contains the risk associated with its effort. The MBSE methodology captures these risks in the obsolescence model. The MBSE methodology feeds back the risks identified by the IMS into the obsolescence risks. Based on the risks, the program office either modifies their planning or accepts the risks

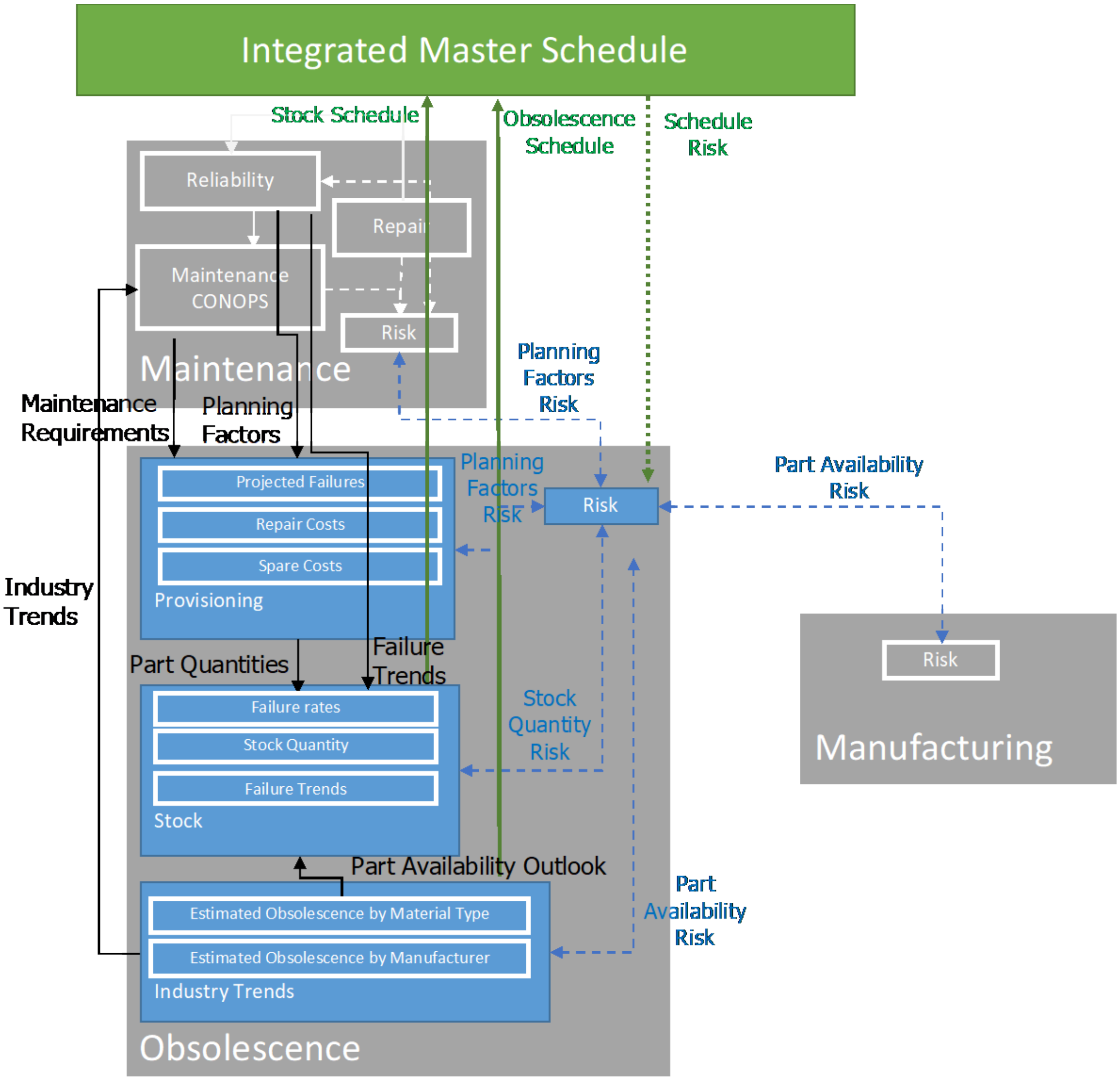


Figure 13. Obsolescence Model.

During development, the program office may not have considered manufacturability of the design or there was minimal effort applied to ensuring the manufacturability of the design (Willoughby 1985). It may be beneficial to the program to do minor re-designs to make the product more manufacturable. These are generally structural modifications, such as bolt types and bolt locations that do not affect performance. To identify whether the change influences performance, a system model is beneficial to identify any impacts to requirements due to the change in the structure by updating the structural model. If the program office develops a system model, the program office is able to identify the impact to the system due to the changes in the structural model with minimal effort.

Once the program office makes the decisions overcome sub-optimal planning, the program office needs to ensure that they optimize the day-to-day processes. In the context of this thesis, either planning which the program office did not perform correctly or evolving conditions during development can cause sub-optimal planning. Figure 14 shows an example of an organizational chart. Each group, such as sourcing, implements its own processes and collects the data that is necessary for them to do its job. This leads to inefficiencies. If the data collection is a manual process then it drives additional inefficiencies. The inefficiencies from manual data collection can cause a lack of production control by providing data late as well as almost ensuring disparate data. Automation and complexity in manufacturing has significantly increased since the Second World War. The increased reliance on automation along with the complexity drives increased inefficiencies into manual processes. It is important to be able to pull all necessary data together in a consistent format to make real-time decisions. The manufacturing model incorporates the manufacturing data.

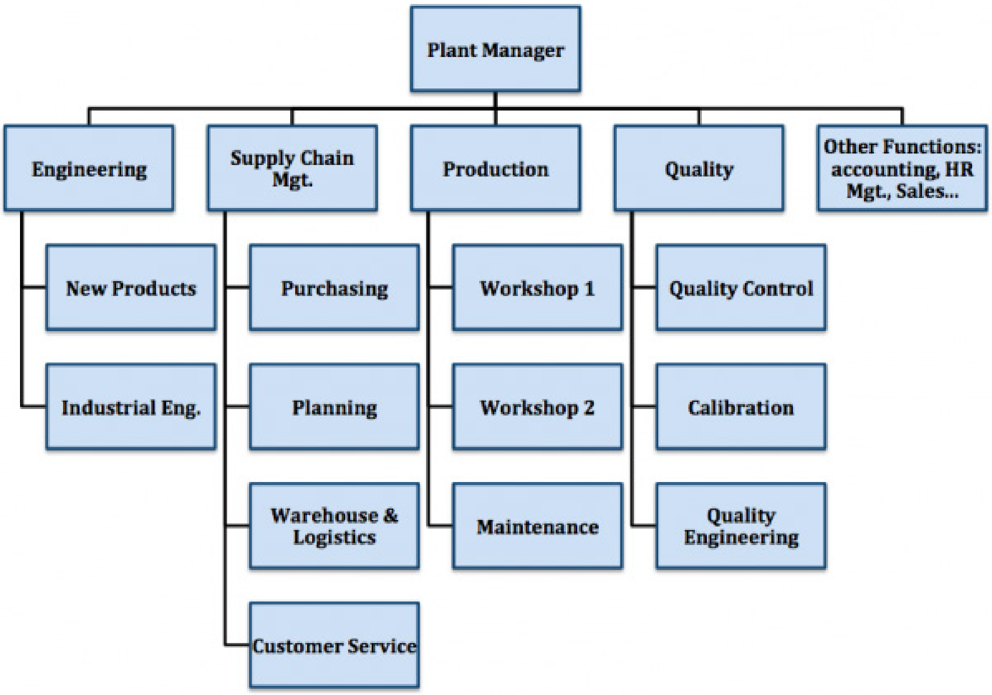


Figure 14. Example Manufacturing Organization Chart.
Source: Anjoran (2014).

The key to making MBSE beneficial from the day-to-day manufacturing operations perspective is the integration of manufacturing data into a model to be able to automate processes, such as sourcing, and provide manufacturing time data. As the program generates data from the manufacturing processes, the model incorporates the data. Combining sourcing data, such as lead-time for components, with the manufacturing data, the model is able to predict when the program consumes components in inventory and informs the production staff when the program office needs to procure components based on the lead times. The model updates the sourcing data regularly to ensure that the model reflects the most current lead times. This type of model helps prevent zero stock as well as excess inventory. Zero stock occurs when parts are no longer available in stock. When this occurs, the production line shuts down, potentially causing a loss of the trained staff. The program office then uses resources to train new staff. To prevent the production line from shutting down, the program office pays expedite fees to the vendors to put a higher priority on delivering the component (Plex Systems 2018). When excess inventory occurs, resources that the program office could invest somewhere else is invested in material sitting on a shelf. Sometimes a vendor or contractor charges the program office a holding cost for storage of material taking away resources needlessly. Automating these processes provides an opportunity for the staff to focus their efforts on critical areas.

Implementing MBSE during the production phase is not only for the benefit of production. During this phase, it is also important to consider the sustainment aspect of the program. Implementing MBSE during sustainment is discussed in its own section. While it is discussed in its own section, the logic still applies if MBSE is implemented during production.

D. IMPLEMENTING MBSE DURING SUSTAINMENT

In the prior section, Figure 10 identifies the implementation of MBSE during production. The same figure is also applicable to implementing MBSE as part of sustainment. Schedule and the resources required to conduct the identified scope drive sustainment that the model incorporates into an IMS. Sustainment efforts can vary greatly between different programs. Some programs can have minimal sustainment efforts, such as hard drives, where it is more cost effective to replace the components rather than sustain the existing component. On the other hand, programs like the OHIO Class submarines, which commissioned beginning in the early 1980s and will be in service through 2040, have an extremely long sustainment effort. A hard drive and the OHIO Class submarines are at the far ends of the spectrum and most programs will be in the sustainment phase between 10 to 20 years. The longer the sustainment phase, the more beneficial MBSE is to implement. Understanding the unique requirements of each program and attempting to develop a tool to provide a recommendation to implement MBSE and to what extent is a very daunting task. There are nearly infinite numbers of decision variables to drive the recommendation. The Excel MBSE analysis tool developed for sustainment only considers the key decisions to provide a general recommendation. Ultimately, the decision whether to implement MBSE during sustainment comes down to the program office's risk assessment on the planning and tracking of obsolescence as well as whether setting up the MBSE infrastructure reduces future program costs. During this phase, it is important to have planned for obsolescence and to track the parts usage to understand if they are following the planned usage or if the program office needs to update the plan.

When implementing MBSE during the sustainment phase, it is critical to understand the ROI. The Excel MBSE analysis tool calculates ROI using a cost model to determine the cost of implementing MBSE and compares it to the cost risk that currently exists on the program. The number of years that the program office planned for sustainment indirectly determines the ROI. The longer the planned sustainment, the more likely there is a ROI. Developing models for MBSE requires a good amount of resources to develop and implement, including time. It is not unheard of for a program to take over three years to develop and implement MBSE. For example, the Submarine Warfare Federated Tactical Systems (SWFTS) transitioned to MBSE in 2013. SWFTS required two years to implement the model and one year to phase out the traditional systems engineering processes (Pavalkis 2014). The justification for a program that that the program office plans to sustain for less than five years is extremely difficult, as the resources the program office applies should be to the replacement program to establish MBSE early. For a program that the program office plans to sustain for five to ten years, the program likely requires a single major refresh. By the time the MBSE framework is in place, it is likely that the opportunity to utilize MBSE for that system has passed. However, the loss of the technical experts is a concern of the federal workforce and models can capture their knowledge. Implementing MBSE on a program that has a sustainment phase planned longer than 10 years not only is able to provide a ROI to that program but also is able to lay the groundwork for future programs.

Time is not the only factor to consider. Understanding the complexity of the system is nearly as important. If the program is developing advanced technology that has a limited number of experts and is highly specialized, it could be beneficial to implement MBSE to capture knowledge before the people who have the knowledge retire. Capturing their knowledge in a model allows easier translation and ensures a common understanding when the next generation picks up the effort on the replacement.

When a program has a sustainment phase that is over ten years, the program office needs to capture is the identification of when components will go obsolete and capture it in an obsolescence model. It is important to plan for obsolescence, as poorly planned obsolescence management will influence the end users. Either the program loses the capability or the program cannibalizes parts from other systems reducing capability. Obsolescence management requires collecting data on similar parts to provide initial estimates for obsolescence. As time goes on, the model collects data on real-time performance of that part to identify whether its specific failure rates are similar to what the program estimated.

Once the program has the obsolescence planned for the entire life cycle, logistics is the area where there are systemic challenges in executing the program. A logistic model integrates the supply chain model, obsolescence model, and a maintenance model. The maintenance model, as shown in Figure 15, consists of a reliability model, maintenance CONOPS model, and a repair model. The MBSE methodology implements the reliability model as an asset diagram that provides reliability statistics, such as mean time to repair (MTTR), mean time to failure (MTTF) and mean time between maintenance (MTBM), for each piece of material in the BOM. The maintenance CONOPS model is an asset diagram that captures the maintenance requirements based on the maintenance plan. It includes where the program office can repair each item, what items the program office can repair, and what items are consumable. The maintenance CONOPS model provides the maintenance requirements to the repair model. The MBSE methodology implements the repair model as an activity diagram that captures the repair procedures based on the maintenance requirements and tracks the repair activities. The repair model provides the projected repair and replacement schedule for each component in the system to the IMS. The maintenance CONOPS model and the repair model capture the risks associated with their activities. Figure 15 identifies the high-level risks. The IMS identifies risks associated with how the repair and replacement schedule influences program efforts. The planning for the maintenance model uses the risks as feedback. Either the program office adjusts planning to mitigate the risks or the program office may choose to accept the risks.

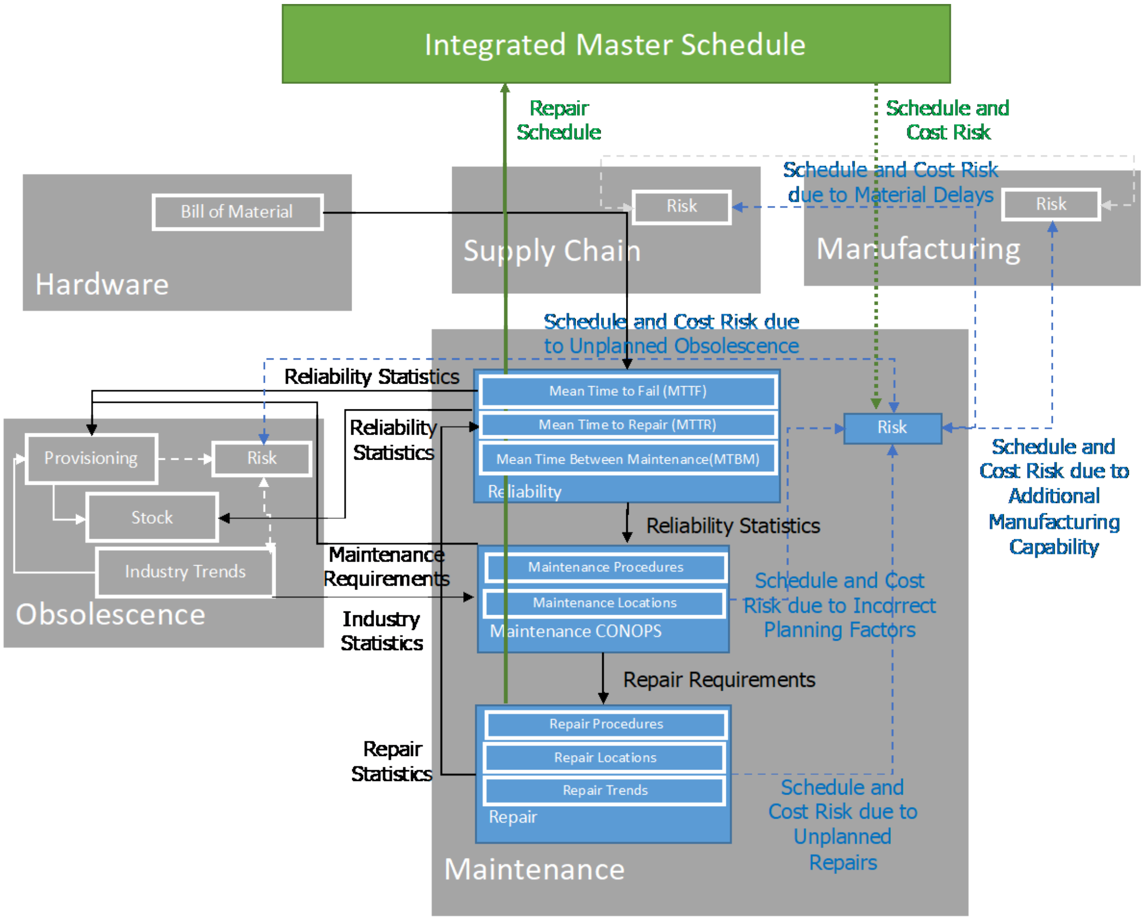


Figure 15. Maintenance Model.

To have success in implementing a logistical program, it is important to ensure that the models that the program uses for predictions are robust and consider uncertainties. To be successful in implementing MBSE, it is important to ensure that there is integration across the models that the program uses to automate the process as much as possible. When the program office uses logistics modeling today, it is usually a labor-intensive process and the program office does not used uncertainties in the data. The labor-intensive process consists of implementing a model in an Excel spreadsheet with data entered manually. What is more beneficial is to implement a model that performs data mining on failure reports from the users and automatically updates projections. Implementation of prognostics tools that provides predicted failures and identifies potential obsolescence issues based on collected data makes the prediction of when the program predicts obsolescence to occur more meaningful. This assists the program office in planning obsolescence refreshes as well as better planning of logistics.

Once the program office identifies and plans for the components, which have a risk of obsolescence, the program office needs to estimate the part failure rates and provide the data to logistics to properly stage parts. In today's paradigm, the process to track part failures and identify stock requirements is a labor-intensive process of entering data into Excel. With MBSE, the program is able to develop models that pull data from various sources, perform data mining, generate reports and calculate trends. Based on the information, the logistics group is able to identify the parts that are in high demand. The attributes of where those parts came from as well as the operating environment to understand any trends based on locations.

When obsolescence does occur, it can drive a major refresh of the system. For example, the Electrostatically Supported Gyro Navigators (ESGNs) designed in the 1980s and are on the OHIO Class submarines. The ESGNs deployed as the primary inertial navigation system (INS) in the early 1990s. They use a gyroscope that utilizes a beryllium ball for the spinning mass that requires a highly trained person with significant experience to produce. Due to beryllium being a known cancer-causing material, it is also difficult to find a place that allows its use in manufacturing. Due to the age, technology, and the cost to produce the key component, it became obsolete. The INS for the OHIO Class submarine is a unique system that has requirements beyond any other INS. A program office had to develop new INS to replace the ESGN's to sustain the OHIO Class until it retires. The ESGN Replacement program cost in a rough order of magnitude about $500 million. It is a significant development program that the program office considers sustainment. When this type of refresh occurs, although it does not have to be this major of a refresh, the use of MBSE is highly recommended with a slightly modified MBSE approach from that found in literature. The wrinkle in the implementation of MBSE for use in a refresh is that the entire system is not refreshed, only a subsystem or major component. This leads to the dilemma of whether to, and if so, how to implement a system model at the system level to perform a subsystem refresh.

Whether the program office implements a system model at the weapon system level instead of implementing a system model at the subsystem level depends on whether there are weapon system level trades that need to ensure the refresh, or future refreshes, is cost efficient. A system model at the weapon system level is generally a significant task as it reaches across several subsystems. It is difficult to justify a system model at the weapon system level when only a single subsystem is obsolete and requires a refresh. To maximize the use of a system model at the weapon system level, the program office needs to coordinate refreshes to occur around the same time on multiple subsystems. This way the program office can justify expending resources to develop system models at the weapon system level to influence design trades across subsystems and potentially reducing future cost.

When the program office decides not to implement a system model at the weapon system level, the next best option is to develop a system model and instantiate the other subsystems based on the interface requirements documents. This approach does not provide the optimal design for the system as the only trades that occur are within the subsystem. This does not provide how the systems relate to each other in reality but represents the impacts to the documented requirements. The nuance is subsystems, as designed, may be different from the requirements that the program documented or that the program did not accurately document all requirements. Modeling to documented requirements, as opposed to modeling to the design implementation, can lead to misinterpretation of the results. The program office must capture and plan for this risk through test planning. What this approach does is it provides the program office insight into how changes within the subsystem influence requirements and to some extent performance at the system level.

E. EXCEL MODEL-BASED SYSTEMS ENGINEERING ANALYSIS TOOL IMPLEMENTATION

This research developed a Microsoft Excel spreadsheet for the program office to identify whether investment into implementing MBSE to mitigate the identified risks from occurring. The spreadsheet asks several questions based on the risk identified in the literature review. The spreadsheet contains four tabs. One tab consists of the production risks identified for sub-optimal planning and production risks due to sub-optimal processes, one consists of sustainment risks due to sub-optimal planning and sub-optimal processes, one tab for the cost to implement MBSE for production, and the final for the cost to implement MBSE for sustainment.

The goal to utilizing this approach is to allow the program office the ability to tailor their MBSE approach based on their needs. By providing scores to mitigate a particular root cause gives the program office the ability to mitigate a single root cause if that is the only score that they consider high enough to provide the resources for the mitigation activities. For example, it is possible to have a high score for immature processes while having a low score for low yields. The program office is then be able to implement an MBSE approach just for immature processes and not implement all the infrastructure for requirement sensitivity analysis.

In implementing this approach for sub-optimal planning for production, as shown in Table 1, the first thing that the methodology requires is to capture the common risks. The common risks that that the literature review identifies are:

- low [production] yield rate;
- increasing time needed to procure [critical parts and material];
- late availability of needed facilities and equipment;
- difficulty in getting special tooling and test equipment to achieve the degree of accuracy required by component part specification; and
- re-designs. (Bowsher 1985)

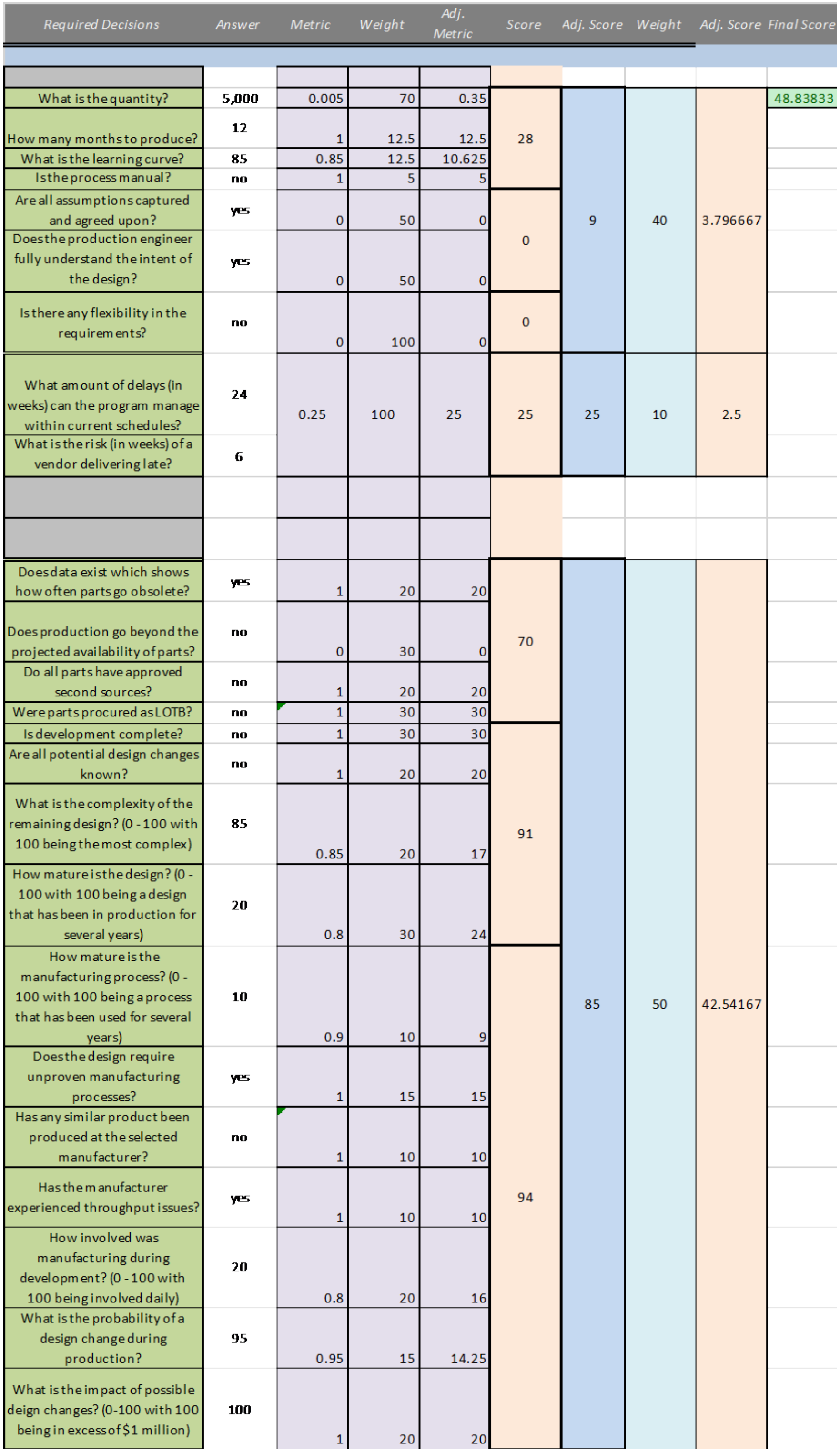
This research decomposes the risks into the root causes. Each risk has at least one root cause and some have multiple root causes. Once the Excel MBSE analysis tool identifies the root causes, the Excel MBSE analysis tool assesses the root causes on whether implementing MBSE mitigates that root cause from occurring. For example, in Table 1, the immature technology causes low production yield rate. In this case, MBSE cannot mitigate immature technology once the program is post Milestone C. The Excel MBSE analysis tool identifies the root cause in the second column and captures whether MBSE is beneficial to that root cause in the third column. For this example, the third column contains a no. The fourth column contains a rationale for why the third column is answered either yes or no. For the example given, implementing MBSE does not advance immature technology. As an example, for a case where MBSE is beneficial, immature processes are a root cause for low production yield rate. The implementation of MBSE may be beneficial. The rationale is, MBSE can model processes and simulated within the model. This provides a way to mature the processes quickly. Whether MBSE is beneficial is only part of the question that the program office needs to answer. Each root cause that the program mitigates through MBSE decomposes the root cause into several questions that the program office needs to answer to determine the level of risk the program maintains. For the immature process example, it is important to know the quantity that that program is producing as it is not beneficial to invest in MBSE to improve processes for a build of one. It is also important to understand how long the current process takes to build one. If the build is only one hour, the improvement due to MBSE is of limited benefit.

Table 1. Modeling Identification for Sub-Optimal Production Planning Decomposition.

Common Issue	Root cause	Can MBSE be Beneficial	Rationale	Required Decisions
Due to Sub-Optimal Planning				
Low Production Yield Rate	Immature technology	No	MBSE will not advance technology	
	Immature processes	Yes	Models can quickly provide the impact of many different processes to optimize the solution	What is the quantity?
				How many months to produce?
				What is the learning curve?
				Is the process manual?
	Lack of alignment between design engineer and production engineer	Yes	Models will reduce vagueness of design in drawings	Are all assumptions captured and agreed upon?
				Does the production engineer fully understand the intent of the design?
	Requirements are too tight	Yes	Models can perform sensitivity analysis and allow tradeoffs of requirements	Is there any flexibility in the requirements?
Increasing time needed to procure parts and material	Lack of alignment between purchaser and supplier	Yes	Schedules with built-in monte carlo risk assessments	What amount of delays (in weeks) can the program manage within current schedules?
				What is the risk (in weeks) of a vendor delivering late?
Late availability of needed facilities and equipment	Started late in process	No	MBSE will not accelerate schedules	
Difficulty in getting special tooling and test equipment	Started late in process	No	MBSE will not accelerate schedules	
Re-designs	Obsolescence	Yes	Schedules with built-in risk assessments	Does data exist which shows how often parts go obsolete?
				Does production go beyond the projected availability of parts?
				Do all parts have approved second sources?
				Were parts procured as LOTB?
	Concurrent Development	Yes	Models will allow tradeoffs of designs to determine the optimal solution	Is development complete?
				Are all potential design changes known?
				What is the complexity of the remaining design? (0 - 100 with 100 being the most complex)
			Models will allow quicker production turnaround for design changes	How mature is the design? (0 - 100 with 100 being a design that has been in production for several years)
	Design changes for manufacturability	Yes	Models can show bottlenecks in the production process which may be mitigated by a design change	How mature is the manufacturing process? (0 - 100 with 100 being a process that has been used for several years)
				Does the design require unproven manufacturing processes?
				Has any similar product been produced at the selected manufacturer?
				Has the manufacturer experienced throughput issues?
				How involved was manufacturing during development? (0 - 100 with 100 being involved daily)
			Models will be able to perform tradeoffs of cost, schedule, and performance of design changes to determine if a change provides a ROI	What is the probability of a design change during production?
				What is the impact of possible deign changes? (0-100 with 100 being in excess of $1 million)

Once the Excel MBSE analysis tool generates the questions for each of the root causes, this research develops a method to quantify the decisions. For this Excel MBSE analysis tool, this research created a method to provide scores based on the answers to the questions. Based on the answer to each question, the Excel MBSE analysis tool provides a metric. Some of the answers are binary answers and have a metric of either a zero or one. Other metrics created are an arbitrary ratio or a scale of zero to 100. The user weights each metric to provide flexibility to adjust based on program priorities, as shown in Table 2. The sum of the weights equal 100 for each root cause. For the previous example of the immature processes, the Excel MBSE analysis tool gives a score of 70 to the question, “What is the quantity?” as the quantity is the biggest factor in determining the benefit of MBSE. The Excel MBSE analysis tool gives a weight of 12.5 to the questions, “How many months to produce?” and “What is the learning curve?” as the answers to the questions have small benefits unless the answer was significantly large. Whether a product takes five months instead of seven months does not drive the decision to implement MBSE. The remaining weight of five is given to the question, “Is the process manual?” as it has minimal impact to reducing the risk of an immature process. Once the program office answers the questions in the Excel MBSE analysis tool, the Excel MBSE analysis tool generates a metric and then weighted and the Excel MBSE analysis tool provides an adjusted metric for each question. The Excel MBSE analysis tool sums the adjusted metrics to provide a score for each common risk. The Excel MBSE analysis tool averages the score for each root cause within the common risk to provide an adjusted score for the common risk. For example, the common risk of low production yield rate has three root causes that MBSE can be beneficial to mitigate; immature processes, lack of alignment between the design engineer and production engineer, and requirements that are too restrictive. The Excel MBSE analysis tool generates a score for each of the three root causes that the Excel MBSE analysis tool averages to provide an adjusted score for the low production yield rate risk. The Excel MBSE analysis tool weights the adjusted score based on program priorities. The weight is equal to 100 for the risk due to sub-optimal production planning. The Excel MBSE analysis tool sums the adjusted scores to provide a final score to mitigate the risk due to sub-optimal production planning.

Table 2. Modeling Identification for Sub-Optimal Production Planning Scoring.



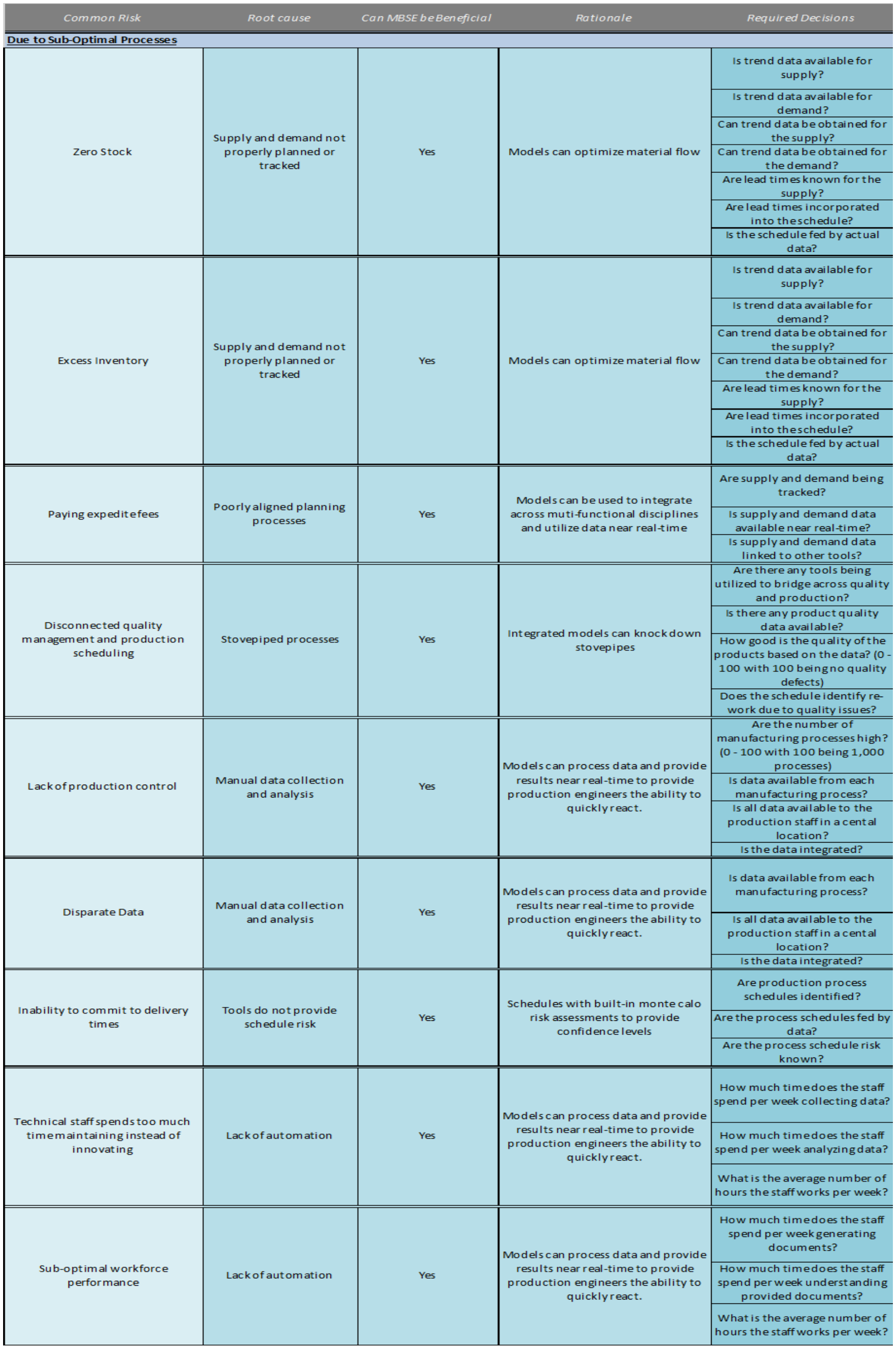
Required Decisions	Answer	Metric	Weight	Adj. Metric	Score	Adj. Score	Weight	Adj. Score	Final Score
What is the quantity?	5,000	0.005	70	0.35	28	9	40	3.796667	48.83833
How many months to produce?	12	1	12.5	12.5					
What is the learning curve?	85	0.85	12.5	10.625					
Is the process manual?	no	1	5	5					
Are all assumptions captured and agreed upon?	yes	0	50	0	0				
Does the production engineer fully understand the intent of the design?	yes	0	50	0					
Is there any flexibility in the requirements?	no	0	100	0	0				
What amount of delays (in weeks) can the program manage within current schedules?	24	0.25	100	25	25	25	10	2.5	
What is the risk (in weeks) of a vendor delivering late?	6								
Does data exist which shows how often parts go obsolete?	yes	1	20	20	70	85	50	42.54167	
Does production go beyond the projected availability of parts?	no	0	30	0					
Do all parts have approved second sources?	no	1	20	20					
Were parts procured as LOTB?	no	1	30	30					
Is development complete?	no	1	30	30	91				
Are all potential design changes known?	no	1	20	20					
What is the complexity of the remaining design? (0 - 100 with 100 being the most complex)	85	0.85	20	17					
How mature is the design? (0 - 100 with 100 being a design that has been in production for several years)	20	0.8	30	24					
How mature is the manufacturing process? (0 - 100 with 100 being a process that has been used for several years)	10	0.9	10	9	94				
Does the design require unproven manufacturing processes?	yes	1	15	15					
Has any similar product been produced at the selected manufacturer?	no	1	10	10					
Has the manufacturer experienced throughput issues?	yes	1	10	10					
How involved was manufacturing during development? (0 - 100 with 100 being involved daily)	20	0.8	20	16					
What is the probability of a design change during production?	95	0.95	15	14.25					
What is the impact of possible deign changes? (0-100 with 100 being in excess of $1 million)	100	1	20	20					

The remaining tables all follow the same logic. Table 3 identifies the following risks due to sub-optimal processes identified in the literature review:

- zero stock;
- excess inventory;
- paying expedite fees;
- disconnected quality management and production scheduling;
- lack of production control;
- disparate data;
- inability to commit to delivery times;
- technical staff spends too much time maintaining instead of innovating; and
- sub-optimal workforce performance. (Plex Systems 2018)

This research decomposes common risks into root causes. For the sub-optimal process risk, each common risk has a single root cause. Model-based systems engineering mitigates each of the root causes of sub-optimal production processes that this research identifies. This research provides a rationale as to why MBSE can mitigate each of the root causes. This research decomposes the root causes into several questions that the program office needs to answer for each of the root causes to determine if the program office should implement MBSE to mitigate the risk.

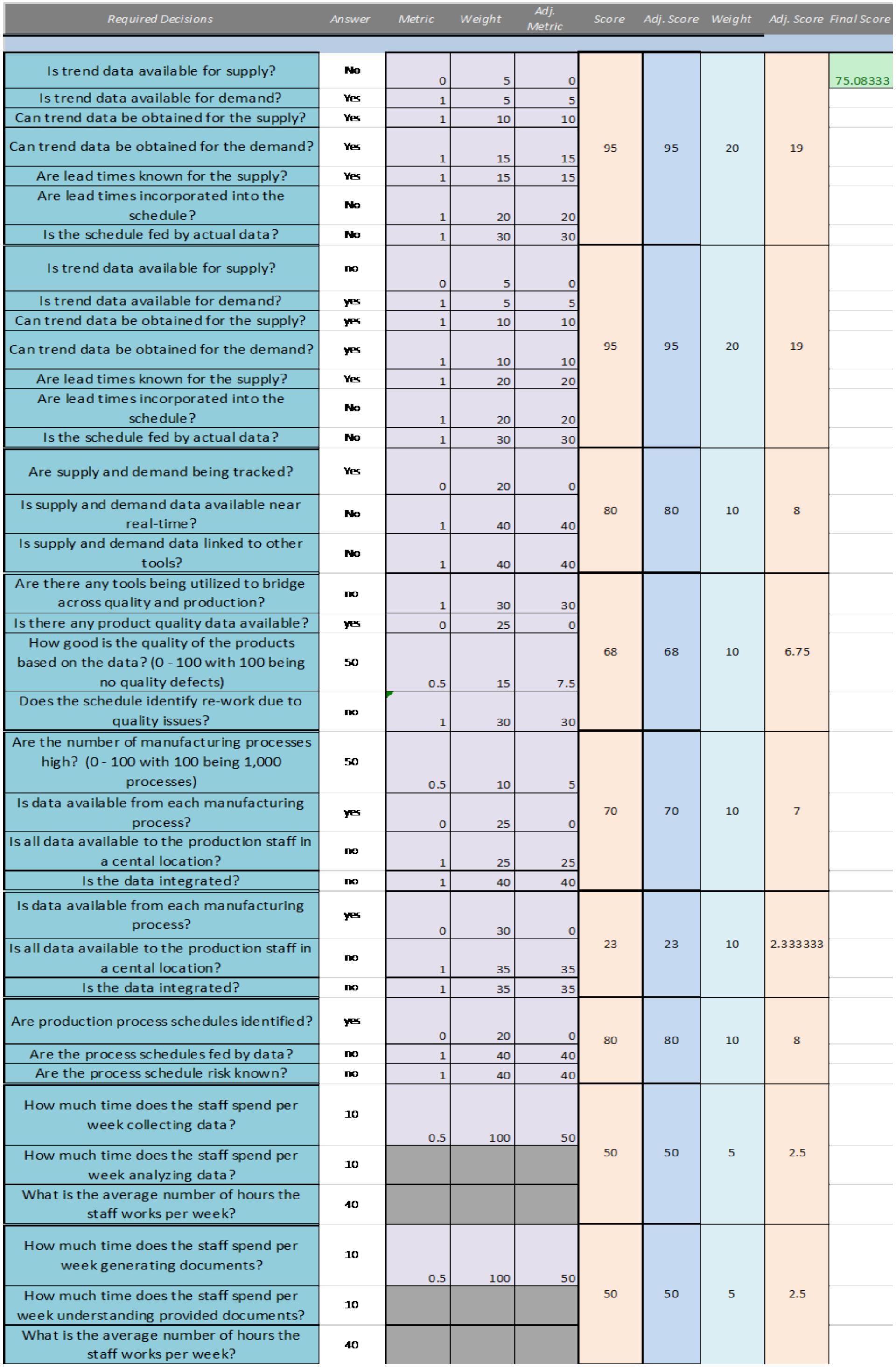
Table 3. Modeling Identification for Sub-Optimal Production Processes Decomposition.



Common Risk	Root cause	Can MBSE be Beneficial	Rationale	Required Decisions
Due to Sub-Optimal Processes				
Zero Stock	Supply and demand not properly planned or tracked	Yes	Models can optimize material flow	Is trend data available for supply? Is trend data available for demand? Can trend data be obtained for the supply? Can trend data be obtained for the demand? Are lead times known for the supply? Are lead times incorporated into the schedule? Is the schedule fed by actual data?
Excess Inventory	Supply and demand not properly planned or tracked	Yes	Models can optimize material flow	Is trend data available for supply? Is trend data available for demand? Can trend data be obtained for the supply? Can trend data be obtained for the demand? Are lead times known for the supply? Are lead times incorporated into the schedule? Is the schedule fed by actual data?
Paying expedite fees	Poorly aligned planning processes	Yes	Models can be used to integrate across muti-functional disciplines and utilize data near real-time	Are supply and demand being tracked? Is supply and demand data available near real-time? Is supply and demand data linked to other tools?
Disconnected quality management and production scheduling	Stovepiped processes	Yes	Integrated models can knock down stovepipes	Are there any tools being utilized to bridge across quality and production? Is there any product quality data available? How good is the quality of the products based on the data? (0 - 100 with 100 being no quality defects) Does the schedule identify re-work due to quality issues?
Lack of production control	Manual data collection and analysis	Yes	Models can process data and provide results near real-time to provide production engineers the ability to quickly react.	Are the number of manufacturing processes high? (0 - 100 with 100 being 1,000 processes) Is data available from each manufacturing process? Is all data available to the production staff in a cental location? Is the data integrated?
Disparate Data	Manual data collection and analysis	Yes	Models can process data and provide results near real-time to provide production engineers the ability to quickly react.	Is data available from each manufacturing process? Is all data available to the production staff in a cental location? Is the data integrated?
Inability to commit to delivery times	Tools do not provide schedule risk	Yes	Schedules with built-in monte calo risk assessments to provide confidence levels	Are production process schedules identified? Are the process schedules fed by data? Are the process schedule risk known?
Technical staff spends too much time maintaining instead of innovating	Lack of automation	Yes	Models can process data and provide results near real-time to provide production engineers the ability to quickly react.	How much time does the staff spend per week collecting data? How much time does the staff spend per week analyzing data? What is the average number of hours the staff works per week?
Sub-optimal workforce performance	Lack of automation	Yes	Models can process data and provide results near real-time to provide production engineers the ability to quickly react.	How much time does the staff spend per week generating documents? How much time does the staff spend per week understanding provided documents? What is the average number of hours the staff works per week?

As with the risk of sub-optimal production planning, this research only partially answers the question on whether to implement MBSE to mitigate the risks. The next step is to provide data that the program office can utilize to make a decision, as shown in Table 4. The Excel MBSE analysis tool is setup to be the same methodology as the risk of sub-optimal production planning. The Excel MBSE analysis tool generates a metric from the questions and the Excel MBSE analysis tool weights the metric to provide an adjusted metric. The Excel MBSE analysis tool then sums the adjusted metrics to provide a score. The Excel MBSE analysis tool does not average the score in this case as each common risk has only one root cause. The Excel MBSE analysis tool then weights the score for the risk of sub-optimal processes and summed to provide a final score.

Table 4. Modeling Identification for Sub-Optimal Production Processes Scoring.



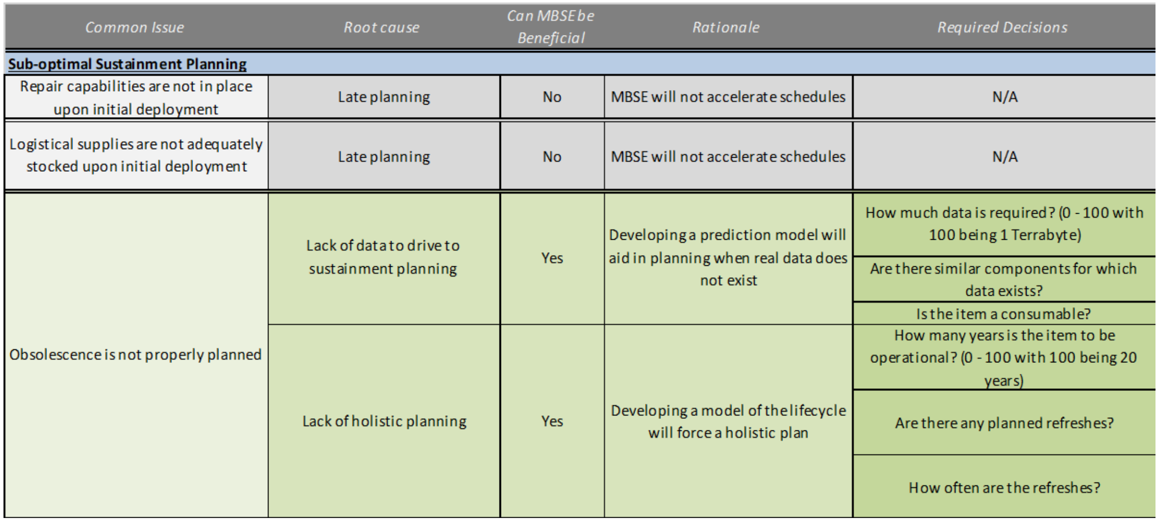
Required Decisions	Answer	Metric	Weight	Adj. Metric	Score	Adj. Score	Weight	Adj. Score	Final Score
Is trend data available for supply?	No	0	5	0	95	95	20	19	75.08333
Is trend data available for demand?	Yes	1	5	5					
Can trend data be obtained for the supply?	Yes	1	10	10					
Can trend data be obtained for the demand?	Yes	1	15	15					
Are lead times known for the supply?	Yes	1	15	15					
Are lead times incorporated into the schedule?	No	1	20	20					
Is the schedule fed by actual data?	No	1	30	30					
Is trend data available for supply?	no	0	5	0	95	95	20	19	
Is trend data available for demand?	yes	1	5	5					
Can trend data be obtained for the supply?	yes	1	10	10					
Can trend data be obtained for the demand?	yes	1	10	10					
Are lead times known for the supply?	Yes	1	20	20					
Are lead times incorporated into the schedule?	No	1	20	20					
Is the schedule fed by actual data?	No	1	30	30					
Are supply and demand being tracked?	Yes	0	20	0	80	80	10	8	
Is supply and demand data available near real-time?	No	1	40	40					
Is supply and demand data linked to other tools?	No	1	40	40					
Are there any tools being utilized to bridge across quality and production?	no	1	30	30	68	68	10	6.75	
Is there any product quality data available?	yes	0	25	0					
How good is the quality of the products based on the data? (0 - 100 with 100 being no quality defects)	50	0.5	15	7.5					
Does the schedule identify re-work due to quality issues?	no	1	30	30					
Are the number of manufacturing processes high? (0 - 100 with 100 being 1,000 processes)	50	0.5	10	5	70	70	10	7	
Is data available from each manufacturing process?	yes	0	25	0					
Is all data available to the production staff in a cental location?	no	1	25	25					
Is the data integrated?	no	1	40	40					
Is data available from each manufacturing process?	yes	0	30	0	23	23	10	2.333333	
Is all data available to the production staff in a cental location?	no	1	35	35					
Is the data integrated?	no	1	35	35					
Are production process schedules identified?	yes	0	20	0	80	80	10	8	
Are the process schedules fed by data?	no	1	40	40					
Are the process schedule risk known?	no	1	40	40					
How much time does the staff spend per week collecting data?	10	0.5	100	50	50	50	5	2.5	
How much time does the staff spend per week analyzing data?	10								
What is the average number of hours the staff works per week?	40								
How much time does the staff spend per week generating documents?	10	0.5	100	50	50	50	5	2.5	
How much time does the staff spend per week understanding provided documents?	10								
What is the average number of hours the staff works per week?	40								

The risks associated with sustainment are much simpler than the production risks. Based on the literature review, there are three common risks associated with sub-optimal sustainment planning as shown in Table 5:

- repair capabilities are not in place upon initial deployment,
- the program office did not adequately stock logistical supplies upon initial deployment, and
- the program office did not properly plan obsolescence.

This research identifies that the only risk that MBSE can mitigate is the risk due to obsolescence planning. Implementing MBSE does not mitigate the impacts of late planning. The common risk of the program office not properly planning obsolescence has two identified root causes. One of the causes is due to a lack of data and the other root cause is due to the program office focuses planning towards development and production. The Excel MBSE analysis tool decomposes the root causes into several questions that the program office needs to answer for each of the root causes to determine if the Excel MBSE analysis tool recommends the implementation of MBSE to mitigate the risk.

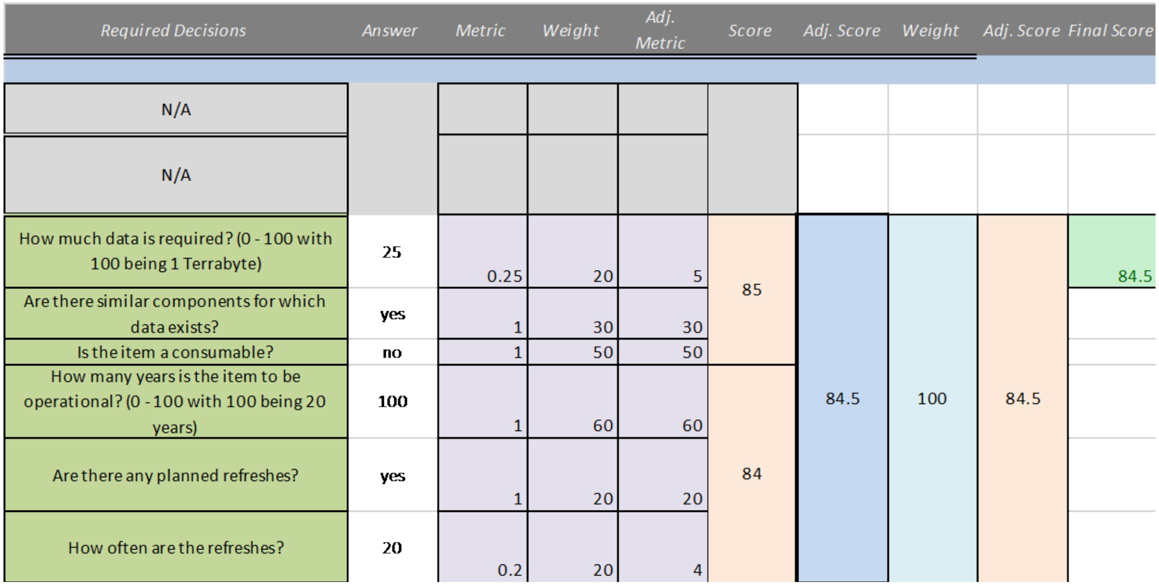
Table 5. Modeling Identification for Sub-Optimal Sustainment Planning Decomposition.



Common Issue	*Root cause*	*Can MBSE be Beneficial*	*Rationale*	*Required Decisions*
Sub-optimal Sustainment Planning				
Repair capabilities are not in place upon initial deployment	Late planning	No	MBSE will not accelerate schedules	N/A
Logistical supplies are not adequately stocked upon initial deployment	Late planning	No	MBSE will not accelerate schedules	N/A
Obsolescence is not properly planned	Lack of data to drive to sustainment planning	Yes	Developing a prediction model will aid in planning when real data does not exist	How much data is required? (0 - 100 with 100 being 1 Terrabyte)
				Are there similar components for which data exists?
				Is the item a consumable?
	Lack of holistic planning	Yes	Developing a model of the lifecycle will force a holistic plan	How many years is the item to be operational? (0 - 100 with 100 being 20 years)
				Are there any planned refreshes?
				How often are the refreshes?

Once the Excel MBSE analysis tool decomposes the root causes into questions, the next step is to provide a metric that the program office can use to make decisions. The methodology is the same as the previous tables. The Excel MBSE analysis tool generates a metric based on the answers that the program office provided. The Excel MBSE analysis tool weights the metric and generates an adjusted metric. The Excel MBSE analysis tool sums the adjusted metric by each root cause to provide a score. The Excel MBSE analysis tool averages the score to provide an adjusted score. As there is only a single common risk, the adjusted score is the final score as shown in Table 6.

Table 6. Modeling Identification for Sub-Optimal Sustainment Planning Scoring.



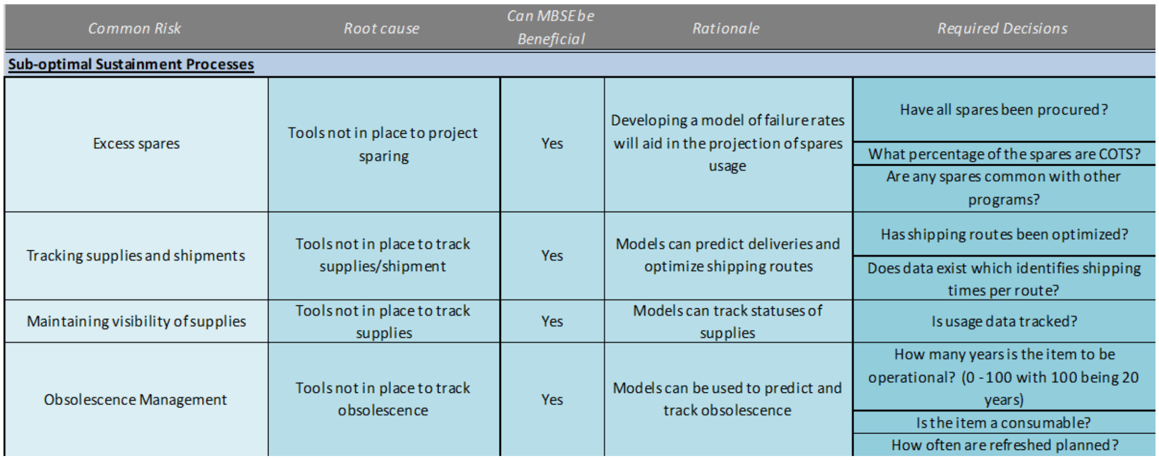
Required Decisions	Answer	Metric	Weight	Adj. Metric	Score	Adj. Score	Weight	Adj. Score	Final Score
N/A									
N/A									
How much data is required? (0 - 100 with 100 being 1 Terrabyte)	25	0.25	20	5	85	84.5	100	84.5	84.5
Are there similar components for which data exists?	yes	1	30	30					
Is the item a consumable?	no	1	50	50					
How many years is the item to be operational? (0 - 100 with 100 being 20 years)	100	1	60	60	84				
Are there any planned refreshes?	yes	1	20	20					
How often are the refreshes?	20	0.2	20	4					

The final decomposition is the decomposition of the sub-optimal sustainment processes as shown in Table 7. Based on the literature review, the sub-optimal sustainment processes risk identified four common risks:

- excess spares (Mihm 2017),
- tracking supplies and shipments (Mihm 2017),
- maintaining visibility of supplies (Mihm 2017), and
- obsolescence management (Singh and Sandborn 2006).

All the identified risks for sub-optimal sustainment processes identified a single root cause. Implementing MBSE can mitigate each root cause. The Excel MBSE analysis tool decomposes the root causes into at least a single question that the program office answers to determine the ability of MBSE to mitigate the risk.

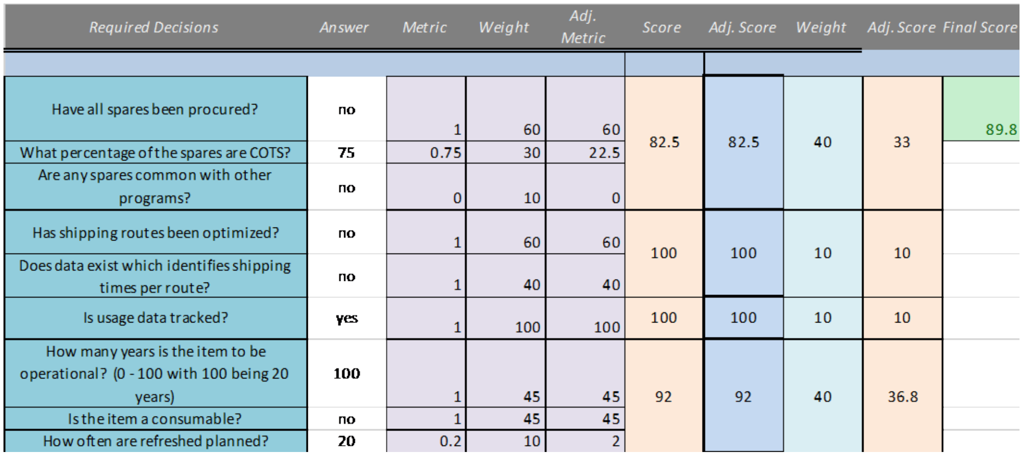
Table 7. Modeling Identification for Sub-Optimal Sustainment Processes Decomposition.



Common Risk	*Root cause*	*Can MBSE be Beneficial*	*Rationale*	*Required Decisions*
Sub-optimal Sustainment Processes				
Excess spares	Tools not in place to project sparing	Yes	Developing a model of failure rates will aid in the projection of spares usage	Have all spares been procured?
				What percentage of the spares are COTS?
				Are any spares common with other programs?
Tracking supplies and shipments	Tools not in place to track supplies/shipment	Yes	Models can predict deliveries and optimize shipping routes	Has shipping routes been optimized?
				Does data exist which identifies shipping times per route?
Maintaining visibility of supplies	Tools not in place to track supplies	Yes	Models can track statuses of supplies	Is usage data tracked?
Obsolescence Management	Tools not in place to track obsolescence	Yes	Models can be used to predict and track obsolescence	How many years is the item to be operational? (0 -100 with 100 being 20 years)
				Is the item a consumable?
				How often are refreshed planned?

Once the Excel MBSE analysis tool decomposes the root causes into questions, the next step is to identify whether the Excel MBSE analysis tool recommends implementing MBSE based on the risk. The Excel MBSE analysis tool generates a metric based on the answers provided as shown in Table 8. The Excel MBSE analysis tool weights the metric and generates an adjusted metric. The Excel MBSE analysis tool sums the adjusted metrics based on the common risk to provide a score. The Excel MBSE analysis tool weights the score to provide an adjusted score based on the program priorities. The user weights the adjusted scores and the Excel MBSE analysis tool sums the adjusted score to provide a final score.

Table 8. Modeling Identification for Sub-Optimal Sustainment Processes Scoring.



Required Decisions	*Answer*	*Metric*	*Weight*	*Adj. Metric*	*Score*	*Adj. Score*	*Weight*	*Adj. Score*	*Final Score*
Have all spares been procured?	no	1	60	60	82.5	82.5	40	33	89.8
What percentage of the spares are COTS?	75	0.75	30	22.5					
Are any spares common with other programs?	no	0	10	0					
Has shipping routes been optimized?	no	1	60	60	100	100	10	10	
Does data exist which identifies shipping times per route?	no	1	40	40					
Is usage data tracked?	yes	1	100	100	100	100	10	10	
How many years is the item to be operational? (0 - 100 with 100 being 20 years)	100	1	45	45	92	92	40	36.8	
Is the item a consumable?	no	1	45	45					
How often are refreshed planned?	20	0.2	10	2					

Tables 1 through 8 only identify whether implementing an MBSE approach can mitigate the risk. It does not identify whether the program should implement an MBSE approach. To identify whether a program should implement an MBSE approach, the program office needs to perform a ROI analysis. A simple cost model is developed for this thesis. It includes rough estimates of how much each model type can cost. The Excel MBSE analysis tool sums the cost for sub-optimal production planning, sub-optimal production processes, sub-optimal sustainment planning, and sub-optimal sustainment processes. The Excel MBSE analysis tool sums the costs for sub-optimal production planning and sub-optimal production processes to determine the total cost for implementing MBSE for production. Similarly, the Excel MBSE analysis tool sums the cost for the sub-optimal sustainment planning and the sub-optimal sustainment processes to determine total cost to implement MBSE for sustainment.

To determine the ROI, the program office must determine the cost of their associated risks on their program associated with production and sustainment. The cost model has an input for the production and sustainment risk. The Excel MBSE analysis tool compares the cost of implementing MBSE to the cost risk. If the cost of implementing MBSE is less than the cost risk on the program, then the Excel MBSE analysis tool recommends implementing MBSE. If the cost is more, then the Excel MBSE analysis tool does not recommend implementing MBSE. Where this approach falls short is utilizing the overall cost of the program to provide input. A program that has a $100,000 budget, a $10 million risk, and a cost to implement MBSE of $9 million should not implement MBSE even though this tool does provide that recommendation. Table 9 shows the cost to implement MBSE for production while Table 10 shows the cost to implement MBSE for sustainment.

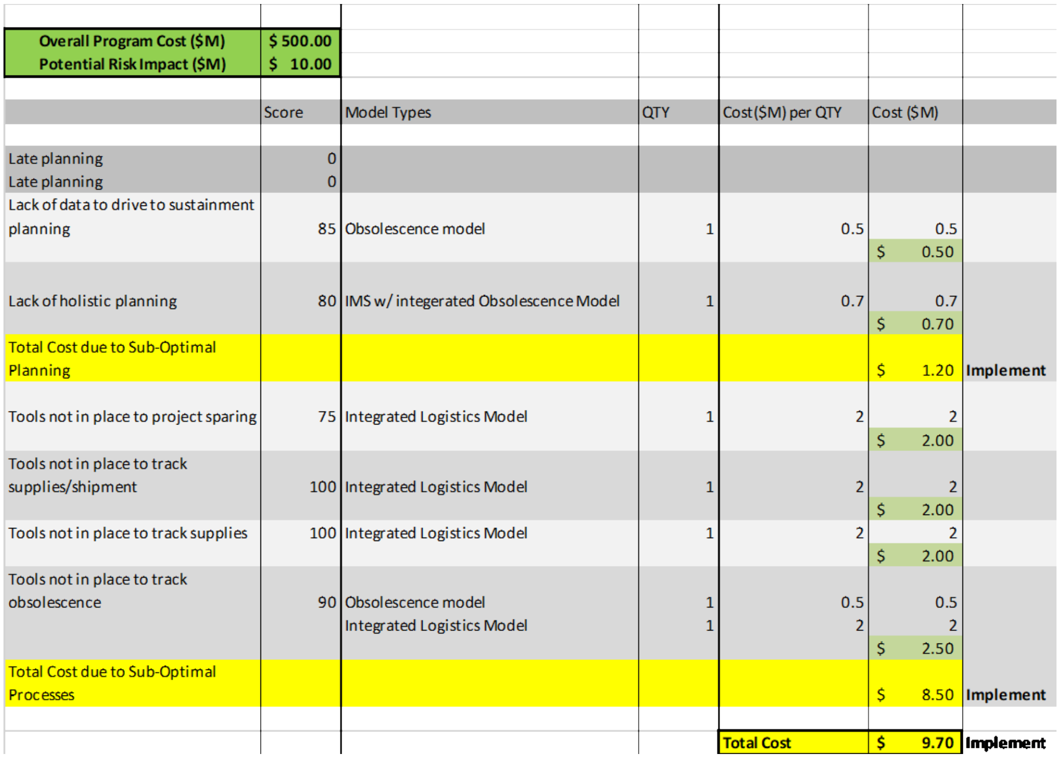
As shown in Table 9, the top left of the table captures the total program cost and the potential production risk impact. These determine the ROI for implementing MBSE. If the total cost to implement MBSE is less than the potential cost impact due to the risk, then the Excel MBSE analysis tool recommends implementing MBSE. There is a recommendation for the sub-optimal production planning, sub-optimal production processes, and one for the total production risk. It is possible that the Excel MBSE analysis tool will recommend either the sub-optimal planning or sub-optimal processes, and not both. This allows the program office to tailor the implementation of MBSE to meet the needs of their program. The Excel MBSE analysis tool includes a column for model types that are to mitigate the risk that are a result of the root cause. The program office needs to add the number of drawings and processes. The program office also provides an estimate cost per drawing and process. The tool provides an example cost based on data from a single program.

The Excel MBSE analysis tool used the same methodology for the sustainment cost model. The Excel MBSE analysis tool captures total program cost and potential sustainment risk in the top left. The third column captures the model type and the fourth column captures the estimated cost per model. The estimated cost is an example based on a single program. The sustainment cost model provides three recommendations based on the cost to implement the models and the sustainment risk cost. The recommendation is either to implement or not to implement MBSE to mitigate the risks to sub-optimal sustainment planning, sub-optimal sustainment processes, and total sustainment risk.

Table 9. Cost to Implement MBSE for Production.

Overall Program Cost ($M)	**$ 500.00**					
Potential Risk Impact ($M)	**$ 10.00**					
	Score	Model Types	QTY	Cost($M) per QTY	Cost ($M)	
Immature technology	0.00					
			(# of processes)			
Immature processes	63.13	Manufacturing model	10	0.02	0.2	
					$ 0.20	
			(# of drawings)			
Lack of alignment between design engineer and production engineer	100.00	Design Drawings	105	0.02	2.1	
		Electronic Work Instructions	20	0.05	1	
					$ 3.10	
			(# of models)			
Requirements are too tight	100.00	Performance Model	4	0.5	2	
		Structural Model	8	0.1	0.8	
					$ 2.80	
			(# of schedules)			
Lack of alignment between purchaser and supplier	5.77	IMS w/ integrated schedule risks	1	0.25	0.25	
					$ 0.25	
Started late in process	0.00					
Started late in process	0.00					
			(# of models)			
Obsolescence	70.00	IMS w/ integrated Cost Model	1	0.25	0.25	
		Trend Models	20	0.01	0.2	
					$ 0.45	
			(# of models)			
Concurrent Development	91.00	Performance Model	4	0.5	2	
		Structural Model	8	0.1	0.8	
					$ 2.80	
			(# of models)			
Design changes for manufacturability	74.25	Process model	10	0	0	
		System Model	1	2	2	
		Animations	5	0.05	0.25	
		Trend models	20	0.01	0.2	
					$ 1.12	
Total for Production Sub-Optimal Processes					$ 10.72	**Do Not Implement**
Supply and demand not properly planned or tracked	95	Supply Chain Model	1	0.5	0.5	
					$ 0.50	
Supply and demand not properly planned or tracked	95	Supply Chain Model	1	0.5	0.5	
					$ 0.50	
Poorly aligned planning processes	80	Supply Chain Model	1	0.5	0.5	
					$ 0.50	
Stovepiped processes	67.5	Detailed IMS	1	0.3	0.3	
					$ 0.30	
Manual data collection and analysis	95	Custom/COTS Software	1	1	1	
					$ 1.00	
Manual data collection and analysis	66.66667	Custom/COTS Software	1	1	1	
					$ 1.00	
Tools do not provide schedule risk	80	IMS w/ integrated schedule risk	1	0.3	0.3	
					$ 0.30	
Lack of automation	50	Custom/COTS Software	1	1	1	
					$ 1.00	
Lack of automation	50	Custom/COTS Software	1	1	1	
					$ 1.00	
Total Cost for Production Sub-Optimal Processes					$ 6.10	**Implement**
				Total	$ 16.82	**Do Not Implement**

Table 10. Cost to Implement MBSE for Sustainment.



Overall Program Cost ($M)	**$ 500.00**					
Potential Risk Impact ($M)	**$ 10.00**					
	Score	Model Types	QTY	Cost($M) per QTY	Cost ($M)	
Late planning	0					
Late planning	0					
Lack of data to drive to sustainment planning	85	Obsolescence model	1	0.5	0.5	
					$ 0.50	
Lack of holistic planning	80	IMS w/ integerated Obsolescence Model	1	0.7	0.7	
					$ 0.70	
Total Cost due to Sub-Optimal Planning					$ 1.20	**Implement**
Tools not in place to project sparing	75	Integrated Logistics Model	1	2	2	
					$ 2.00	
Tools not in place to track supplies/shipment	100	Integrated Logistics Model	1	2	2	
					$ 2.00	
Tools not in place to track supplies	100	Integrated Logistics Model	1	2	2	
					$ 2.00	
Tools not in place to track obsolescence	90	Obsolescence model	1	0.5	0.5	
		Integrated Logistics Model	1	2	2	
					$ 2.50	
Total Cost due to Sub-Optimal Processes					$ 8.50	**Implement**
				Total Cost	**$ 9.70**	**Implement**

F. SUMMARY

The research conducted as part of this thesis generated a MBSE methodology and Excel MBSE analysis tool for use during the production and sustainment phases. If metrics are in place early in the planning process, the program office can better manage and assess program risks. Model-based systems engineering can be a very powerful tool to assist the program office in making critical decisions quickly based on data. When the program develops an integrated IMS to influence decisions, a schedule built from the bottom up to ensure the program office identifies all tasks with risks associated with the schedule. Employing Monte Carlo simulations within the schedule identifies the confidence in that schedule. Integrating a supply chain model identifies system level impacts of late receipt of material from vendors. In all, integrating the models into an IMS provides the program office the ability to optimize their resources by providing them the entire cost, schedule, and risk assessment of the program.

IV. CASE STUDY

The previous chapter discussed the methodology for implementing MBSE into production and sustainment and provided a cost model to determine the ROI for implementing MBSE. This chapter looks at a case study of a navigation subsystem, called Program A, and a guidance subsystem, called Program B, to apply the methodology to these programs. Program A and Program B are both subsystems of a missile system and both programs are post Milestone C. As these programs are actual programs that are in the sustainment phase, and the program office has not released all information outside of the program office, this thesis is withholding the real names of these programs.

A. INTRODUCTION

Program A and Program B are both major subsystems within a missile system. Program A provides the initial conditions for Program B. Program B provides the guidance of the missile. The first contract award to build the replacement inertial navigation system (INS) for Program A occurred in 2001 with an initial deployment date planned for 2012 (Beaufait 2017). The Beaufait whitepaper stated that Program A is developing a new fiber optic gyroscopes (FOG) based INS to replace the aging INS and it included that by 2008, the program office terminated the contract to develop the replacement INS for Program A for convenience. The Beaufait whitepaper also included that in 2009, the program office conducted a competition to select a prime contractor to develop the replacement INS and that the program office awarded the contract in 2010 with an initial value of approximately $200 million over five years to deliver engineering development modules (EDM). Beaufait further stated that the program office awarded follow-on contracts yearly between 2015 through 2019 to complete the design and begin production and the program is currently completing the TDP and has begun production with an expected deployment date in 2020. Program B awarded the first contract in 2003 to develop a FOG based guidance system. This program was able to perform test flights successfully in 2013 to begin deployment.

B. NAVIGATION PROGRAM

The program office designed the current deployed navigation subsystem in the 1980s and deployed in the 1990s (Beaufait 2017). The Beaufait whitepaper indicated that the program employed the traditional approach to sustainment where the program office made decisions based on stock levels and maintenance trends. The Beaufait report suggested that when stock was low, the program office procured more parts and when maintenance began being too costly, the program office refreshed the system. Based on the assessment of the unpublished whitepaper written by James Beaufait, “A Funny Thing Happened along the Way,” Program A did not have insight into data to make informed decisions related to sustainment. This forced the program office to provide significant resources quickly to solve obsolescence issues when vendors no longer support repair or replacement parts. The program office did not have the resources in place to react quickly as the sustainment of the navigation subsystem manually tracks spares, failures, and when obsolescence refreshes will occur. The data is often not readily available and when the data is available, it is generally not in one place and does not provide all the data necessary to make decisions.

1. Assessment of Sustainment

This research assessed the state of the program during its sustainment phase post Milestone C leading up to 2001 based on my experience working the program and historical documents related to the program. The assessment concluded the following:

- While the program was tracking spare quantities, the program was unable to determine how long the current stock of parts could support the system.
- While the program kept track of the number of failures, the program was unable to track failure trends of the deployed system.
- While the program had repair capability established, the program was unable to predict manufacturer trends to determine how long those repair capabilities would last.
- While the program was able to successfully maintain capability within the fleet, the program office made decisions based on engineering estimates, which were based on experience, and those decisions were sometimes less than optimal due to the input not being data driven.

- While the program had significant engineering experience, the deployed system was the first major experience the program office had with COTS, and the experience was not completely applicable.
- While there were budget plans in place for several years, the long-term plans were related to maintaining the current system and did not contain a long-range vision for modernization.

Based on those findings, the case study utilized the Excel MBSE analysis tool developed as part of this research. Within the Excel MBSE analysis tool, there are three common risks associated with sub-optimal planning. The first two of those risks are not applicable as repair capabilities and logistical supplies were in place. The third common risk is applicable as the obsolescence planning was a reactive approach. The approach to obsolescence was to deal with the issues once they began to impact budgets or schedules. A lack of data that could drive sustainment planning, such as failure and stock trends, and a lack of holistic planning drive the root causes of these issues.

To determine the applicability of MBSE to solve the issue, the user must answer the questions in the Excel MBASE analysis tool. The first question involves the amount of data that the program office requires. The more data that the program office requires, the more applicable MBSE becomes as it becomes harder for a person to manage due to the complexity. The amount of data required for Program A is minimal. The amount of data required is in the megabyte range. The score provided is based on a ratio between a megabyte and a terabyte. A terabyte is equal to 100 based on the criteria in the Excel MBSE analysis tool. This research assumes that the ratio is logarithmic relationship where the benefit of MBSE increases rapidly as the data size moves from a kilobyte to a megabyte. As the data reaches around a terabyte, the benefit levels off. The curve shown in Figure 16 developed as part of this research, is the curve utilized to determine the score. The case study provided a weight of 35 as that is approximately where a megabyte worth of data begins. The next question that the user needs to answer is, “Are there similar components for which data exists?” For Program A, the parts outside of the gyroscope used standard parts. Either the program office machined the parts or they were COTS parts, such as a slip ring. The gyroscopes were custom built, but significant data existed on the gyroscope as the Navy used the gyroscopes for a couple of decades. Based on that analysis, the answer to the question is that data does exist. The next question that the user needs to answer is, “Is the item consumable?” For the INS in Program A, there is a mixture of consumable items and repairable items. Whether a component is a consumable or repairable item is determined at a DoD stock item level. While the DoD can consider a part at the DoD stock level to be repairable, the parts that get repaired are often a consumable at the vendor level. For example, an iPhone with a cracked screen is repairable. When a vendor repairs an iPhone, it consumes the broken screen. For this assessment, the concern is primarily at the DoD stock level. For Program A, the critical parts are repairable for the INS.

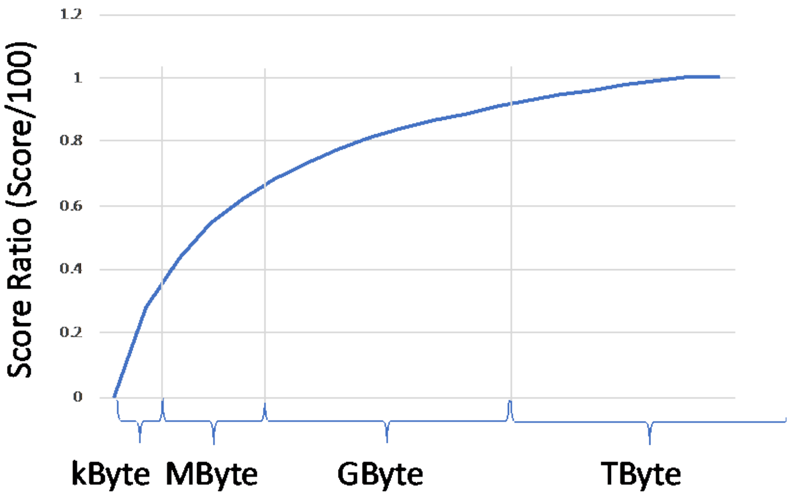
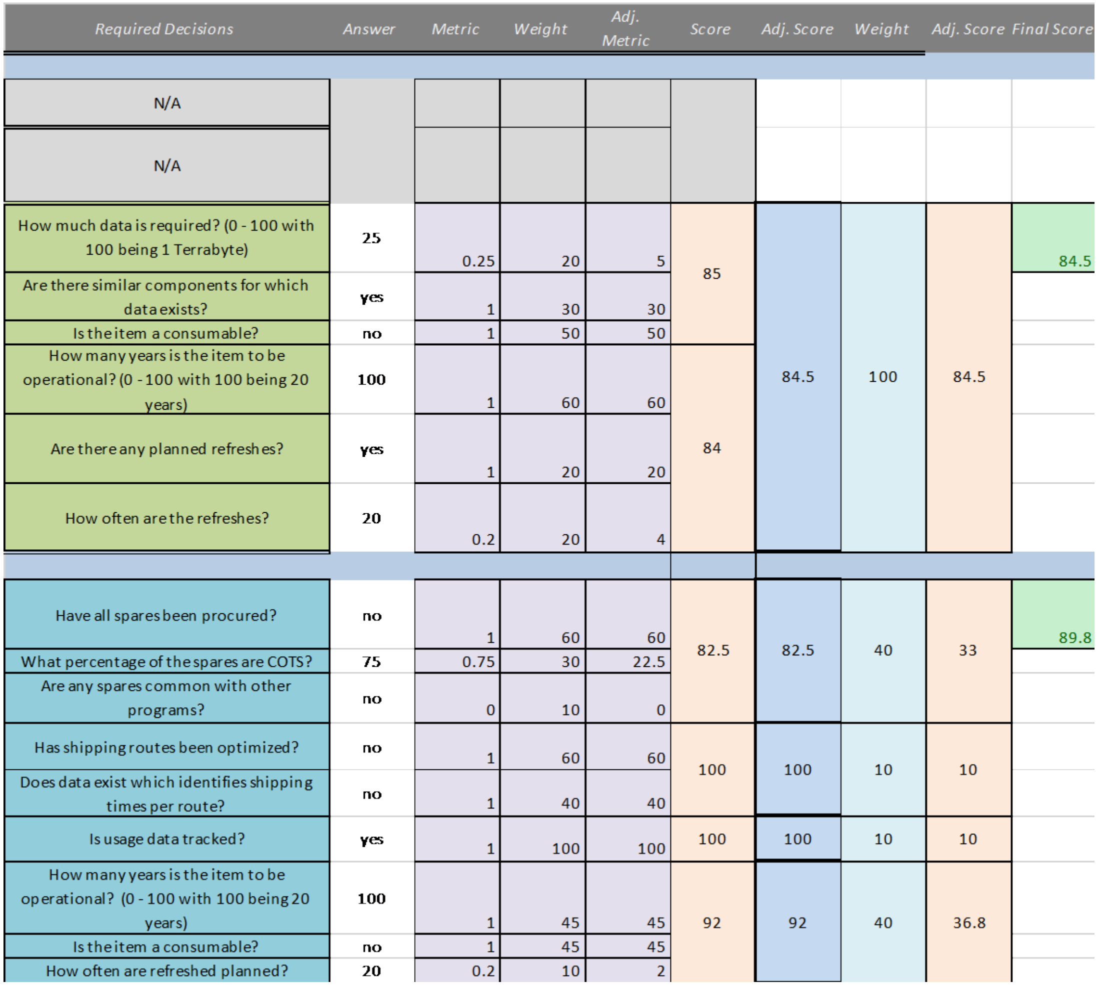


Figure 16. Data Size Curve.

The Excel MBSE analysis tool populated the metrics based on the answers, as shown in Table 11, when the user provides answers to the questions. The next step in the process is to distribute the weights for the metrics. For this assessment, whether the program office can repair the items drives the benefit of implementing MBSE for the root cause of a lack of data to drive sustainment planning. This is because if an item is repairable, understanding the time it takes to repair an item, shipping and receiving times, part re-certification, and re-stock can be difficult to manage within current toolset, such as Microsoft Excel. As this is the primary driver, the case study provides a weight of 50. The next most important metric is the amount of data that is available. If data does not exist, then the benefit of MBSE is minimal. The benefit of implementing MBSE comes from utilizing data in a way that makes issues visible. This is nearly equal in importance to how much data the program office requires. It does not make sense to implement MBSE on a program that only needs three lines in Excel. The benefit of MBSE comes in when managing the complexity of the data. That is why the case study applies a weight of 30 to whether data exists and the case study applies a weight of 20 to the amount of data that the program office requires. Based on the answers, the Excel MBSE analysis tool provides a calculated score of 87 for the lack of data to drive sustainment planning, as shown in Table 11. This means that from a technical standpoint, it is highly likely that MBSE would have provided benefit to Program A during sustainment.

Table 11. Program A Sustainment Assessment.



Required Decisions	*Answer*	*Metric*	*Weight*	*Adj. Metric*	*Score*	*Adj. Score*	*Weight*	*Adj. Score*	*Final Score*
N/A									
N/A									
How much data is required? (0 - 100 with 100 being 1 Terrabyte)	25	0.25	20	5	85	84.5	100	84.5	84.5
Are there similar components for which data exists?	yes	1	30	30					
Is the item a consumable?	no	1	50	50					
How many years is the item to be operational? (0 - 100 with 100 being 20 years)	100	1	60	60	84				
Are there any planned refreshes?	yes	1	20	20					
How often are the refreshes?	20	0.2	20	4					
Have all spares been procured?	no	1	60	60	82.5	82.5	40	33	89.8
What percentage of the spares are COTS?	75	0.75	30	22.5					
Are any spares common with other programs?	no	0	10	0					
Has shipping routes been optimized?	no	1	60	60	100	100	10	10	
Does data exist which identifies shipping times per route?	no	1	40	40					
Is usage data tracked?	yes	1	100	100	100	100	10	10	
How many years is the item to be operational? (0 - 100 with 100 being 20 years)	100	1	45	45	92	92	40	36.8	
Is the item a consumable?	no	1	45	45					
How often are refreshed planned?	20	0.2	10	2					

For a lack of holistic planning, there are three questions to answer. The first question to answer is, “How many years is the item to be operational?” The importance of this question is to determine the ROI. The longer the program office sustains the program, the better the ROI will be. The case study established a ratio in the Excel MBSE analysis tool where 20 years provides a score of 100 and zero years provides a score of zero. For this ratio, the case study assumes it to be a linear relationship from zero to twenty years. From twenty to forty years, that may not be an accurate assumption. For the assessment of Program A, the case study provides a score of 100 as the plan was for a sustainment of 20 years. The second question is, “Are there any planned refreshes?” The program office for Program A did have budgets planned for refreshes. The program office did not plan the scope of the refreshes. The answer to this question is yes. The third question is, “How often are the refreshes?” The answer is a ratio based on the answer for how many years is the system to be operational. For Program A, the plan was to have refreshes once every five years. Based on a 20-year operational life, the refreshes have an answer of 25.

The Excel MBSE analysis tool provides metrics based on the answers, and now the weights need to be provided. The driver to determine the benefit for a lack of holistic planning is the number of years that the program office expects the program to be operational. The longer the operational life post Milestone C, the more likely a ROI will be achieved. The longer life cycle also drives the needs for refreshes. For this reason, the case study applies a weight of 60. Whether a program has planned refreshes and the numbers of refreshes are equal weights. This is due to the two questions being complements of each other. If one happens, then the other one happens. As they are equal, they were each given half of the remaining weight. Based on the weighting, the score calculated by the tool for a lack of holistic post Milestone C is 85. The case study averages the score of 85 with the previous score of 87 for a lack of data to drive sustainment planning to provide a final score of 86 for the common risk of obsolescence not being properly planned as shown in Table 11.

There are nine questions that the user must answer for sub-optimal sustainment processes post Milestone C. The case study answers first three questions to provide the assessment of the benefit MBSE will have on excess spares. The first question that the case study answers is, “Have all spares been procured?” If the program office procures all spares for the operational life cycle, it does not make sense to implement MBSE to reduce the risk of excess spares. For Program A, the program office did not procure all spares. The second question that this case study answers is, “What percentage of the spares are commercial parts?” This question is important as the program office needs to pay closer attention to the obsolescence as they have less control over the availability of those parts if there are spares that are commercial parts. For Program A, about 75% of the parts are commercial parts based on my assessment. The third question that this case study answers is, “Are any spares common with other program?” For the critical components of Program A, no other program uses the same parts.

After answering the questions, the Excel MBSE analysis tool populates the metrics. Now the case study assigns the weights to the metric. For question, “Have all spares been procured?” the case study assigns a weight of 60. This is due to the answer being critical to the decision to implement MBSE. If the program office procured all spares, this drives the score to a low value. The question, “What percentage of the spares are commercial parts?” is allocated a weight of 30. While the answer does provide some value to the benefit of MBSE, it is not a critical driver in whether the program office implements MBSE. Whether spares are in use on other programs is not going to drive the decision to implement MBSE as the benefits are minimal. If there were common spares, it is helpful to model the entire stock of parts instead of just the spares allocated to the program office. Based on the weighted metric, the score for excess spares is 83, as shown in Table 11.

For the common risk of being able to track supplies and shipments post Milestone C, there are two questions that the case study answers. The first question that the case study answers is, “Has shipping routed been optimized?” If the program office has not optimized shipping routes shipping routes, the program office could shorten shipping times or be more consistent. Program A did not optimize the shipping routes. The second question is, “Does data exist that identifies shipping times per route?” This answer is important as it identifies how well the program office understands the shipping times. For Program A, the program office did not track shipping times.

Once the user answers the questions, the metrics populate and the weights are then populated. The case study provides the question, “Does data exist that identifies shipping times per route?” a weight of 60. For planning purposes, it is more important to understand the current shipping times. Then the program office can plan around the current times. This process can be inefficient, which is why the case study provides the question, “Has shipping routes been optimized?” a weight of 40. Model-based systems engineering can provide benefits by collecting shipping data and providing optimized solutions. Once the weights are allocated, the Excel MBSE analysis tool provides a score. For Program A, the Excel MBSE analysis tool calculated a score of 100 for tracking supplies and shipments.

There is one question for maintaining visibility of supplies. That question is, “Is usage data tracked?” The importance of this answer is to understand whether data is available for the use in an MBSE methodology post Milestone C. The availability of the data increases the ROI for the MBSE implementation. For Program A, there is data usage available. As there is only one question, the weight is 100. The metric is a binary yes, so the score is 100.

The remaining three questions are related to the common risk of obsolescence refresh post Milestone C. These questions are the same has the discussed previously for a lack of holistic planning. The INS for Program A had a planned operational life of 20 years, the critical items are repairable, and the planned refreshes occur every five years. The weighting applied to the questions is the same weights allocated to the lack of holistic planning questions. The operational life is allocated a weight of 60 while the other two are allocated a weight of 20. The score for obsolescence management is 85.

Once the Excel MBSE analysis tool calculates all the scores, the user provides additional weights to the different common risks. Being able to mitigate excess spares and obsolescence management are the two most important aspects to benefitting from MBSE during post Milestone C sustainment. For this reason, both each was allocated a weight of 40. The benefit of implementing MBSE post Milestone C decreases significantly if the program office does not integrate supply management and obsolescence management. Tracking supplies and shipments and maintaining visibility of supplies are each allocated a weight of 10. This is because they are not a major driver to implementing MBSE. Program offices manage both successfully though modern processes. When the user applies the weights to the score, the Excel MBSE analysis tool sums the results to provide a final score. The final score for implementing MBSE post Milestone C to mitigate the risk of sub-optimal sustainment processes is 87 as shown in Table 11.

Had Program A implemented the logistics model as part of an MBSE methodology as described in the previous chapter, the program would have understood the schedule and resources required to sustain the current deployed INS. Figure 17 shows how the program office implements MBSE to achieve this capability. The details of each model are found in the previous chapter. This potentially changes some of the decisions made, such as eliminating repair capabilities or not terminating the replacement INS program. The knowledge does not exist today to say conclusively that MBSE would have driven different behavior or decisions, but MBSE is able to provide a disciplined approach and the knowledge to make better-informed decision.

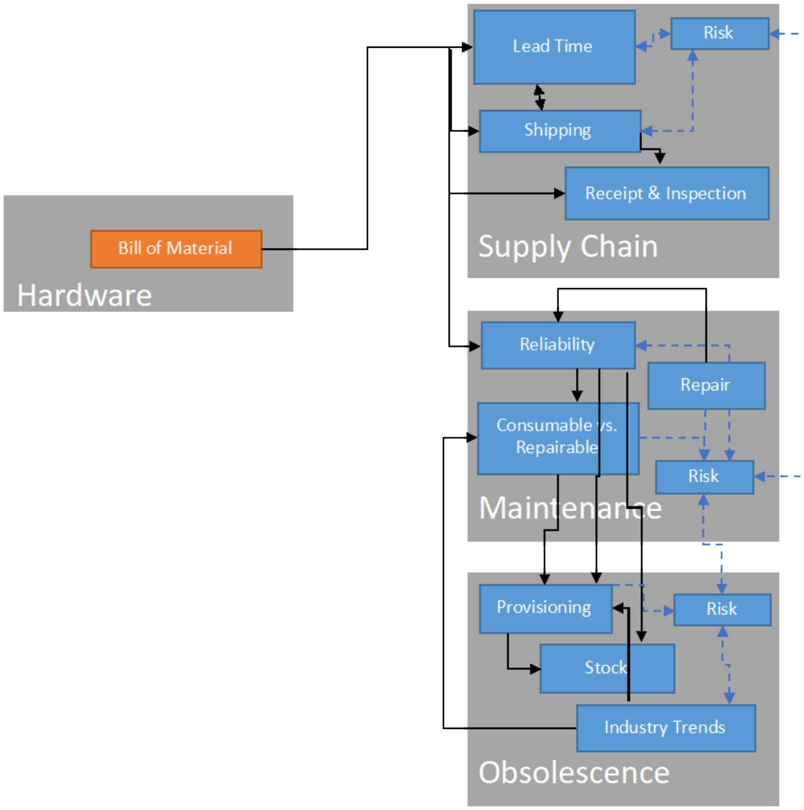
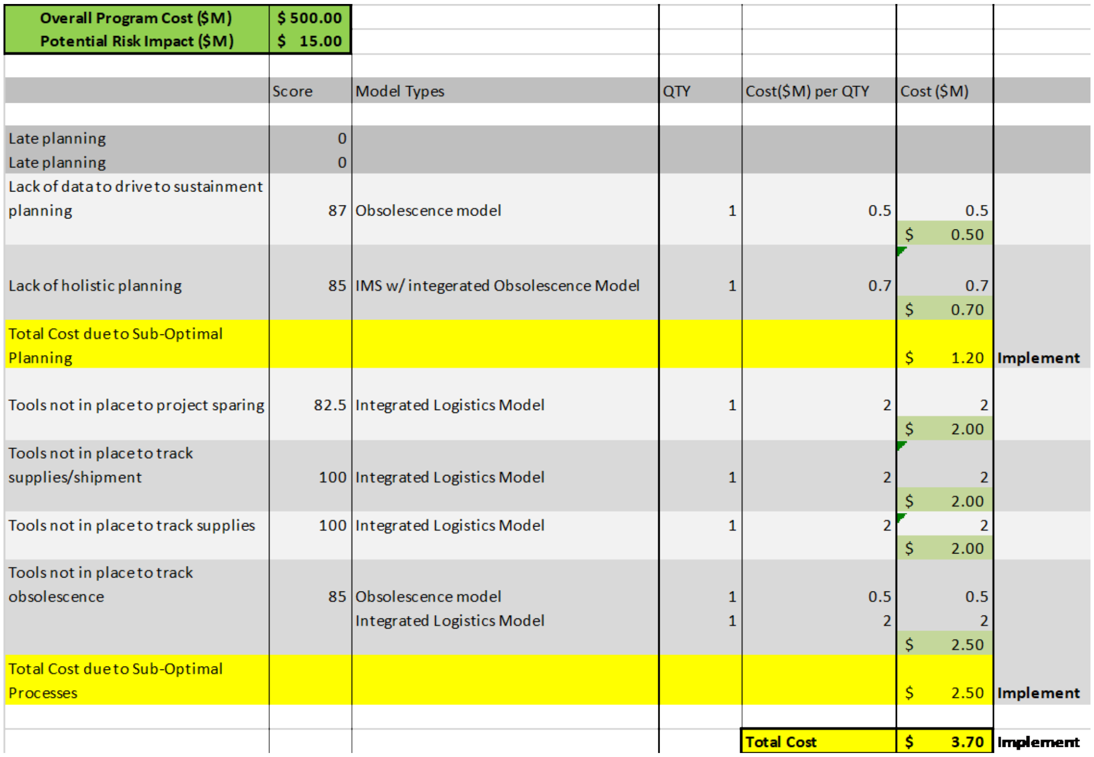


Figure 17. High-Level Logistics Model.

Based on the cost analysis performed as part of this assessment, the cost to implement MBSE for sustainment post Milestone C is approximately $3.7 million as shown in Table 12. The estimates for the models are based on my experience with contractors such as Lockheed Martin and Boeing. The Excel MBSE analysis tool does not sum the costs as there are duplicate models in the cost model as the logistics model fulfills several needs. The estimated cost of implementing an obsolescence model is $500,000, the cost model estimates the logistics model to be $2 million, and integrating the models with the IMS is about $700,000. Data does not exist to capture the optimized resourced obtained from using MBSE, so a data driven ROI cannot be performed. The implementation of MBSE is less than 1% of the overall program cost. SWFTS achieved a 13% savings to their program by implementing MBSE (Pavalkis 2014), so achieving more than a 1% cost savings is achievable.

Table 12. Cost to Implement MBSE for Sustainment post Milestone C.



Overall Program Cost ($M)	**$ 500.00**					
Potential Risk Impact ($M)	**$ 15.00**					
	Score	Model Types	QTY	Cost($M) per QTY	Cost ($M)	
Late planning	0					
Late planning	0					
Lack of data to drive to sustainment planning	87	Obsolescence model	1	0.5	0.5 $ 0.50	
Lack of holistic planning	85	IMS w/ integereated Obsolescence Model	1	0.7	0.7 $ 0.70	
Total Cost due to Sub-Optimal Planning					$ 1.20	**Implement**
Tools not in place to project sparing	82.5	Integrated Logistics Model	1	2	2 $ 2.00	
Tools not in place to track supplies/shipment	100	Integrated Logistics Model	1	2	2 $ 2.00	
Tools not in place to track supplies	100	Integrated Logistics Model	1	2	2 $ 2.00	
Tools not in place to track obsolescence	85	Obsolescence model Integrated Logistics Model	1 1	0.5 2	0.5 2 $ 2.50	
Total Cost due to Sub-Optimal Processes					$ 2.50	**Implement**
				Total Cost	**$ 3.70**	**Implement**

2. Initial Inertial Navigation System Replacement Program

The INS replacement began development in 2001 (Beaufait 2017). The case study conducts an assessment of the program as part of this research that identified numerous challenges. Those challenges were common with the findings of the literature review:

- The program office focused on meeting technical requirements
- The program faced funding instability
- The technology was immature
- The processes were immature
- There was a lack of understanding in the requirements

The requirements of the missile program drive the need for an extremely accurate navigation capability for the system (Beaufait 2017). These requirements are extremely challenging to meet even with mature technology. Immature technology, such as fiber optic gyroscopes in 2001, likely drove the team to be development focused. The Beaufait whitepaper states that the number one goal of the program was to meet performance requirements followed by meeting schedule and that the goal to meet performance drove the program to focus solely on building performance-based models, such as analytical models. The Beaufait whitepaper further indicates that program kept the same architecture as the program assumed that changing the architecture increases cost. The FOG-based INS is a different technology with different error characteristics than a spinning mass gyro-based INS. However, the INS replacement for Program A is requiring the FOG-based INS to behave in the same fashion as the spinning mass INS as there was no system level architecture trades performed (Beaufait 2017). Program A had the flexibility to re-architect the components and subsystem design if the external interfaces remained the same.

Based on the research of this thesis, it is evident that there was high risk to product yield rate issues when the program began manufacturing the replacement to the INS. Out of 30 gyroscopes contracted, the contractor delivered less than half. Of those that the contractor delivered, all of them were re-worked due to a lack of understanding in the requirements. The prime contractor had sub-contracted the gyroscope design and build. The requirements that the prime contractor placed on the gyroscope drove the sub-contractor to make design decisions that made the gyroscope non-functioning in the system.

Had the program office implemented the MBSE methodology described in the previous chapter during the development of the replacement to the INS, the program would have been able to mitigate post Milestone C risks. The system-level model architecture, as shown in Figure 18, if implemented mitigates the risks that the program realized. In this modeling architecture there is a systems model. The structural, behavioral, and interface models define the requirements within the system model. This drives Program A to understand and agree to requirements prior to beginning hardware builds that reduces the risk of building hardware that did not meet system requirements. This is a more detailed look of the functions in Figure 10 within Chapter III. Program A should have started with a functional model of the system and then developed an architectural model. The program office could have used a block definition diagram (BDD), or similar model to define the functional requirements as well as the architecture. An example of an INS BDD is provided in Figure 19. A fully implemented model, as shown in Figure 18, allows the program office to perform trade studies to determine the optimal architecture and allows design trades to meet that architecture. As the design matures, the program develops hardware and software models that digitally link to the systems model. For Program A, the gyroscopes, accelerometers, and an inertial measurement unit (IMU) decompose the INS. Program A developed gyroscope models, accelerometer models, and IMU models. These models are mostly covariance models for use in error budgeting. Some physics-based models exist. The issue with Program A is the models are disparate. The models are based on requirements that have been allocated in a document. The impacts at the system level are not apparent when making component level design trades. A fully implemented model allows the ability to perform design trade studies at the component level to understand system level impacts. Concurrently, the program develops simulation models. The simulation model allows the software that the program develops to integrate with the hardware models to ensure that performance at a subsystem and at a weapon system is being met. Hardware is used to replace the functions in the simulation models to validate the assumptions in the model. This assists in reducing the risk and time to perform integration.

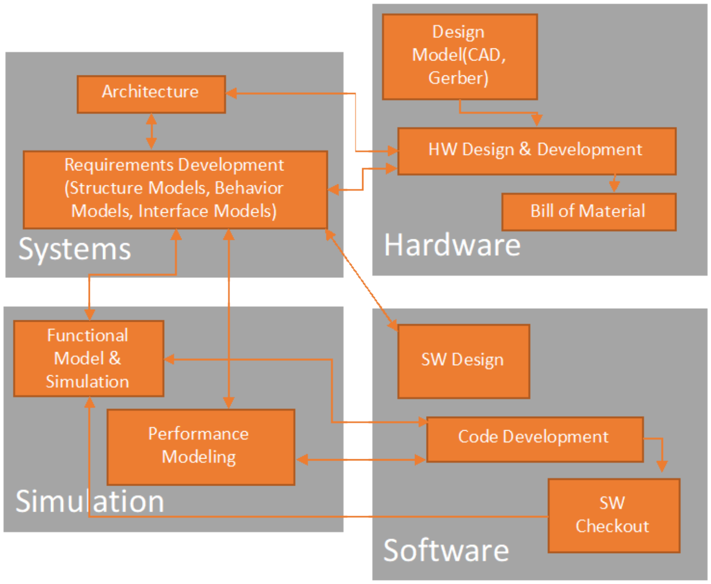


Figure 18. System-Level Model Architecture.

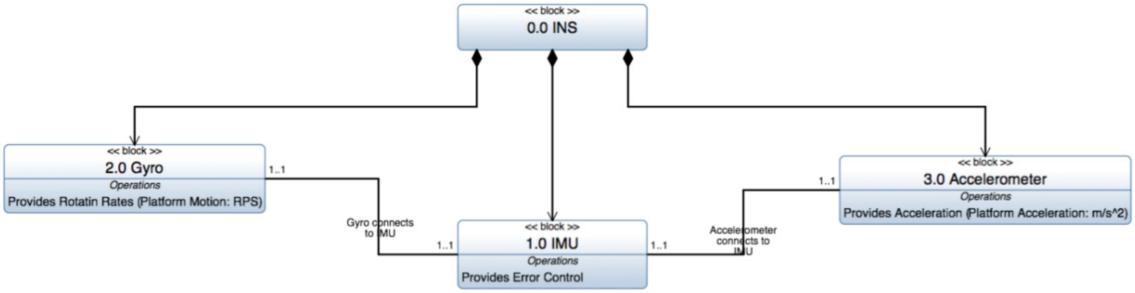
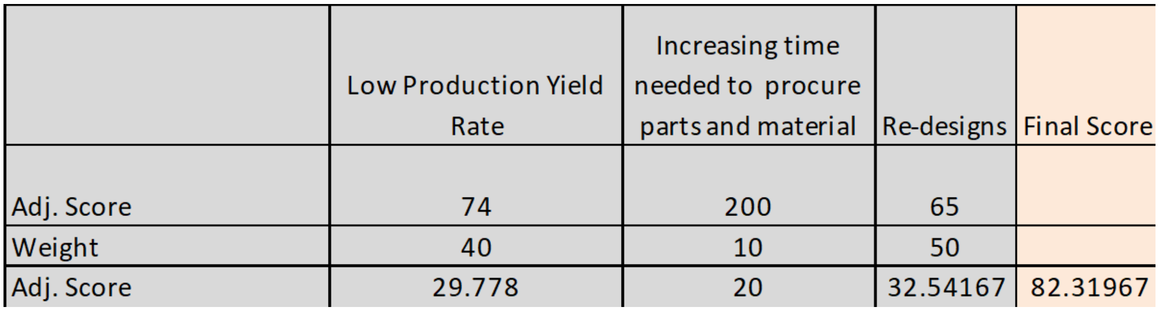


Figure 19. INS Block Definition Diagram Example.

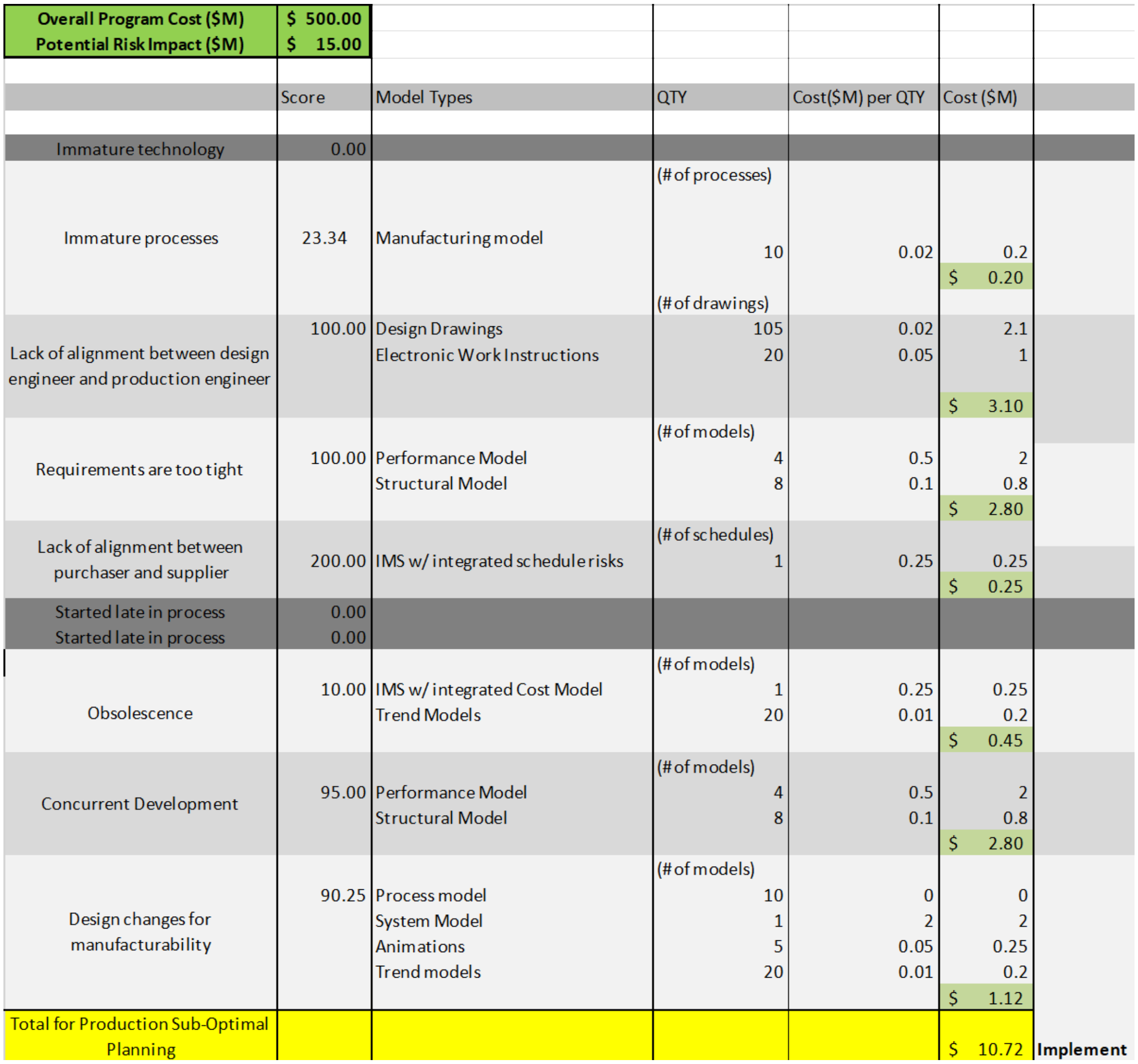
The Excel MBSE analysis tool does not perform an assessment on a development program. For that reason, the case study conducts the assessment using the Excel MBSE analysis tool based on the production of the initial 30 prototype gyroscopes that the program office contracted for. The assessment also was only for the sub-optimal production planning. The sub-optimal production processes are not applicable to the building of prototypes. The goal of prototyping is to develop a design that meets performance and not for optimizing production processes. The Excel MBSE analysis tool has a value of 82, as shown in Table 13, for sub-optimal planning for the prototypes and indicates that the program office should have implemented MBSE to mitigate all the common risks apart from obsolescence. The weights were allocated to re-designs and low production yield rate as MBSE essentially provides an equal benefit to both. The case study provided a slightly higher weight to re-designs as it has the biggest cost impact. During prototyping, the program can manage through delays in material procurement so the weight of 10 was allocated to increasing time needed to procure parts and material. The calculation on ROI also indicated that the program office should have implemented MBSE to mitigate risk to low product yield rates. To implement MBSE would have cost the program about $11 million or 3% of its overall budget, as shown in Table 14. The cost risk far exceeded the cost to implement MBSE as the cost to terminate the replacement of the INS in 2008 and then re-start the program in 2010 effectively cost the program over $50 million (Beaufait 2017).

Table 13. Sub-Optimal Production Planning Assessment for Program A.



	Low Production Yield Rate	Increasing time needed to procure parts and material	Re-designs	Final Score
Adj. Score	74	200	65	
Weight	40	10	50	
Adj. Score	29.778	20	32.54167	82.31967

Table 14. Sub-Optimal Production Planning Cost Assessment for Program A.

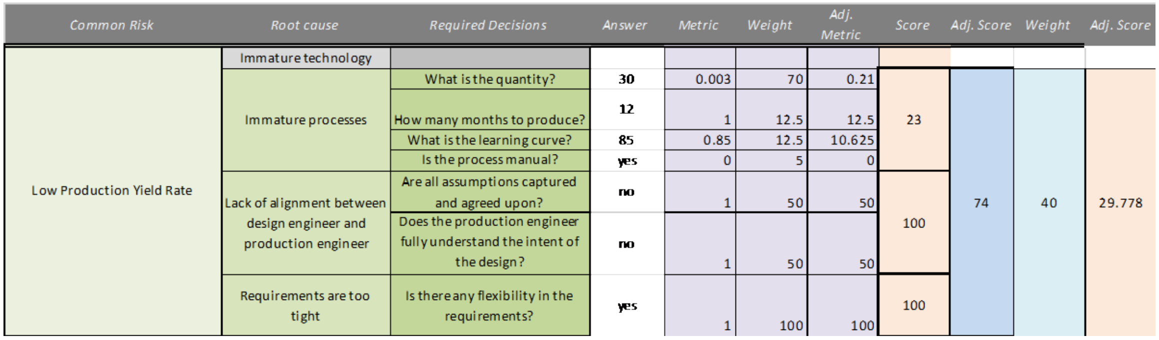


Overall Program Cost ($M)	**$ 500.00**					
Potential Risk Impact ($M)	**$ 15.00**					
	Score	Model Types	QTY	Cost($M) per QTY	Cost ($M)	
Immature technology	0.00					
Immature processes	23.34	Manufacturing model	(# of processes) 10	0.02	0.2 $ 0.20	
Lack of alignment between design engineer and production engineer	100.00	Design Drawings Electronic Work Instructions	(# of drawings) 105 20	0.02 0.05	2.1 1 $ 3.10	
Requirements are too tight	100.00	Performance Model Structural Model	(# of models) 4 8	0.5 0.1	2 0.8 $ 2.80	
Lack of alignment between purchaser and supplier	200.00	IMS w/ integrated schedule risks	(# of schedules) 1	0.25	0.25 $ 0.25	
Started late in process	0.00					
Started late in process	0.00					
Obsolescence	10.00	IMS w/ integrated Cost Model Trend Models	(# of models) 1 20	0.25 0.01	0.25 0.2 $ 0.45	
Concurrent Development	95.00	Performance Model Structural Model	(# of models) 4 8	0.5 0.1	2 0.8 $ 2.80	
Design changes for manufacturability	90.25	Process model System Model Animations Trend models	(# of models) 10 1 5 20	0 2 0.05 0.01	0 2 0.25 0.2 $ 1.12	
Total for Production Sub-Optimal Planning					$ 10.72	**Implement**

To calculate those numbers, the user answers the questions in the Excel MBSE analysis tool. Table 15 shows the answers to the low production yield rate. The program office contracted for thirty gyroscopes and the process to build a FOG was highly manual that requires skilled technicians. The processes to build a FOG were immature and it took approximately a year to produce one FOG (Beaufait 2017). The case study estimates the learning to be an 85% learning curve. This estimation is consistent with the standard learning curve for aerospace manufacturing (Stewart 1995). The context that the case study used to answer questions related to alignment between the production and design engineer was whether the customer for the FOG is in alignment with the producer of the FOG. The prototype FOGs that the contractor produced did not work in the system even though they worked under component level tests, so there was a lack of alignment. As the program was still prototyping, there was flexibility in requirements.

The weights, as assigned in Table 15, are due to the quantity as it drives the benefit of implementing MBSE. Any resource savings that MBSE provides is minimal compared to the build of 30 FOGs. Whether the customer and producer of the FOG understand and agree to the assumptions and whether the producer understand the design intent are equal in weights. If either happens, the risk of Program A not getting what they want is equal. There is only one question for requirements being too tight, so it has a weight of 100. The scores for immature processes, a lack of alignment, and requirements being too tight are average to provide an adjusted score of 74 to mitigate low production yield rates.

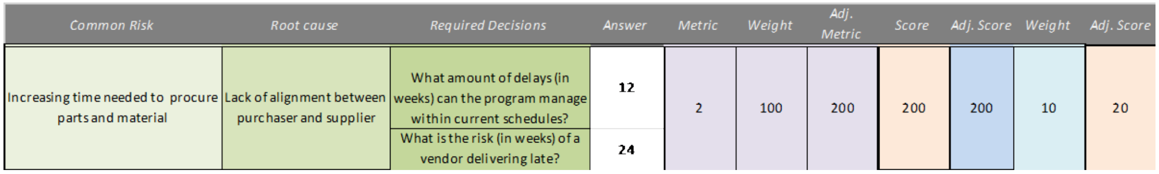
Table 15. Low Production Yield Rate Assessment.



Common Risk	Root cause	Required Decisions	Answer	Metric	Weight	Adj. Metric	Score	Adj. Score	Weight	Adj. Score
Low Production Yield Rate	Immature technology									
	Immature processes	What is the quantity?	30	0.003	70	0.21	23	74	40	29.778
		How many months to produce?	12	1	12.5	12.5				
		What is the learning curve?	85	0.85	12.5	10.625				
		Is the process manual?	yes	0	5	0				
	Lack of alignment between design engineer and production engineer	Are all assumptions captured and agreed upon?	no	1	50	50	100			
		Does the production engineer fully understand the intent of the design?	no	1	50	50				
	Requirements are too tight	Is there any flexibility in the requirements?	yes	1	100	100	100			

Table 16 shows the assessment for increasing time needed to procure parts and material. This common risk only consists of two questions and is related to the schedule risk that is acceptable to Program A. Program A could have experienced a year delay in schedule and the program office would still consider the program to be successful. The case study assessed the vendors schedule risk to be two years. It takes a year to build a FOG, so any issue discovered in the build could have delayed the program an additional year. If the program office discovered that issue near the end of the build, the delay would be two years. While there are two questions, there is a single metric. The metric is a ratio of the acceptable schedule risk and the vendor's schedule risk. As there is a single metric, the weight is 100. The score for the common risk is 200.

Table 16. Increasing Time Needed to Procure Parts and Material Assessment.



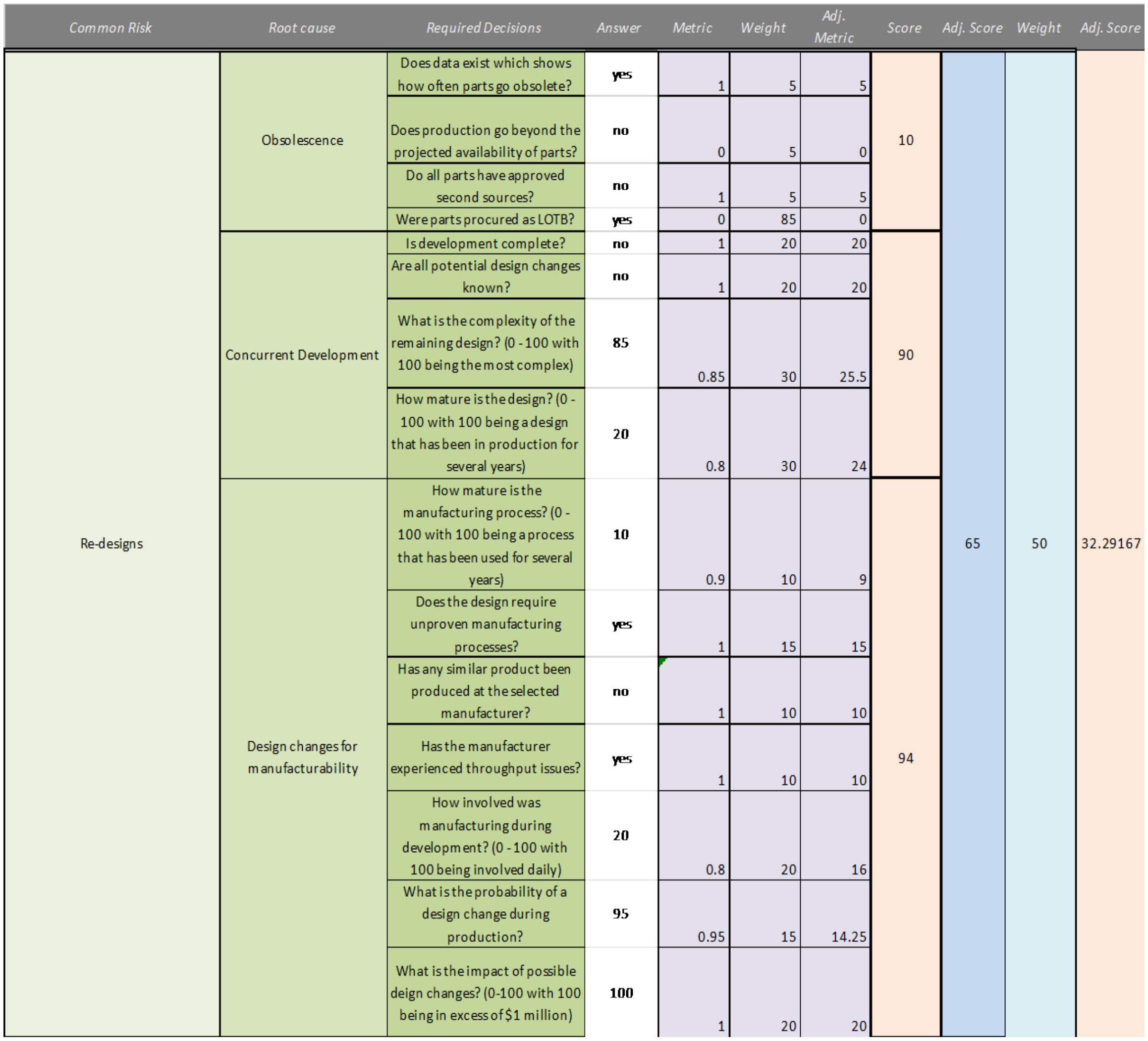
Common Risk	Root cause	Required Decisions	Answer	Metric	Weight	Adj. Metric	Score	Adj. Score	Weight	Adj. Score
Increasing time needed to procure parts and material	Lack of alignment between purchaser and supplier	What amount of delays (in weeks) can the program manage within current schedules?	12	2	100	200	200	200	10	20
		What is the risk (in weeks) of a vendor delivering late?	24							

Table 17 shows the assessment for re-designs. The root cause of obsolescence has four questions that the case study answers. Program A had data for how often parts go obsolete based on how many times the program had to qualify new parts. The program office did not use this data for tracking obsolescence. For the build of the 30 FOGs, the program office purchased all material was on the same purchasing order. All parts were available at the start of production to build all FOGs. Essentially the program office procured the parts as a LOTB item for the prototype units. There were no second sources for components. For the weights, all parts purchased as a LOTB for the thirty prototype units for reasons outside of a risk of obsolescence. For this reason, a weight of 85 was allocated to the question, "Were parts procured as LOTB?" The other three questions are insignificant and are each given a weight of 5. The overall score calculated to mitigate obsolescence risk post Milestone C on Program A is a 10.

The assessment of concurrent development answered the four questions in Table 17. Development was not complete as the program was still prototyping and not all design changes were known. The complexity of the design is high so the case study provides an answer of 85. The design was immature, so the case study provides a score of 20. The weight allocated to whether development is complete is 40. This is because if development is complete, there is no risk of concurrent development. Knowing potential design changes is allocated a weight of 30. This is because if design changes are known, the complexity and design are less important. Complexity of the design is allocated a weight of 20 as it is more important than the maturity of the design. Design maturity is allocated a weight of 10. Based on the answers and the weights, concurrent development has a score of 95.

The assessment of design changes for manufacturability required for the case study to answer seven questions. The manufacturing process was immature and the case study provided an answer of 10 on a scale of 100. The design required unproven manufacturing process, such as fiber coil winding. The manufacturer did not produce similar items at the time the prototypes were built. The manufacturer experienced throughput issues on other programs. The FOGs were built in an engineering environment, so manufacturing and the design engineer were the same. This made manufacturing involved daily in the design. The intent of the question though is how influential is the manufacturability of the design during the development process. For that reason, the answer given was 50 as the goal was to develop a design that met performance requirements. Manufacturability was addressed later. As the program was producing prototypes, the probability of design changes is near 100%. The case study provides an answer of 95% as there is a small chance the design is perfect the very first time. The impact of a design change during production is over $1 million. Each FOG costs over $100,000. A design change during production can easily have a cost impact over $1 million. The weights are all essentially equal for all questions. They are all allocated a weight of 15 except for whether the manufacturer has experienced throughput issues. That is the least important question as it does not drive a decision to implement MBSE. The Excel MBSE analysis tool averages the scores for obsolescence, concurrent development, and design changes for manufacturability and provides an adjusted score of 65 for re-designs.

Table 17. Re-Design Assessment.



Common Risk	Root cause	Required Decisions	Answer	Metric	Weight	Adj. Metric	Score	Adj. Score	Weight	Adj. Score
Re-designs	Obsolescence	Does data exist which shows how often parts go obsolete?	yes	1	5	5	10	65	50	32.29167
		Does production go beyond the projected availability of parts?	no	0	5	0				
		Do all parts have approved second sources?	no	1	5	5				
		Were parts procured as LOTB?	yes	0	85	0				
	Concurrent Development	Is development complete?	no	1	20	20	90			
		Are all potential design changes known?	no	1	20	20				
		What is the complexity of the remaining design? (0 - 100 with 100 being the most complex)	85	0.85	30	25.5				
		How mature is the design? (0 - 100 with 100 being a design that has been in production for several years)	20	0.8	30	24				
	Design changes for manufacturability	How mature is the manufacturing process? (0 - 100 with 100 being a process that has been used for several years)	10	0.9	10	9	94			
		Does the design require unproven manufacturing processes?	yes	1	15	15				
		Has any similar product been produced at the selected manufacturer?	no	1	10	10				
		Has the manufacturer experienced throughput issues?	yes	1	10	10				
		How involved was manufacturing during development? (0 - 100 with 100 being involved daily)	20	0.8	20	16				
		What is the probability of a design change during production?	95	0.95	15	14.25				
		What is the impact of possible deign changes? (0-100 with 100 being in excess of $1 million)	100	1	20	20				

3. Re-started Inertial Navigation Subsystem Replacement Program

In 2010, the program office awarded a prime contract for the INS replacement based on a competitive contract (Beaufait 2017). The Beaufait whitepaper suggests that the program office still maintained meeting accuracy requirements and schedule as the primary goals of the program as the program leveraged the previous INS replacement program and continued the same approach. Design engineers dominated the program office. The Beaufait whitepaper further indicates that as the development progressed, the program experienced delays in delivering hardware and cost growth and that these delays caused the TDP for both the IMU and the gyroscope to be late. The IMU is the inertial error control to mitigate the gyroscope errors. The IMU and the gyroscopes make up the INS. While the TDPs were late, the deployment schedule did not change (Beaufait 2017). This caused both development and production to be concurrent without a stable design and without certified manufacturing processes. The concurrent production and development increases risk to schedule and cost growth due to re-designs.

As delays occurred on hardware deliveries, so too was integration testing as the program relied on hardware to understand the impacts on the interfaces (Beaufait 2017). The program did not develop models to cross boundaries. The Beaufait whitepaper states that the models developed were covariance models to understand the errors of the navigation subsystem. The Beaufait whitepaper further discussed the assumption was that the program captured all requirements in interface documents. If the subsystem met the interface document, then the system should work. This is an assumption that causes failures most of the time as specifications do not capture not all requirements and not all requirements that are captured are clearly expressed in a way that is not open to interpretation.

In addition to late hardware causing late integration testing, late software was also impacting the validity of the integration testing (Beaufait 2017). Beaufait stated that as hardware was late, the team was unable to complete software development as the program required hardware to test software functionality and this drove the program to perform integration testing at a system level at the same time as development testing at a subsystem level. The Beaufait whitepaper further argued that this resulted in system failures due to software bugs that lower level testing should have identified. Not only was the software late, but the program reduced functionality from what the program office planned in order to maintain the test schedule and the software that was being testing was not representative of the software that the program office planned for production (Beaufait 2017).

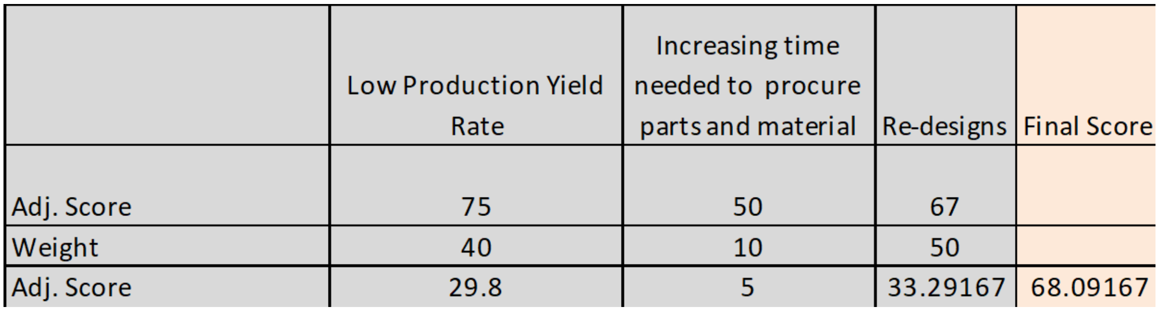
As the program began having cost growth, the program office delayed the production planning efforts to ensure the program met the accuracy requirement (Beaufait 2017). Beaufait argued this caused the late delivery of production test equipment and a failure in ensuring that the program office established the production facility prior to entering production. The Beaufait whitepaper stated that on top of the difficulties in establishing production, several vendors who supply critical components stopped producing their component. The Beaufait whitepaper reported that both the delay in establishing the production facilities as well as the obsolescence issues are causing delays in production. Based on the research of this thesis, this is expected.

Had the MBSE methodology described in the previous chapter been implemented, the program office would have functionally decomposed the system and created a system model as described in Figure 18. Leading up to the production, the program should have implemented MBSE as discussed previously for the initial INS replacement program. The program office is then able to perform subsystem trades to determine the optimal subsystem architecture and design. The program office is able to make an informed decision on whether to force a new technology into the same form, fit, and function as a means of cost savings. The program office should have built hardware from the bottoms up based on the functions and verified the functional models prior to integrating the hardware. This allows the use of the models as a means of interface testing and software development as they are verified against hardware. This decouples the interface testing and software development from the delivery of hardware and reduces risk to the program. Potentially, it reduces cost as well by either reducing hardware quantities, reducing the number of hardware tests, or both. Not only does it have the potential to reduce cost, but it also could have mitigated schedule risk by understanding issues prior to hardware and software delivery.

To determine whether the program office should implement MBSE for sub-optimal production planning, the case study answers the questions in the Excel MSBE analysis tool. The final score upon answering the questions is 68 as shown in Table 18. The weights are the same based on the same rationale as discussed previously. This means that implementing MBSE mitigates the risk of sub-optimal planning. The Excel

MBSE analysis tool also shows that implementing MBSE returns a positive ROI as shown in Table 19. However, this does not take into schedule. The program will not stop to implement MBSE. Assuming that the program office can implement MBSE during the pre-production phase, the benefit within the Excel MBSE analysis tool will be accurate. The farther the program gets into production, the less ROI the program will receive. This is due to the time it takes to implement MBSE as well as the risk reduction due to the production process becoming more mature.

Table 18. Program A Production Planning Assessment for Production Build.



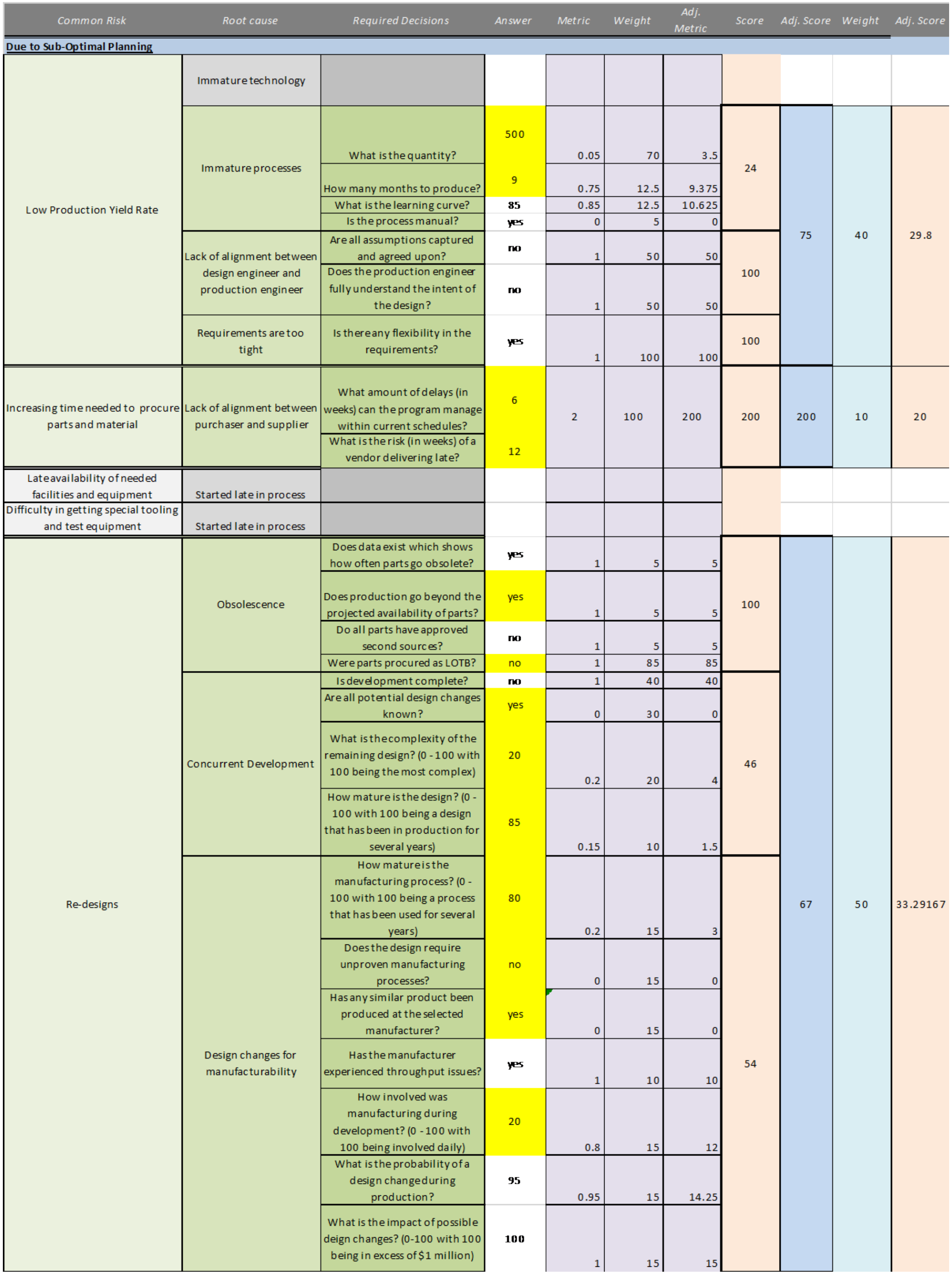
	Low Production Yield Rate	Increasing time needed to procure parts and material	Re-designs	Final Score
Adj. Score	75	50	67	
Weight	40	10	50	
Adj. Score	29.8	5	33.29167	68.09167

Table 19. Assessment to Implement MBSE on INS Replacement for Sub-Optimal Production Planning.

Overall Program Cost ($M)	**$ 500.00**					
Potential Risk Impact ($M)	**$ 15.00**					
	Score	Model Types	QTY	Cost($M) per QTY	Cost ($M)	
Total for Production Sub-Optimal Planning					$ 10.72	**Implement**

The process to obtain the calculation of those values is similar to what was previously described in the initial INS replacement program. Table 20 shows the Excel MBSE analysis tool for this and the change from the previous assessment is highlighted in yellow. The differences in the answers to the questions involves the increased quantities, decrease in schedule margin, increased maturity of the FOG design, and the increased maturity of the manufacturing processes. The quantity increased from 30 to 500. The manufacturer has become a significant producer of FOGs. The FOGs are produced quicker. The program faced delays in development that reduced the schedule margin from 12 months to 6 months. The manufacturer matured the FOG manufacturing capability and their schedule risk decreased from 24 months to 12 months. The production of the FOGs are now over eight years and the probability of obsolescence increases. Due to the number of gyroscopes and the production years, the program does not have the capability to buy all the parts LOTB. The program is post Critical Design Review (CDR) so the design is well known. The complexity of the remaining design is low as the program is post CDR. The manufacturing of FOGs has become common and the manufacturing processes are mature. The design of the gyroscope did not include the manufacturer during the design.

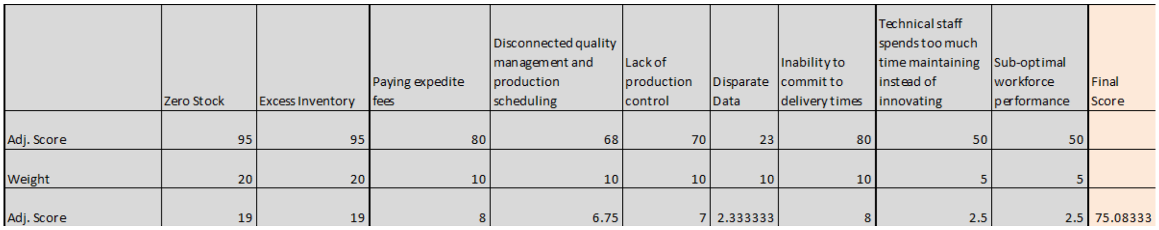
Table 20. Program A Sub-Optimal Production Planning Assessment.



Common Risk	*Root cause*	*Required Decisions*	*Answer*	*Metric*	*Weight*	*Adj. Metric*	*Score*	*Adj. Score*	*Weight*	*Adj. Score*
Due to Sub-Optimal Planning										
Low Production Yield Rate	Immature technology									
	Immature processes	What is the quantity?	500	0.05	70	3.5	24	75	40	29.8
		How many months to produce?	9	0.75	12.5	9.375				
		What is the learning curve?	85	0.85	12.5	10.625				
		Is the process manual?	yes	0	5	0				
	Lack of alignment between design engineer and production engineer	Are all assumptions captured and agreed upon?	no	1	50	50	100			
		Does the production engineer fully understand the intent of the design?	no	1	50	50				
	Requirements are too tight	Is there any flexibility in the requirements?	yes	1	100	100	100			
Increasing time needed to procure parts and material	Lack of alignment between purchaser and supplier	What amount of delays (in weeks) can the program manage within current schedules?	6	2	100	200	200	200	10	20
		What is the risk (in weeks) of a vendor delivering late?	12							
Late availability of needed facilities and equipment	Started late in process									
Difficulty in getting special tooling and test equipment	Started late in process									
Re-designs	Obsolescence	Does data exist which shows how often parts go obsolete?	yes	1	5	5	100	67	50	33.29167
		Does production go beyond the projected availability of parts?	yes	1	5	5				
		Do all parts have approved second sources?	no	1	5	5				
		Were parts procured as LOTB?	no	1	85	85				
	Concurrent Development	Is development complete?	no	1	40	40	46			
		Are all potential design changes known?	yes	0	30	0				
		What is the complexity of the remaining design? (0 - 100 with 100 being the most complex)	20	0.2	20	4				
		How mature is the design? (0 - 100 with 100 being a design that has been in production for several years)	85	0.15	10	1.5				
	Design changes for manufacturability	How mature is the manufacturing process? (0 - 100 with 100 being a process that has been used for several years)	80	0.2	15	3	54			
		Does the design require unproven manufacturing processes?	no	0	15	0				
		Has any similar product been produced at the selected manufacturer?	yes	0	15	0				
		Has the manufacturer experienced throughput issues?	yes	1	10	10				
		How involved was manufacturing during development? (0 - 100 with 100 being involved daily)	20	0.8	15	12				
		What is the probability of a design change during production?	95	0.95	15	14.25				
		What is the impact of possible deign changes? (0-100 with 100 being in excess of $1 million)	100	1	15	15				

The gyroscope which is under development as part of the INS replacement program is exiting the Production Readiness Review (PRR) and there is minimal data to determine the effectiveness of production processes. Based on the Excel MBSE analysis tool, implementing MBSE to mitigate sub-optimal production processes has a final score of 75, as shown in Table 21. This means that it is beneficial to implement MBSE. In terms of the ROI, the cost indicates that the program office should implement MBSE to improve sub-optimal processes, as shown in Table 22. The cost risk assumption is $15 million and the ROI is minimal for the INS replacement program that has a life cycle cost well over $500 million. The Excel MBSE analysis tool also shows that the program will receive a positive ROI if the program office implements MBSE to mitigate risks to both production sub-optimal processes and planning, as shown in Table 23. With the errors in the estimates, the ROI will be cost neutral. It may be slightly positive or it could be slightly negative.

Table 21. Program A Production Process Assessment for Production Build.

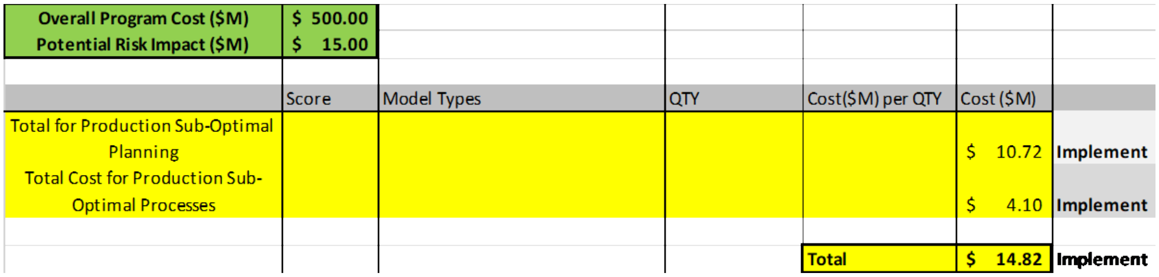


	Zero Stock	Excess Inventory	Paying expedite fees	Disconnected quality management and production scheduling	Lack of production control	Disparate Data	Inability to commit to delivery times	Technical staff spends too much time maintaining instead of innovating	Sub-optimal workforce performance	Final Score
Adj. Score	95	95	80	68	70	23	80	50	50	
Weight	20	20	10	10	10	10	10	5	5	
Adj. Score	19	19	8	6.75	7	2.333333	8	2.5	2.5	75.08333

Table 22. Assessment to Implement MBSE on INS Replacement for Sub-Optimal Production Processes.

Overall Program Cost ($M)	**$ 500.00**					
Potential Risk Impact ($M)	**$ 15.00**					
	Score	Model Types	QTY	Cost($M) per QTY	Cost ($M)	
Total Cost for Production Sub-Optimal Processes					$ 4.10	**Implement**

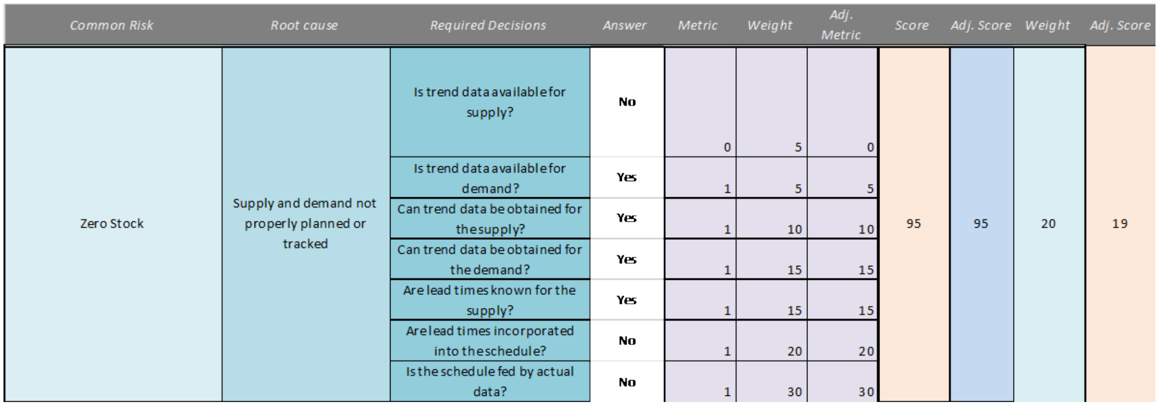
Table 23. Assessment to Implement MBSE on INS Replacement for both Sub-Optimal Production Processes and Sub-Optimal Production Planning.



Overall Program Cost ($M)	**$ 500.00**					
Potential Risk Impact ($M)	**$ 15.00**					
	Score	Model Types	QTY	Cost($M) per QTY	Cost ($M)	
Total for Production Sub-Optimal Planning					$ 10.72	**Implement**
Total Cost for Production Sub-Optimal Processes					$ 4.10	**Implement**
				Total	**$ 14.82**	**Implement**

The case study performs an assessment of the sub-optimal production processes by answering several questions that decomposes the common risks. To assess the benefit of MBSE to mitigate the risk of zero stock during production post Milestone C, the case study answers seven questions as shown in Table 24. Trend data for supply is not available as the program has not stocked supply. Trend data for demand is available as the program ordered parts. Trend data for supply is obtained once supply data is available. Trend data for demand is available so therefore it is obtainable. Lead times for the parts are known as the parts are common within the FOG industry. The program did not incorporate lead times into the schedule, at least not in any detail. The schedule has a six-month estimate for receipt of parts that is not based on data. A weight of 30 is allocated to the question, “Is the schedule fed by actual data?” As discussed in the previous chapter, the schedule needs data input to receive the most out of implementing MBSE post Milestone C. To mitigate the risk of zero stock, it is important to incorporate the lead times into the schedule. Therefore, the case study provides a weight of 20 to the question, “Are lead times incorporated into the schedule?” A complement to that question is whether data is available for the lead times. The case study gives the question a weight of 20 as the program office cannot incorporate the data into the schedule if it does not exist. The trend data is not a driver for implementing MBSE. The case study provides the questions pertaining to whether the program can obtain data a weight of 10. The case study gives a weight of 5 to the questions pertaining to the availability of the data. Once the user assigns the weights the Excel MBSE analysis tool calculates the score. For zero stock, the score is 95 that show that MBSE will mitigate the risk of zero stock for Program A. To mitigate this risk, the recommendation is to implement the supply chain model as discussed in the previous chapter.

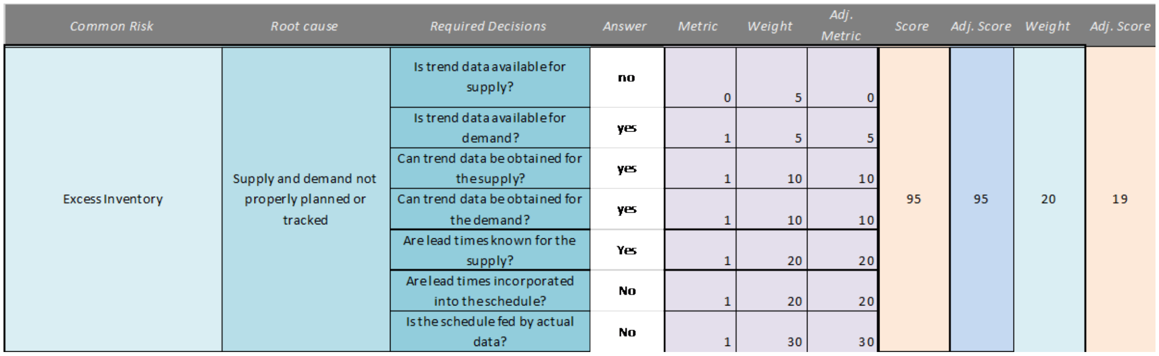
Table 24. Program A Zero Stock Assessment.



Common Risk	Root cause	Required Decisions	Answer	Metric	Weight	Adj. Metric	Score	Adj. Score	Weight	Adj. Score
Zero Stock	Supply and demand not properly planned or tracked	Is trend data available for supply?	No	0	5	0	95	95	20	19
		Is trend data available for demand?	Yes	1	5	5				
		Can trend data be obtained for the supply?	Yes	1	10	10				
		Can trend data be obtained for the demand?	Yes	1	15	15				
		Are lead times known for the supply?	Yes	1	15	15				
		Are lead times incorporated into the schedule?	No	1	20	20				
		Is the schedule fed by actual data?	No	1	30	30				

Table 25 shows the assessment of the excess inventory risk. This common risk has seven questions that the case study answers. These questions are the same questions in the zero-stock assessment. The answers and weights are the same. As the answers and the weights are the same, the score is the same. The recommendation is to implement the supply chain model as discussed in the previous chapter.

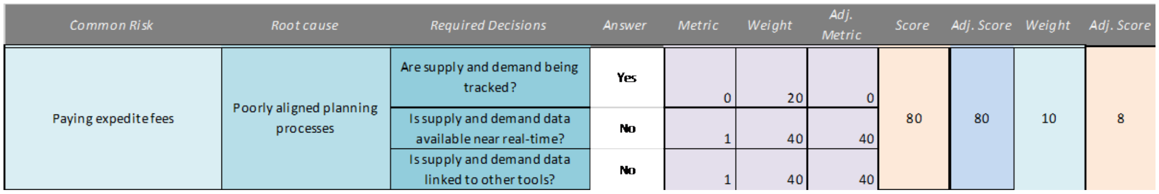
Table 25. Program A Excess Inventory Assessment.



Common Risk	Root cause	Required Decisions	Answer	Metric	Weight	Adj. Metric	Score	Adj. Score	Weight	Adj. Score
Excess Inventory	Supply and demand not properly planned or tracked	Is trend data available for supply?	no	0	5	0	95	95	20	19
		Is trend data available for demand?	yes	1	5	5				
		Can trend data be obtained for the supply?	yes	1	10	10				
		Can trend data be obtained for the demand?	yes	1	10	10				
		Are lead times known for the supply?	Yes	1	20	20				
		Are lead times incorporated into the schedule?	No	1	20	20				
		Is the schedule fed by actual data?	No	1	30	30				

Table 26 shows the assessment of the paying expedite fees. This common risk has three questions that the case study answers. For Program A, the program is tracking the supply and demand, but the data is not available near real-time nor is the data linked to any tool. The linking of the data to another tool and the availability of the data near real-time are each allocated a weight of 40. Both are essential to implement MBSE and will provide the biggest benefit. The case study provides the tracking of supply and demand a weight of 20 due to it being important, but not as critical as the other two questions. After allocating the weights, the MBSE tool calculates a score of 80 for paying expedite fees. The recommendation is to implement the supply chain model as discussed in the previous chapter.

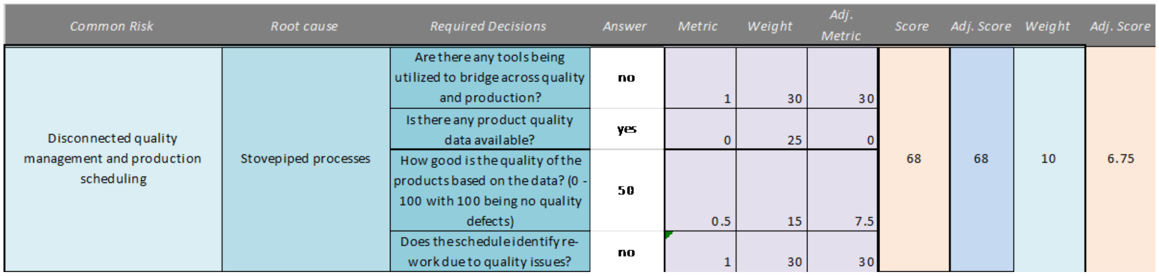
Table 26. Program A Paying Expedite Fees Assessment.



Common Risk	*Root cause*	*Required Decisions*	*Answer*	*Metric*	*Weight*	*Adj. Metric*	*Score*	*Adj. Score*	*Weight*	*Adj. Score*
Paying expedite fees	Poorly aligned planning processes	Are supply and demand being tracked?	Yes	0	20	0	80	80	10	8
		Is supply and demand data available near real-time?	No	1	40	40				
		Is supply and demand data linked to other tools?	No	1	40	40				

Table 27 shows the assessment of a disconnected quality management and production scheduling. This common risk has four questions that the case study answers. The program is not using tools being between quality and production. Quality data is available as FOGs are in production. The case study assesses quality to be 50 out of 100. The FOGs that are built meet performance requirements at the system level, but to not meet all gyroscope level requirements. The schedule is an optimistic schedule that does not account for re-work and is only achievable if everything goes as planned. Whether tools are used to bridge between quality and production is allocated a weight of 30. That weight is the same as was allocated to whether re-work is scheduled. These weights were allocated as they are the key to ensuring alignment between quality and production. A weight of 25 is allocated to the availability of quality data as MBSE is not particularly useful if there is no data. The case study gives a weight of 15 to the quality assessment as it is not as important as the availability of data. With the allocated weights, the score for a disconnected quality management and production scheduling is 68. Based on the score, the recommendation is to implement the manufacturing model discussed in the previous chapter.

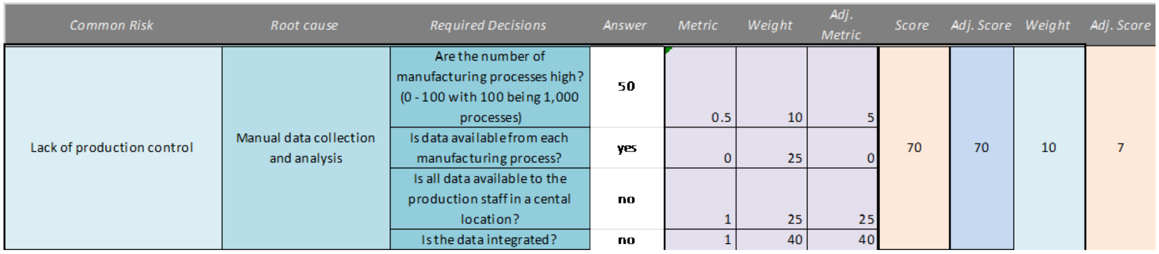
Table 27. Program A Disconnected Quality Management and Production Scheduling.



Common Risk	Root cause	Required Decisions	Answer	Metric	Weight	Adj. Metric	Score	Adj. Score	Weight	Adj. Score
Disconnected quality management and production scheduling	Stovepiped processes	Are there any tools being utilized to bridge across quality and production?	no	1	30	30	68	68	10	6.75
		Is there any product quality data available?	yes	0	25	0				
		How good is the quality of the products based on the data? (0 - 100 with 100 being no quality defects)	50	0.5	15	7.5				
		Does the schedule identify re-work due to quality issues?	no	1	30	30				

Table 28 shows the assessment of a lack of production control. The common risk of lack of production control has four questions that the case study answers. The manufacturing of a FOG does not contain many processes that are different. The case study provides an answer of 50 out of 100, where 100 is a thousand different processes. Data is available from each step in the manufacturing process. This data is kept for records. The program does not store data in a central location. The program spreads data across several different tools. The program does not integrate data. The integration of the data was allocated a weight of 40 as that is the dominant factor in determining if the program office should implement MBSE. The two questions related to data availability were each allocated a weight of 25 as they are equally important, but not as important as data integration. The case study gives the number of manufacturing processes a weight of 10. This is due to the number of processes not being that important. One complex process may be more important than a thousand simple processes. With the weights allocated, the Excel MBSE analysis tool provides a score of 70 for a lack of production control. The recommendation is to implement the manufacturing model described in the previous chapter.

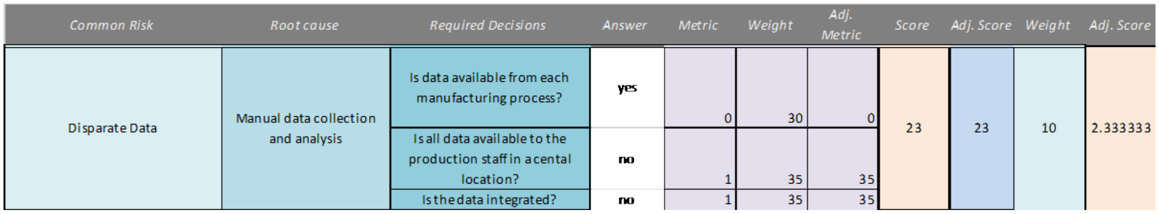
Table 28. Program A Lack of Production Control Assessment.



Common Risk	Root cause	Required Decisions	Answer	Metric	Weight	Adj. Metric	Score	Adj. Score	Weight	Adj. Score
Lack of production control	Manual data collection and analysis	Are the number of manufacturing processes high? (0 - 100 with 100 being 1,000 processes)	50	0.5	10	5	70	70	10	7
		Is data available from each manufacturing process?	yes	0	25	0				
		Is all data available to the production staff in a cental location?	no	1	25	25				
		Is the data integrated?	no	1	40	40				

Table 29 shows the assessment of disparate data. This common risk has three questions that the case study answers. Data is available from the manufacturing process. The data is not available in a central location. The program did not integrate the data. The weights are nearly equal. The weight allocated to the integration of data and the availability of data in a central location is 35. The weight of the availability of data from each manufacturing process is 30. This question is slightly less important than the other two. The recommendation is to implement the manufacturing model discussed in the previous chapter.

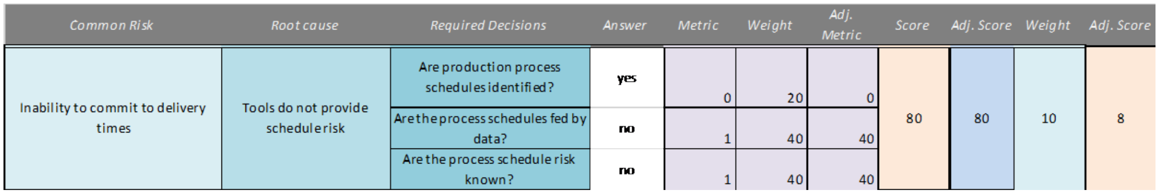
Table 29. Program A Disparate Data Assessment.



Common Risk	Root cause	Required Decisions	Answer	Metric	Weight	Adj. Metric	Score	Adj. Score	Weight	Adj. Score
Disparate Data	Manual data collection and analysis	Is data available from each manufacturing process?	yes	0	30	0	23	23	10	2.333333
		Is all data available to the production staff in a cental location?	no	1	35	35				
		Is the data integrated?	no	1	35	35				

Table 30 shows the assessment of the inability to commit to delivery times. This common risk has three questions that the case study answers. The time it takes to complete a production process is known and is in the schedule. The schedule input is not data driven and the schedule risk is not captured. The benefit to implementing MBSE for understanding delivery times is associated with understanding the schedule risk and having a data driven schedule. Therefore, the case study provides each of those questions a weight of 40. The case study provides a weight of 20 to identifying the production process schedules due to it being less important. With the weights allocated, the Excel MBSE analysis tool calculates a score of 80 for the inability to commit to delivery times. The recommendation is to implement the manufacturing model discussed in the previous chapter.

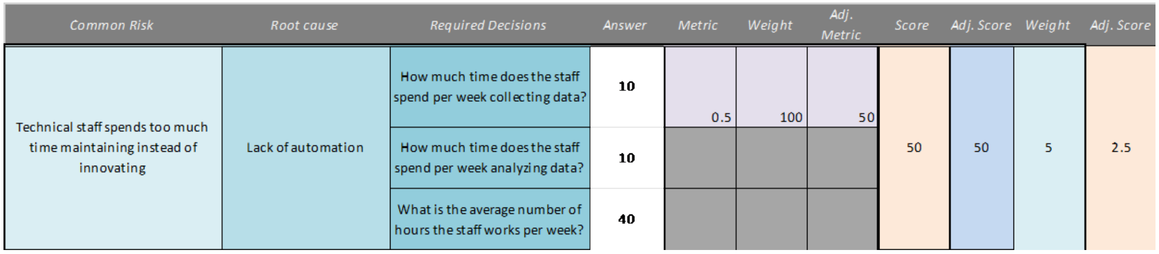
Table 30. Program A Inability to Commit to Delivery Times Assessment.



Common Risk	Root cause	Required Decisions	Answer	Metric	Weight	Adj. Metric	Score	Adj. Score	Weight	Adj. Score
Inability to commit to delivery times	Tools do not provide schedule risk	Are production process schedules identified?	yes	0	20	0	80	80	10	8
		Are the process schedules fed by data?	no	1	40	40				
		Are the process schedule risk known?	no	1	40	40				

Table 31 shows the assessment of the technical staff spends too much time maintaining instead of innovating. This common risk has three questions that the case study answers. All three questions are related. The staff that is referenced in the questions is the program management staff. The staff spends about ten years collecting data, another ten hours analyzing the data, and the average workweek consists of 40 hours. This is an estimate that does not have data to validate the estimate. To calculate the metric, the Excel MBSE analysis tool sums the hours spent collecting data and the hours spent analyzing data and then divided by the number of hours in the workweek. The weight allocated is 100 as there is only one metric. With the weight allocated, the Excel MBSE analysis tool provides a score of 50. In this case, the recommendation is not to implement a model solely based on this assessment.

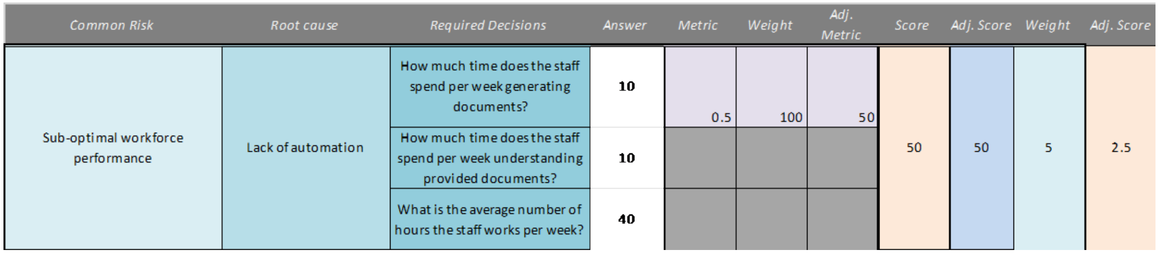
Table 31. Program A Technical Staff Spends Too Much Time Maintaining Instead of Innovating Assessment.



Common Risk	Root cause	Required Decisions	Answer	Metric	Weight	Adj. Metric	Score	Adj. Score	Weight	Adj. Score
Technical staff spends too much time maintaining instead of innovating	Lack of automation	How much time does the staff spend per week collecting data?	10	0.5	100	50	50	50	5	2.5
		How much time does the staff spend per week analyzing data?	10							
		What is the average number of hours the staff works per week?	40							

Table 32 shows the assessment of a sub-optimal workforce performance. This common risk has three questions. The questions are similar to the previous assessment. The difference is that this assessment focuses on the generation of documents instead of data. The program management staff spends about 10 hours per week generating documents, 10 hours per week reviewing documents, and the work week consists of 40 hours. This is based on estimates that do not have data to validate the estimates. The metric is a sum of the hours generating documents and the hours reviewing documents divided by the hours in a workweek. The weight is 100 as the there is only one metric. With the weight allocated, the Excel MBSE analysis tool provides a score of 50. The recommendation is not to implement MBSE solely based on this assessment.

Table 32. Program A Sub-Optimal Workforce Performance.



Common Risk	Root cause	Required Decisions	Answer	Metric	Weight	Adj. Metric	Score	Adj. Score	Weight	Adj. Score
Sub-optimal workforce performance	Lack of automation	How much time does the staff spend per week generating documents?	10	0.5	100	50	50	50	5	2.5
		How much time does the staff spend per week understanding provided documents?	10							
		What is the average number of hours the staff works per week?	40							

Looking at the post Milestone C aspect of the INS replacement, there is potentially a significant reduction in risk to future INS replacements. The capability is delayed by at least seven years that the program office attempted to deploy with the initial INS replacement. The total cost estimate is over $100 million due to the schedule delays and the poor planning. As discussed in the next section, having MBSE tools utilized on a program cannot only reduce risk of schedule delays and cost overruns by providing the program office the tools to properly plan, but it does also have the potential to reduce cost. The program office is planning for the INS replacement program to go obsolete in about 20 years and the weapon system will be sustained for an additional 40 years after the next refresh.

C. MISSILE GUIDANCE REPLACEMENT

The purpose of this section is to provide some evidence to validate the Excel MBSE analysis tool. The program office implemented MBSE on the missile guidance program during development and the program is successful. The focus of this research has been on how to implement MBSE into a program during production and sustainment post Milestone C. This research developed the Excel MBSE analysis tool to identify whether MBSE should be implemented during production and sustainment post Milestone C. If the program office implemented MBSE during development, the MSBE analysis tool identifies that additional MBSE implementations is not required. Based on the assessment performed, that is what occurs.

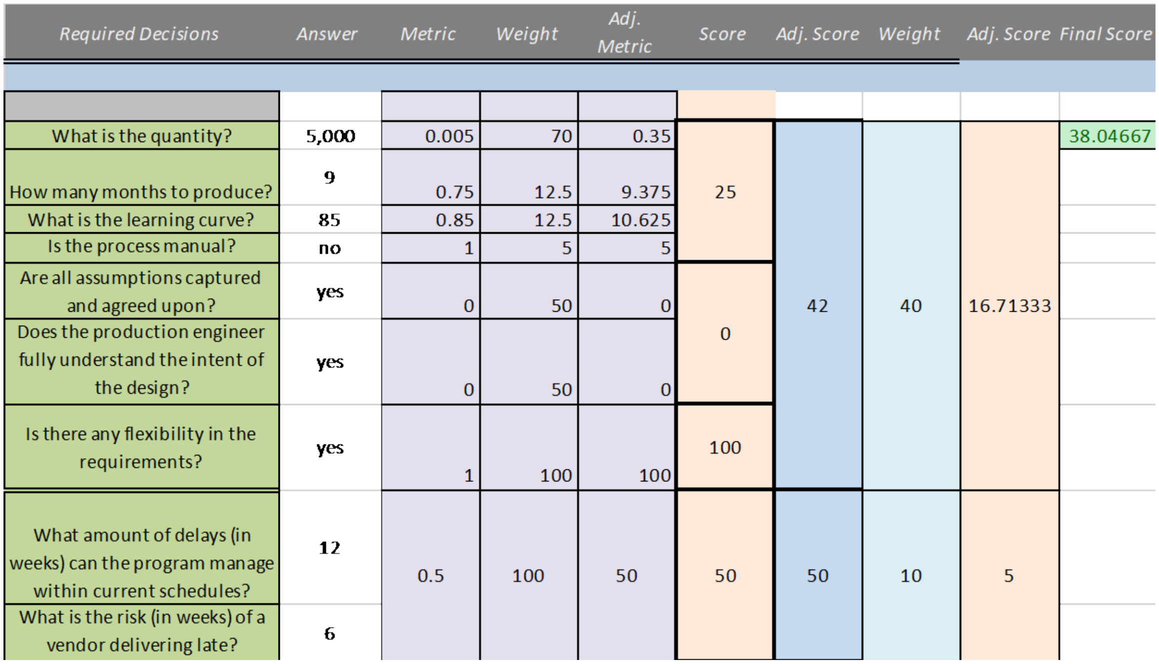
There are two sets of inertial equipment programs in the missile program; one for navigation and one for guidance. Program B developed a new FOG based guidance system. This FOG began development around 2003. Conceptually, it is the same as the INS developed by Program A as they both have the same number of FOGs, accelerometers, and both have an IMU. There are differences in requirements that drive unique designs as Program A requires longer-term stability in the errors. Both Program A and Program B utilize the same subcontractor for the gyroscope design and build, but the prime contractors are different.

The prime for Program B developed and uses a MBSE approach. The program office decided to define boundaries early, perform a functional decomposition and developed a system model. Program B began by developing functional models and then building and testing hardware at the functional level to verify model assumptions. The program updated the models with the new knowledge. When the models behaved as the hardware behaved the program integrated the models and the process started over at a subsystem level. Once the integrated subsystem model is mature, Program B replaced a function in the model with hardware and verified that the system still performed as assumed. When the program verified all functions with real hardware, then the program integrated more hardware together. Eventually the program integrated the subsystem hardware together and verified against the subsystem model. As a result of utilizing MBSE, Program B was able to remove certain system level tests as it was performed using models that were able to reduce test costs by several millions of dollars due to not requiring missiles to be flown. This avoids the cost of several hundreds of instruments and missiles that the program office would have used in missile flight tests. While the development for Program B was successful, there were several issues related to production, such as supply chain management and hardware designs that are difficult to produce that delayed production builds.

While Program B began a year after Program A, the program began deployment in 2013, which is currently seven years prior to Program A deployment. The major difference between the two programs is the prime for Program B utilized formal MBSE processes that allowed them to perform system level trades early in the program to prove out assumptions. When it came time for production, the requirements were well defined and the program office understood the system performance. Based on those assumptions, the Excel MBSE analysis tool answered the questions accordingly and the final score for sub-optimal planning is 38, as shown in Table 33.

In reality, the program office already implemented MBSE so the decision to continue with MBSE is simple but it will have minimal impact as there was low risk of sub-optimal planning. The Excel MBSE analysis tool does show that the continuation of MBSE for sub-optimal processes is still beneficial to the program with a score of 75 as is the same as Table 21. This is the same as Program A as the production processes are nearly identical between the two programs. Given that Program B has had issues during production, the Excel MBSE analysis tool provided a score that is expected. Both programs utilized the same subcontractor as the gyroscope design lead and the producer of the gyroscope. In terms of ROI, it is difficult to calculate as Program B already has the MBSE infrastructure in place and is the baseline plan. To calculate the ROI, the case study needs to make assumptions to understand what the risk would have been if the program office did not implement the MBSE approach.

Table 33. Program B Production Planning Assessment for Production Build.



Required Decisions	Answer	Metric	Weight	Adj. Metric	Score	Adj. Score	Weight	Adj. Score	Final Score
What is the quantity?	5,000	0.005	70	0.35	25	42	40	16.71333	38.04667
How many months to produce?	9	0.75	12.5	9.375					
What is the learning curve?	85	0.85	12.5	10.625					
Is the process manual?	no	1	5	5					
Are all assumptions captured and agreed upon?	yes	0	50	0	0				
Does the production engineer fully understand the intent of the design?	yes	0	50	0					
Is there any flexibility in the requirements?	yes	1	100	100	100				
What amount of delays (in weeks) can the program manage within current schedules?	12	0.5	100	50	50	50	10	5	
What is the risk (in weeks) of a vendor delivering late?	6								

D. SUMMARY

This section assessed Program A and Program B and used the Excel MBSE analysis tool to determine whether the Excel MBSE analysis tool provides realistic recommendations to implement MBSE post Milestone C. The issues encountered on Program A are consistent with the challenges identified in the literature review for post Milestone C activities. Based on the Excel MBSE analysis tool it recommends the use of MBSE to mitigate the challenges associated with sub-optimal planning and sub-optimal processes. When comparing Program A to Program B, Program B was able to enter production with a program that had proper planning in place while Program A struggled to transition into production. The biggest difference between the two programs was the utilization of MBSE tools to provide an understanding of the program. Had Program A utilized the same development approach as Program B, it is likely that the risks would have been avoided that Program A realized, saving both schedule and cost. Once Program A entered production, it would have been cost neutral to implement MBSE. Where the ROI is significant is establishing the infrastructure for future INS replacements.

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V. CONCLUSION

This thesis provides an Excel MBSE analysis tool to identify whether the program office should implement MBSE on a program post Milestone C and to what extent. If the program office decides to implement MBSE on a program post Milestone C, this thesis provides a recommended methodology to implement MBSE. This research and Excel MBSE analysis tool will help program offices to identify the applicability of MBSE to their program to make an informed decision on whether MBSE is right for their program. A case study used the Excel MBSE analysis tool to assess two similar programs within the same program office utilizing the same contractors. This allowed the verification of the Excel MBSE analysis tool.

A. RESULTS AND RECOMMENDATIONS

The findings of the research contained in this thesis, the development of an MBSE methodology, the development of the Excel MBSE analysis tool, and the application to a case study addressed the research questions identified. The objective of the thesis is met in determining whether MBSE should be implemented post Milestone C and developing an Excel MBSE analysis tool that can be used to provide recommendations on whether MBSE should be implemented. The benefit of the research is that it provides a recommendation for MBSE implementation and provides the rationale for implementing MBSE. The research questions follow with the findings.

(1) How can DoD programs benefit from implementing MBSE during post Milestone C activities?

Identifying the challenges associated with programs that are post Milestone C addresses the research question. The use of MBSE was investigated to determine how MBSE can be used to mitigate those challenges. The research identified several models that will benefit programs that are post Milestone C and methodology to provide maximum benefit. A case study identified potential benefits based on a real DoD acquisition program.

(2) What resource requirements exist to initiate a MBSE approach post Milestone C?

The development of an Excel MBSE analysis tool addresses this research question. Based on the challenges that program face in a post Milestone C program, the Excel MBSE analysis tool identifies several questions that the program office should ask. The answers to the questions drive a metric that determine the applicability of MBSE to mitigate the associated challenge. Once the Excel MBSE analysis tool identifies a score for the challenges, the program office needs to provide a cost for each model as well as the cost risk of the program. The Excel MBSE analysis tool then provides a recommendation to implement or to not implement MBSE.

(3) What are the major decisions that the program office needs to make post Milestone C?

The Excel MBSE analysis tool addresses five major decisions identified in the thesis that the program office must make. Should MBSE be implemented to mitigate:

- sub-optimal production planning risks,
- sub-optimal production processes risks,
- sub-optimal sustainment planning risks,
- sub-optimal sustainment processes risks, and
- sustainment risks during the production phase?

The MBSE tool provides a recommendation to the first four questions with an estimated ROI. The answer to the last question should always be yes, if the Excel MBSE analysis tool recommends implementing MBSE.

(4) What challenges exist with implementing MBSE post Milestone C?

Chapter III addresses the challenges. The challenges associated with implementing MBSE post Milestone C are related to cost, schedule, and a lack of understanding of MBSE. The implementation of MBSE has an additional cost that is likely not planned in the budget. Programs are often reluctant to increase cost based on the assumption that it will reduce future risk. The implementation of MBSE takes time. There is no time in the schedule to stop the program to implement MBSE. The program will continue as the program office implements MBSE. If the production is not long enough, the ROI will be negative. The Excel MBSE analysis tool attempts to provide a rationale for the rationale of using MBSE tools to mitigate the post Milestone C challenges.

(5) What are the major decisions that the program office needs to make post Milestone C?

This thesis answers this research question in terms of cost. The cost model within the Excel MBSE analysis tool identifies a rough estimate for the model development. Each program is unique and there is no universal answer. The cost model does provide the program office the ability to identify a more accurate cost associated with their program needs. Outside of cost, there are too many variables and the answer is program specific as to what resources the program office requires for their program. Developing a cost model that is applicable to all programs should be a topic for future research.

B. RECOMMENDATIONS FOR FUTURE RESEARCH

The Excel MBSE analysis tool utilized a simple model in Excel to demonstrate that a model could provide a recommendation on whether to implement MBSE. The questions that the research identified are not meant to account for all program needs, but focuses towards general program use. Further research should be performed to

- Identify a more robust set of questions. This likely requires collecting data from various experts in the field.
- Provide a more comprehensive cost model that utilizes the technical complexity of the program as the cost model utilized cost estimates based on one person’s experience.
- Implement the more comprehensive questions and cost model into a more user-friendly model outside of Excel. A computer software package to incorporate the model and provide a user interface where the questions are tailored to the program. This way the Excel MBSE analysis tool is easier to use.
- Provide a cost model applicable to all program needs.
- Implement MBSE for test purposes post Milestone C and for disposal purposes as it was not considered during this research to complete the research gap.

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