A Proposed Approach to Assess Supply Chain Risks to Meet the New Challenges in the Defense Industry

by

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ABSTRACT

Department of Defense (DoD) had doubled its planned investments in new weapon systems from about $700 billion in 2001 to nearly $1.4 trillion in 2006. Despite the technical superiority of its weapon systems, DoD's weapon systems acquisition process had been plagued with cost increases, schedule delays, and performance shortfalls[1].

To address the maturity gaps, DoD mandated in 2008 that all prime contractors (including Raytheon) for new US government funded defense programs to evaluate/document technology and manufacturing readiness levels (T/MRL) of their supply base. There are 10 manufacturing & 9 technology readiness levels and specific levels need to be met for certain program milestones. DoD has released a set of questionnaires (Deskbooks), designed to evaluate the maturity levels of a supplier in areas such as engineering design, operation, manufacturing, and facility etc.

The goal of this thesis is to develop an assessment method, using the Deskbooks as a reference, to address the core issues in the defense acquisition process. The thesis will also take a deep dive into Raytheon's supply chain management philosophy and analyze how Raytheon's strategic sourcing initiatives align with the new challenges in the defense industry.

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[1] Government Accountability Office. GAO-06-391 Defense Acquisitions: Assessments of Selected Major Weapon Programs. March 2006

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TABLE OF CONTENTS

LIST OF FIGURES

1 INTRODUCTION

The risks to profit margins of major defense contractors, such as Raytheon and Lockheed Martin, had often been negated by cost-plus contracts used by the Department of Defense (DoD). On development programs, CPFF (cost plus fixed fee, one type of cost-plus contracts) helped to reduce the risks to the companies' margins (although there were still significant risks to the companies' reputation and extension of the project if overruns became common place). However, the cost-plus model had placed a heavy burden on the defense budgets and the DoD.

The DoD had doubled its planned investments in new weapon systems from about $700 billion in 2001 to nearly $1.4 trillion in 2006[2]. While some of this increase was due to the increased spending on the war against terror, deficiencies in DoD weapon acquisition process were the main contributors. In a detailed report (GAO-06-391), the Government Accountability Office (GAO) conducted an independent assessment on 52 weapon systems in 2006 and this study revealed gaps in technology, design, and production readiness. Some of the financial and schedule impacts are highlighted below:

Figure 1 Total Projected Cost of DoD's Top Five Programs in fiscal Years 2001 and 2006[3]

Billions of constant 2006 dollars

2001		2006	
Program	**Cost**	**Program**	**Cost**
F-22A Raptor aircraft	$65.0	Joint Strike Fighter aircraft	$206.3
DDG-51 class destroyer ship	$64.4	Future Combat Systems	$127.5
Virginia class submarine	$62.1	Virginia class submarine	$80.4
C-17 Globemaster airlift aircraft	$51.1	DDG-51 class destroyer ship	$70.4
F/A-18E/F Super Hornet fighter aircraft	$48.2	F-22A Raptor aircraft	$65.4
Total	**$290.8**	**Total**	**$550.0**

Figure 2 Cost and cycle time growth for 26 weapon systems[4]

Billions of constant 2006 dollars

	First full estimate	Latest estimate	Percentage change
Total cost	$547.7	$627.4	14.6
RDT&E cost	$120.4	$164.9	37.0
Weighted average acquisition cycle time[a]	154.5 months	180.2 months	16.7

[2] Government Accountability Office. GAO-06-391 Defense Acquisitions: Assessments of Selected Major Weapon Programs. March 2006

[3] Government Accountability Office. GAO-06-391 Defense Acquisitions: Assessments of Selected Major Weapon Programs, Page 5. March 2006

[4] Government Accountability Office. GAO-06-391 Defense Acquisitions: Assessments of Selected Major Weapon Programs, Page 6. March 2006

The consequences of cost and cycle-time growth are particularly crucial because it reduced the buying power of the defense dollars[5]. This is not only a serious problem from a pure financial and budgetary concern but also a potential problem area for national security. In this GAO report, six particular programs were highlighted and the reduction in the defense buying power is highlighted below:

Figure 3 Examples of DoD programs with reduced buying power[6]

Program		Initial estimate	Initial quantity	Latest estimate	Latest quantity	Percent of unit cost increase
Joint Strike Fighter		$189. 8 billion	2,866 aircraft	$206.3 billion	2,458 aircraft	26.7
Future Combat Systems		$82.6 billion	15 systems	$127.5 billion	15 systems	54.4
F-22A Raptor		$81.1 billion	648 aircraft	$65.4 billion	181 aircraft	188.7
Evolved Expendable Launch Vehicle		$15.4 billion	181 vehicles	$28.0 billion	138 vehicles	137.8
Space Based Infrared System High		$4.1 billion	5 satellites	$10.2 billion	3 satellites	315.4
Expeditionary Fighting Vehicle		$8.1 billion	1,025 vehicles	$11.1 billion	1,025 vehicles	35.9

As pointed out in the article from Center for Strategic and International Studies[7], there are several types of cost-plus contracts:

Award-fee contracts ($38B in FY'07) – Tie the contractor fee to the quality of the end product

Incentive fee contracts ($8B in FY'07) – Provide a larger fee for contracts that meet or exceed performance targets such as cost savings

[5] Government Accountability Office. GAO-06-391 Defense Acquisitions: Assessments of Selected Major Weapon Programs. March 2006

[6] Government Accountability Office. GAO-06-391 Defense Acquisitions: Assessments of Selected Major Weapon Programs, Page 9. March 2006

[7] Joachim Hofbauner & Greg Sanders. Defense Industrial Initiatives Current Issue Cost-Plus Contracts.

Fixed-fee contracts ($32B in FY'07) – Entail a pre-negotiated fee for the contractor, providing no incentive for performance or cost savings

Some argue that cost-plus contracts, particularly those with fixed fees, may provide insufficient incentives to reduce cost[8]. This problem only got worse from 2006 and on as seen in an updated GAO report.

Figure 4 Analysis of DoD Major Defense Acquisition Program Portfolios[9]

Fiscal year 2009 dollars

	Fiscal year		
	2003	2007	2008
Portfolio size			
Number of programs	77	95	96
Total planned commitments	$1.2 trillion	$1.6 trillion	$1.6 trillion
Commitments outstanding	$724.2 billion	$875.2 billion	$786.3 billion
Portfolio indicators			
Change to total RDT&E costs from first estimate	37 percent	40 percent	42 percent
Change to total acquisition cost from first estimate	19 percent	26 percent	25 percent
Total acquisition cost growth	$183 billion	$301.3 billion[a]	$296.4 billion
Share of programs with 25 percent increase in program acquisition unit cost growth	41 percent	44 percent	42 percent
Average schedule delay in delivering initial capabilities	18 months	21 months	22 months

As part of the effort to address this issue, DoD had begun a shift from the cost-plus-model to the firm-fix-pricing model. This shift is unavoidable as the topic of defense budget has become a hot political topic. In televised 2008 presidential debates, the candidates attributed one of the causes for the government budget crisis was due to the over-spending of the defense budget based on the cost-plus model[10].

1.1 Project Motivation

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[8] Joachim Hofbauner & Greg Sanders. Defense Industrial Initiatives Current Issue Cost-Plus Contracts.

[9] Government Accountability Office. GAO-09-326 Defense Acquisitions: Assessments of Selected Major Weapon Programs, Page 1. March 2009.

[10] New York Times. The First Presidential Debate between Senator John McCain and Barack Obama in Oxford, Miss. September 26 2008.

Shifting to a firm-fixed pricing model is only a starting point. The other important insight gathered from the GAO reports throughout the years was that mature technologies, stable designs, and production processes in control were characteristics of a successful DoD program[11]. This means all three components must be seamlessly executed in unison. The successful execution of one or a combination of any of the above two will not be sufficient. A mature technology that can't be manufactured is just as damaging to the success of a weapon program as an immature technology in a tightly controlled manufacturing process.

Therefore it is critical to have a way to assess how mature a technology is, how tightly controlled a manufacturing environment is, and most importantly how to transition a technology into production. As Mark Gordon, Director of Defense Programs for the National Center for Advanced Technologies, argued in his presentation dated April 17th 2008, manufacturing is the key to technology transition[12]. The ability to "manufacture a component is not subservient to technology development cycle, but central to it"[13]. He went on to argue that "The capability to produce a technology/material is often not seen as part of technology transition or innovation, and may be ignored by the Science and Technology community. However, it is a core focus in highly competitive commercial markets"[14]. The maturation of technology must be synchronized with the ability to manufacture, support, and test.

This is not to undermine the important of mature technology and design as up to 90% of the total life cycle cost can be locked in even before a program enters into production.

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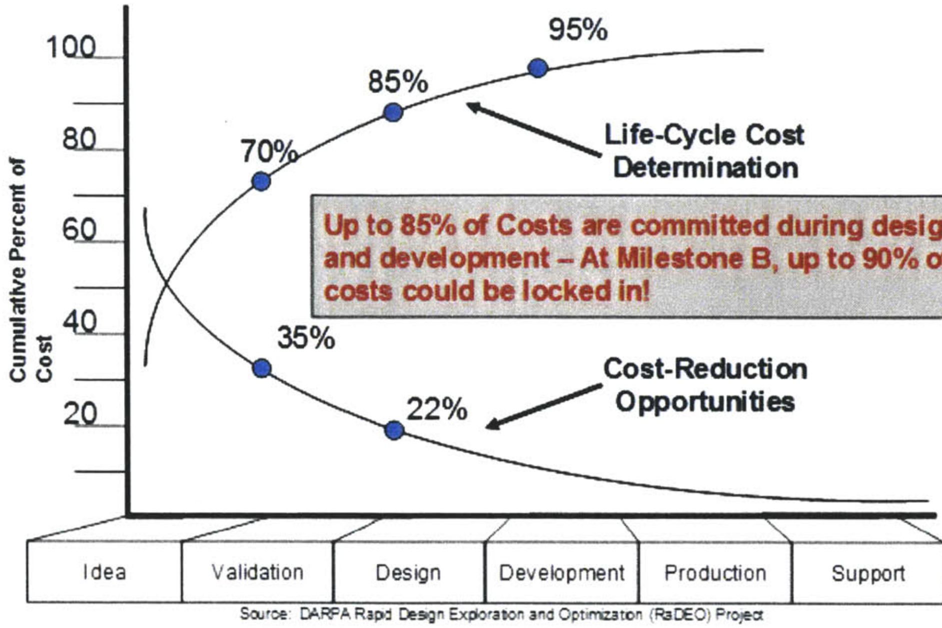
[11] Jim Morgan. Manufacturing Readiness Levels (MRLs) for Multi-Dimensional Assessment of Technology Maturity. May 10th, 2006
[12] Mark Gordon. The Need for Manufacturing Innovation and Readiness. April 17, 2008
[13] Mark Gordon. The Need for Manufacturing Innovation and Readiness, Slide 3. April 17, 2008
[14] Mark Gordon. The Need for Manufacturing Innovation and Readiness, Slide 3. April 17, 2008

Figure 5 Life-Cycle Cost Determination[15]



In Mark Gordon's report, he compared the schedule delays and cost overruns of 62 selected major weapon programs. In addition to the chart below, several additional startling facts were revealed as well:

- Only 16% of programs achieved mature technology at Milestone B (entering system development and demonstration)
- At critical design review, only 44% achieved technology maturity and 27% demonstrated design stability (90% drawings releasable)
- At Milestone C (the start of production), 10% of programs were collecting data on process control (0% in control). 47% reported they have already conducted or planned to conduct a developmental test of a production representative article (i.e. prototype)

[15] Mark Gordon. The Need for Manufacturing Innovation and Readiness, Slide 3. April 17, 2008

Figure 6 Cost & Schedule Comparison of Programs with Mature Vs. Immature Technologies[16]

Based on 62 programs	Technology Status at Beginning of Development	
	Mature	Immature
RDT&E Cost Increase	2.6%	32.3%
Acquisition Unit Cost Increase	<1%	>30%
Average Schedule Delay	1 month	20 months

With this in mind along with the increasing focus and political pressure to address the defense budget issue, John Young, Under Secretary of Defense for Acquisition Technology and Logistics, signed off on the update to DoD 5000.2 Acquisition Reform on December 8th, 2008, requiring manufacturing readiness levels (MRL) and technology readiness levels (TRL) assessments of critical technology elements (CTE) and key manufacturing technologies (KMT) be performed and documented on US government funded defense programs. The assessments shall be executed by prime DoD contractors on their internal processes/technologies as well as their supply base.

With the official release of the *Technology Readiness Assessment Deskbook* in July 2009 and the *Manufacturing Readiness Level Deskbook* in July 2010, MRL and TRL assessments (T/MRA) are now contractual requirements for any defense contracts, for example Raytheon's $214 million dollars preliminary design contracts awarded in February 2011. In addition to contractual requirements, T/MRA will also be used to down-select on further/future contract awards among competing contractors.

In the Deskbook, the different levels of MRLs and TRLs are shown in relations to system milestones and technical reviews (Figure 7). The Deskbooks are essentially comprised of a set of questions designed as a guide to evaluate a supplier's manufacturing and technology maturity levels across various areas such as engineering, production, supply chain, and cost control etc. As shown in

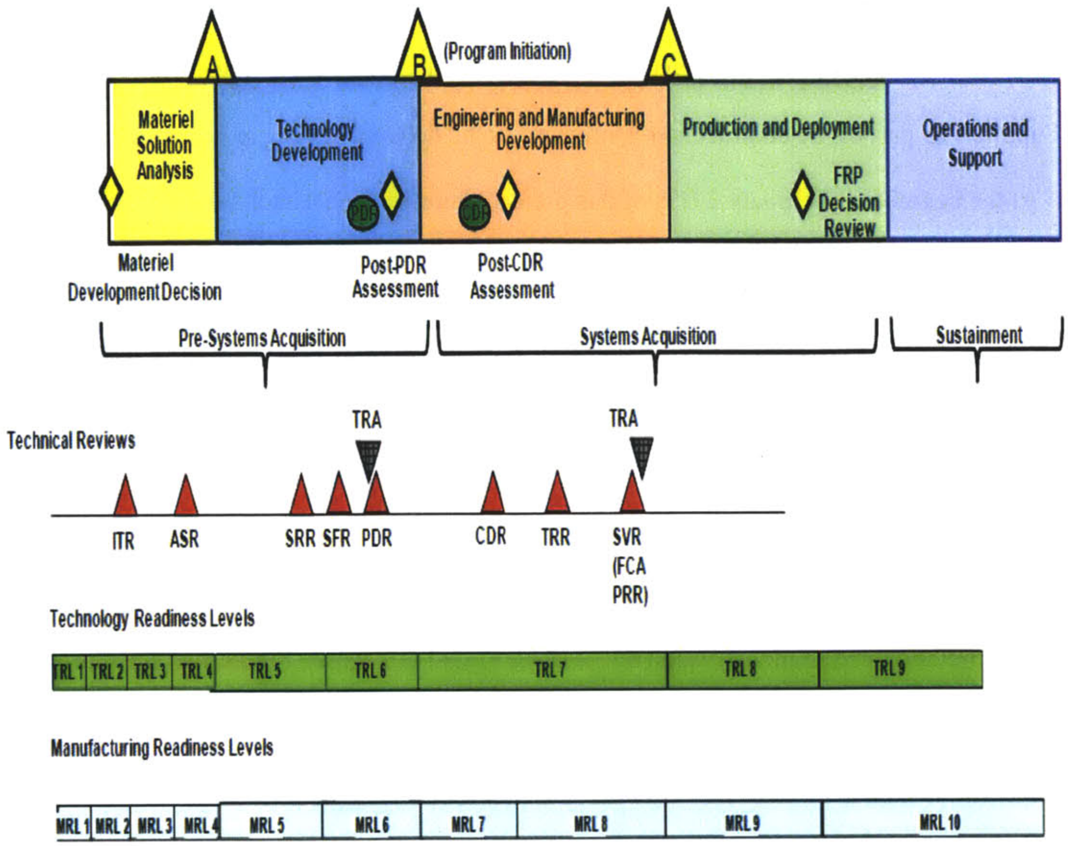
[16] Mark Gordon. The Need for Manufacturing Innovation and Readiness, Slide 5. April 17, 2008

Figure 7, there are 9 and 10 levels for TRA and MRA respectively. As mentioned in the paragraph above, Raytheon will need to **assess, document, report, and achieve** a specified MRL"X" and TRL"X" of several CTEs and KMTs at both the system integrator level (Raytheon) and the supply chain level (1st Tier Supplier) as part of the contractual requirements to be delivered at major program milestone reviews.

At the beginning (February 2011) of this project, there were no established and objective ways to perform this evaluation since the only reference was the MRL and TRL Deskbooks. As a source of competitive advantage, it was critical for Raytheon to take a leading role in an effort to interpret this new requirements from its main customer (U.S. Government & DoD) and to design/implement a process not only as a deliverable to its customer but also as an attempt to shape and guide the direction of T/MRL assessments.

Due to resource constraints and better management of the scope, the project was primarily focused on the interpretation and implementation of the MRL as will this thesis. Furthermore, the project focused on the 1st tier supplier level in order to have a better understanding of technology and manufacturing risks embedded in the supply chain and to formulate a mitigation strategy to address these risks by performing a MRL assessment (MRA).

Figure 7 MRL/TRL Relations to Milestones and Technical Reviews[17]



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[17] OSD Manufacturing Technology Program in collaboration with the joint Service/Industry MRL Working Group. Manufacturing Readiness Level DeskBook, Page 3-2. July 30th, 2010

1.2 Manufacturing Readiness Levels (MRL) Overview

As previously mentioned, there are 10 different levels of MRLs. For each MRL, it establishes expectation s for manufacturing maturity that should result in minimum manufacturing risk for a specific product and build phase (i.e. prototyping, pilot production, Low Rate Initial Production, Full Rate Production, etc.). The matrix below demonstrates the progression in maturity.

Figure 8 MRL Progression

	MRL 4	MRL 5	MRL 6	MRL 7	MRL 8	MRL 9	MRL 10
What has been demonstrated:	Manufacturing Technology	Component Prototype	System Prototype	System Prototype	Pilot Build	LRIP	FRP
What was the Environment:	Lab Environment	Production Relevant Environment	Production Relevant Environment	Production Representative Environment	Production	Production	Production
Preparation is completed for:	Production Relevant Environment	System Prototype, Production Relevant	System Prototype, Production Representative	Pilot Build	LRIP	FRP	Lean Practices Are in Place

There are 9 major areas (Threads) to focus on in order to determine the appropriate MRL: Technology & Industrial Base, Design, Cost & Funds, Materials, Process, Quality, Manufacturing Personnel, Facilities, and Manufacturing Management (Figure 9). Under each thread often there are sub-threads to dive deeper into the particular topic. The detailed breakdown is demonstrated in the Appendix[18] and explains the criteria and requirements in detail for each sub-thread.

With the Appendix as a reference, a questionnaire can be constructed and sent to the targeted supplier(s) for evaluation. By analyzing their responses to the questions, a MRL rating may be generated and assigned to the particular supplier for the specific CTE.

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[18] OSD Manufacturing Technology Program in collaboration with the joint Service/Industry MRL Working Group. Manufacturing Readiness Level DeskBook, Page A-1 to A-17. July 30th, 2010

Figure 9 MRL Sub-Threads Definitions

Thread Description
A . Technology & Industrial Base
Tech Maturity
A.1 Transition to Production
A.2 Manufacturing Technology Development
B . Design
B.1 Producibility Program
B.2 Design Maturity
C . Cost & Funds
C.1 Cost Modeling
C.2 Cost Analysis
C.3 Manufacturing Investment Budget
D. Materials
D.1 Material Maturity
D.2 Material Availability
D.3 Material Supply Chain
D.4 Special Handling
E . Process
E.1 Modeling & Simulation
E.2 Process Maturity
E.3 Yields & Rates
F . Quality
G . Manufacturing Personnel
H. Facilities
H.1 Tooling/STE/SIE
H.2 Facilities
I - Mfg. Mgmt
I.1 Mfg. Planning & Scheduling
I.2 Mfg. Material Planning

1.3 Thesis Overview

In chapter one, the motivation and an overview of MRL have been provided. Chapter two will give a very brief overview of Raytheon Integrated Defense Systems and the Supplier Engineering team that is responsible for carrying out this MRL initiative.

In chapter three, some reviews of past works focusing on supply chain risk/evaluation will be addressed. Some examinations of current supply chain risk assessment methods will also be discussed.

Chapter four will discuss the methodology taken to actually construct the MRA process, what resources were required, what assumptions were made, and what attempts were taken to simplify the process without sacrificing the robustness of the assessment process

In chapter five, the development of metrics will be discussed. The discussion will focus specifically on how the team at Raytheon uses the answers gathered from the suppliers to generate a set of metrics both for reporting externally to the customer and for generating a plan to address the risks associated with the particular supplier internally.

Finally in chapter six, the main points of this thesis will be discussed. Some recommendations for Raytheon will also be addressed on how the MRA process can be improved upon.

2 RAYTHEON COMPANY OVERVIEW

Raytheon Company is the technology and innovation leader specializing in defense, homeland security, and other government markets throughout the world. Raytheon specializes in manufacturing radars and electro-optical sensors (airborne, naval and ground based), satellite sensors, radios and digital communication systems, and missile defense. Company revenue is 2011 was $25B with 71,000 employees worldwide. Raytheon serves customers in over 80 countries. Raytheon's 10-K, filed on February 23rd 2011, indicated 23% of sales were international. This is up from the 20% just over two years ago.

Raytheon operates in six different business segments: Integrated Defense Systems, Intelligence and Information Systems, Missile Systems, Network Centric Systems, Space and Airborne Systems, and Technical Services. The development of the MRA process took place at Raytheon Integrated Defense Systems.

2.1 Raytheon Integrated Defense Systems (IDS)

Headquartered in Tewksbury, Massachusetts, Raytheon Integrated Defense Systems is a leader in global capabilities integration, providing affordable, integrated solutions to a broad international and domestic customer base. IDS leverages its core domain knowledge and capabilities in sensors, command, control and communication (C3), persistent surveillance/intelligence, surveillance and reconnaissance (ISR), effects and mission support, to provide integrated naval, air and missile defense and civil security response solutions. Key customers include the U.S. Navy, Army and Air Force, and the U.S. Missile Defense Agency (MDA), and numerous international customers[19]. The Patriot Air & Missile Defense System for the U.S. Army is one of the well-known products from Raytheon IDS. The three main business segments for Raytheon IDS are Global Integrated Sensors, Integrated Air & Missile Defense,

[19] Raytheon Company. Form 10-K. February 23rd, 2011

and Seapower Capability Systems. As of 2011, Raytheon IDS generated $5B with 13,900 employees worldwide.

2.2 Supplier Engineering Organization

The Supplier Engineering (SE) team is organized under Integrated Supply Chain. The primary function of the team is to act as liaisons between design engineering and Raytheon's supply base. The task of interpreting, designing, and implementing the MRA process fell under the jurisdiction of this department.

2.3 Unique Challenges

The defense industry is driven by engineering and programs while bound by stringent regulatory compliance and has a massive supply base and demanding customers[20].With Pentagon, the world's largest weapons buyer, looking to cut defense expenditures by nearly $500B over the next decade[21], defense contractors such as Raytheon must look to international sales to diversify their revenue portfolio and to mitigate risks. As of 2012, foreign orders account for more than one third of Raytheon's backlog.

While this international expansion plan will give defense contractors such as Raytheon the necessary reserve to weather the federal budget deficit storm, foreign arms sales need to be compliant with ITAR (International Traffic in Arms Regulation). In addition the sales need to be approved by the U.S. Congress, for example the 2011 sales of Patriot Missiles to Taiwan worth over $1B.

In the context of MRL assessment, international sales present another challenge. Often as contractors such Raytheon and Lockheed Martin bid for international contracts, the foreign government would request a certain portion of the contracts go to local manufacturers as was the case with Raytheon's Patriot Missile deal with Turkey[22]. Since Raytheon must work with pre-selected Turkish supplier, the

[20] Gartner. Supply Chain Transformation in the Manufacturing Sector: Raytheon Company. February 24th, 2011
[21] Karen Jacobs and Andrea Shalal-Esa. U.S. Arms Makers See Flat Sales in Face of Cuts. Reuters January 26th, 2012
[22] Hurriyet Daily News. US Raytheon announces missile project worth nearly $4B for Turkey. May 26th, 2011

MRL assessment is now more of a risk mitigation method versus a contractual requirement. Raytheon now must face risks in technology maturity, transition to production, production readiness, cost, and most of important of all, system integration.

In another scenario, Raytheon often is exposed to a sole-source risk because a specific supplier might have a proprietary technology (CTE) that is crucial to the particular weapon system. The CTE might have been requested by the customer or identified by Raytheon engineering. The technology might be mature enough but not to the stage where it can be manufactured with scale and efficiency. In this case the MRL assessment is even more critical as it is now both a contractual requirement to the customer and a basis to form a risk mitigation plan in order for the weapon program to succeed.

2.4 Supply Chain as a Competitive Advantage

With a supply chain as complex as one that Raytheon has, it is critical for Raytheon to manage its supply chain diligently. Excellence in supply chain is not only a prerequisite to ensure program/mission success but also a financial incentive as between 65 and 70[23] cents of every dollar that Raytheon brings in of its $25B revenue is in the supply chain. With an efficient supply chain, Raytheon can obviously be more competitive as it is able to provide better solutions to customers and a level of service that customers expect.

Efficiency in supply chain does not equate to lowest cost. Cost is important so is having best value and providing speed. To achieve this, Raytheon started to rationalize its supply chain. Raytheon set out to reduce the number of suppliers to an optimal level where it is now possible to "sit with them, share with them a business plan, align with their business plan, and have discussions around their capacity and their capability"[24]. Raytheon's goal is to pull the suppliers into the design phase early on to avoid problems later. By reducing the number of the suppliers, Raytheon doesn't have to deal with thousands of suppliers. The suppliers are chosen "purposefully, based on their technology, their capability and their alignment to

[23] SupplyChainBrain. How Raytheon Transformed Its Supply Chain. October 20th, 2011
[24] SupplyChainBrain. How Raytheon Transformed Its Supply Chain. October 20th, 2011

Raytheon's business model"[25]. With this, Raytheon seeks to partner with the suppliers not just for today's need but for tomorrow's as well.

The criticality of supply chain management is echoed by a report published by Apogee Consulting where it was pointed out that "Supply chain management may well be the key to program execution success"[26]. The article did an analysis on two recent DoD programs where Raytheon was responsible for one and a competing defense contractor was responsible for the other. Raytheon's program was successful because "Raytheon invested in its supply chain and worked with its suppliers in a partnership to develop common processes and align approaches"[27]. In other words, Raytheon took the initiatives and the responsibilities to share the risks with the suppliers.

On the other hand, the other defense contractor encountered many problems because it transferred program quality and execution risks to the suppliers. It had the mentality that when the subcontract manager, buyer, or procurement manager said cost/schedule/quality/performance risks have been pushed downward in the supply chain, the risks were mitigated.

Digging a little deeper into Raytheon's strategic supply chain initiatives, we can see that Raytheon adopted common sourcing practices for a small number of commodities. The idea behind this was to provide engineers in selected programs with a common language when purchasing materials across the company[28]. With the key suppliers chosen, Raytheon can "share its technology roadmaps with them so all parties are aligned on systems and business plans. Raytheon will provide suppliers with extended inventory visibility by allowing them access to its material requirements planning system. In turn, Raytheon will gain improved visibility to supplier risk issues so it can proactively mitigate potential snags"[29].

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[25] SupplyChainBrain. How Raytheon Transformed Its Supply Chain. October 20th, 2011
[26] Apogee Consulting. Raytheon Builds on Supply Chain Management Success. April 4th, 2011
[27] Apogee Consulting. Raytheon Builds on Supply Chain Management Success. April 4th, 2011
[28] Industry Week. Raytheon Shores Up Its Supply Chain. March 16th, 2011
[29] Industry Week. Raytheon Shores Up Its Supply Chain. March 16th, 2011

How can other companies in the defense industry learn from Raytheon? Raytheon's supply chain leadership team has identified six initiatives from which other manufacturers can benchmark[30]: supply chain span of control, cross-function alignment, performance management, sourcing and procurement organization redesign, integration with program acquisition and engineering, and finally talent management.

With a supply chain management philosophy such as Raytheon's, Raytheon does not see customer's MRL requirement as a hindrance. Rather, Raytheon sees this as an opportunity to differentiate itself from competition, showcase its unique value proposition to the customer base, and take a leadership role in re-shaping supply chain management to better meet the challenges in the new defense acquisition environment.

[30] Gartner. Supply Chain Transformation in the Manufacturing Sector: Raytheon Company. February 24th, 2011

3 LITERATURE REVIEW

In this chapter, literature reviews will be performed on several topics. The reviews will focus on past researches on trust in supply chain, supplier evaluation, applications of MRL, and current/published methods for assessing MRLs.

3.1 Trust in Supply Chain

In order for Raytheon to carry out the strategic supply chain initiatives discussed in the previous chapter, it is critical to build trust but it is not easy to do so. As argued in thesis of Andrew Corum[31], "although the engineering functions may involve a great deal of collaboration in manufacturing and product design, this is shadowed by the governance functions who, in selecting and writing contracts with suppliers, are distrustful and even adversarial"[32]. This is very true in the defense and aerospace industry where many of the risks are simply passed down to the first-tier suppliers and blame games ensue when things do go wrong. Because of this adversarial nature, how would suppliers view Raytheon as Raytheon approaches them with this MRL initiative?

As Corum mentioned in his thesis, the nature of the supplier-buyer tractions will not be as adversarial if the transaction is not a one-time deal. If the supplier can understand the buyer's long-term interest, then the supplier may trust the buyer not to yield to short-run temptations[33]. This is exactly the approach Raytheon is taking with its key suppliers. With the number of suppliers reduced, Raytheon can now focus on the key suppliers to build a relation, one where mutual understanding and risk sharing are the main themes.

And this is how Raytheon intends to market the MRL assessment with key suppliers. The message being sent out is loud and clear that the MRL assessment is a way to help both Raytheon and the supplier and it is not a one-time purchase. By demonstrating the competency in MRL assessment, Raytheon can be

[31] Andrew Corum. Design and Development of a Supplier Evaluation Process. May 8th, 2009
[32] Andrew Corum. Design and Development of a Supplier Evaluation Process, Page 19. May 8th, 2009
[33] Andrew Corum. Design and Development of a Supplier Evaluation Process. May 8th, 2009

more competitive in bidding for government contracts. In return, as suppliers are being put through the MRL assessments by Raytheon, the suppliers get an in-depth look at how Raytheon's internal processes work, how Raytheon's technology roadmaps align with the ones of the suppliers, and how the suppliers can improve their performance not only on the current program but also on processes across the organization to make themselves more competitive and profitable.

3.2 Supplier Evaluation

Companies such as Dun & Bradstreet and ThomasNet provide some good overviews of domestic suppliers. Unfortunately this information is of little use in the context of the MRL assessments. Raytheon as a whole keeps Dun & Bradstreet data on all of its suppliers as an overview of its supply base with regards to finance and risk management.

As Corum further pointed out in his work, there is no one right way to evaluate a supplier. In fact, "there are virtually infinite possibilities in how to evaluate a supplier"[34]. It is often not wise to focus on a single aspect of a supplier but too broad of a scope will also prove to be cumbersome and inefficient. In Corum's work, the assessment focused on experience, EHS (environment, health, and safety), logistic & delivery, quality, operations, communication, financial records and technical competence[35].

In a similar work by Steven Croce, his risk assessment focused on[36]:

- **Design Risk**
    - **Design Maturity**
    - **Knowledge Transfer**
        - **Language Barriers**
        - **CAD Data Compatibility**
- **Financial Risk**
    - **Supplier financial Standing**
        - **Financial Ratios**
        - **Debt Rating**
        - **Payables**
    - **Exchange Rates**

[34] Andrew Corum. Design and Development of a Supplier Evaluation Process, Page 29. May 8th, 2009
[35] Andrew Corum. Design and Development of a Supplier Evaluation Process. May 8th, 2009
[36] Steven Croce. Risk Management Framework for Evaluating Suppliers. May 7th, 2007

        - **Labor Rates**
        - **Proposed Price**
            - **Cost Audits**
            - **Comparisons of Other Offers**
- **Operation Risk**
    - **Material Purchasing**
    - **Quality Standards**
    - **Shipping Mechanism**
    - **Capabilities**
        - **Capacity**
        - **Lead Time**
        - **Previously Delivered Metrics**
- **Business Risk**
    - **Geopolitical Risks**
    - **Worker Risks**
        - **Unions**
        - **Strikes**
    - **Demand Stability**
    - **Uncategorized Ratings from Online Database**
    - **Licensing**

Looking at some of these past works on supplier evaluating, it becomes evident that MRL assessment covers a large portion of these areas. MRL focuses on determining what the current state of the supplier is, what the desired state of the supplier is, and most importantly what needs to be done, with both Raytheon and the supplier bearing responsibilities, in order for the supplier to get to the desired state. With that in mind, the only topics the MRL does not cover in the two above studies are experience, communication, financial records/standings, geopolitical risks, and licensing. However, Raytheon already has established processes in place that address most of the issues above, therefore the MRL assessment dovetails into Raytheon's overall supplier risk management philosophy quite nicely.

The other issue that often arises from supplier evaluation is consistency. As Corum pointed out, "the best practice for the question and response format was determined to be a direct question that has pre-defined specific and objective responses. By phrasing questions in this manner and restricting the responses to a pre-defined answer, the results of the evaluation would be consistent both across suppliers as well as the evaluators"[37]. In the next chapter, details will be given on how the pre-determined answers were created and how objectivity and consistency were achieved.

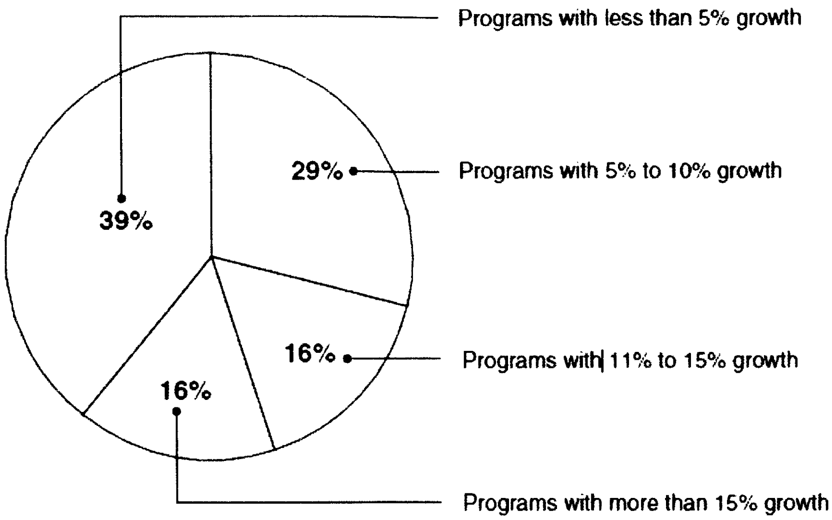
3.3 Applications of MRL

Although it is not until recently that MRL became a requirement, the concept has been around since 2005 when it was adopted by the DoD for usage. MRLs were developed by a joint DoD/industry working group under the sponsorship of the Joint Defense Manufacturing Technology Panel (JDMTP)[38]. The intent was to provide a common metric and vocabulary for assessing and discussing manufacturing maturity, risk, and readiness.

The GAO has argued that the MRL is the best practice for DoD program acquisition outcomes[39] but at the same time the GAO has continuously noted inconsistent application across DoD components[40]. In the report GAO-10-439, the argument for adopting MRLs for best practice can be clear illustrated in Figure 10. If MRL assessments can be performed consistently and accurately, the cost overrun that happens after a production decision should be minimized.

[37] Andrew Corum. Design and Development of a Supplier Evaluation Process, Page 31. May 8th, 2009
[38] Wikipedia. Manufacturing Readiness Level. January 14th, 2012
[39] Government Accountability Office. GAO-02-701 Capturing Design and Manufacturing Knowledge Early Improved Acquisition Outcomes. July 2002
[40] Government Accountability Office. GAO-10-439 DoD Can Achieve Better Outcomes by Standardizing the Way Manufacturing Risks Are Managed. April 2010

Figure 10 Distribution of Average Procurement Unit-Cost Growth after a Production Decision for Ma on for Major Defense Acquisition Programs (For All Major Defense Acquisition Programs Entering Production in Fiscal Year 2000 or Later)[41]



Even before the official release of the MRL Deskbook in 2010, several firms had started applying the MRL frameworks/principles in their programs. GE Healthcare and Honeywell were two such companies.

Although GE Healthcare did not explicitly used MRL framework for the development of its Gemstone Scintillator[42], the product underwent years in laboratory development on a small scale until GE was convinced that this technology was ready to enter into the production phase. In order for the Gemstone Scintillator to work, a mineral composite used for optical component was needed. GE tested thousands of alternatives to find what could meet the technical requirements and be produced in the quantities needed. Once the material was tested and identified, GE began to determine its suppliers and what equipment was needed. GE built a pilot plant to produce the material and the scintillator 2 years before the scintillator entered the firm's gated process[43].

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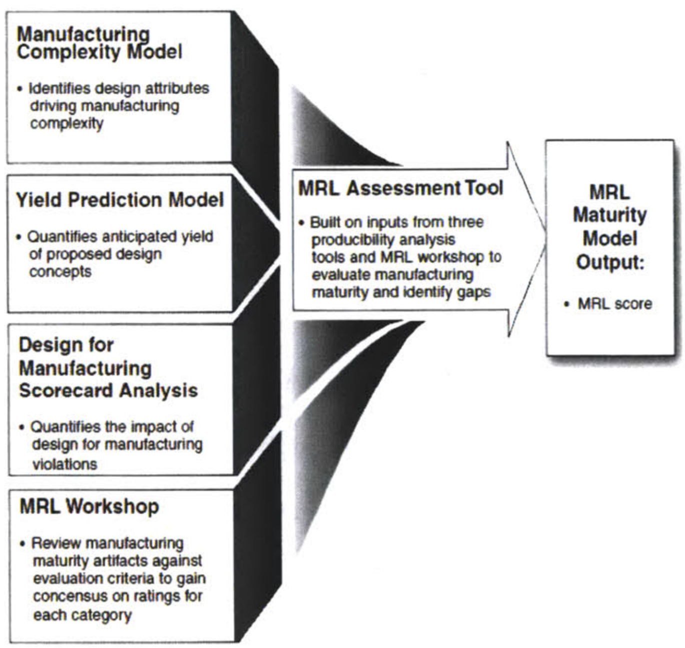
[41] Government Accountability Office. GAO-10-439 DoD Can Achieve Better Outcomes by Standardizing the Way Manufacturing Risks Are Managed, Page 11. April 2010

[42] Government Accountability Office. GAO-10-439 DoD Can Achieve Better Outcomes by Standardizing the Way Manufacturing Risks Are Managed. April 2010

[43] Government Accountability Office. GAO-10-439 DoD Can Achieve Better Outcomes by Standardizing the Way Manufacturing Risks Are Managed. April 2010

The MRL case for Honeywell is more conventional. In 2005, Honeywell determined that they needed analytical tools and models to support evaluations of manufacturing and risk throughout the product-development life cycle[44]. After performing some literature search, Honeywell engineers found DoD's MRLs and they realized this can provide the type of metric needed for a quantitative assessment. Honeywell modified the criteria from the MRL to meet its needs. Honeywell's MRL Maturity Model assessment tool is comprised of three main components: Manufacturing Complexity Model, Yield Prediction Model, and Design for Manufacturing Scorecard Analysis. The output of the tool is an MRL assessment score that can identify gaps and risks. Honeywell's MRL assessment model can be illustrated in the below figure:

Figure 11 Honeywell's MRL Assessment Model[45]



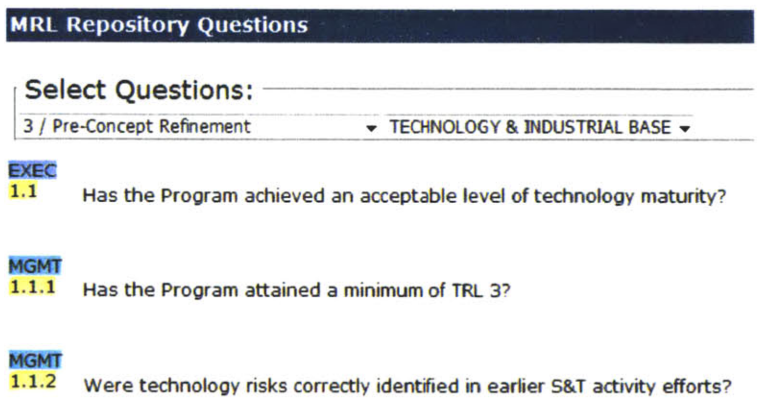
[44] Government Accountability Office. GAO-10-439 DoD Can Achieve Better Outcomes by Standardizing the Way Manufacturing Risks Are Managed. April 2010

[45] Government Accountability Office. GAO-10-439 DoD Can Achieve Better Outcomes by Standardizing the Way Manufacturing Risks Are Managed, Page 30. April 2010

3.4 Current/Published MRL Assessment Methods

As the project at Raytheon was underway, consideration was given on whether currently available templates should be used in place of recreating a brand new tool at Raytheon. One such tool was the MRL Assist Tool Beta 1.3 from the BMP (best manufacturing practice) website[46]. The Beta 1.3 is a web-based tool with input options such as below:

Figure 12 MRL Assist Beta[47]

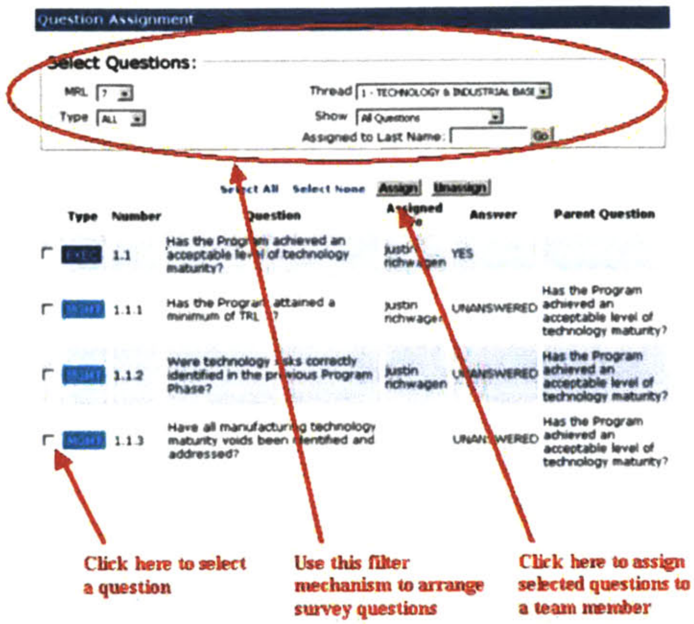


Based on the MRL criteria (MRL1-10) and threads (1 out of 9) desired, a list of questions will be automatically generated. An example of questions and answers is illustrated below:

[46] https://www.mrlassist.bmpcoe.org

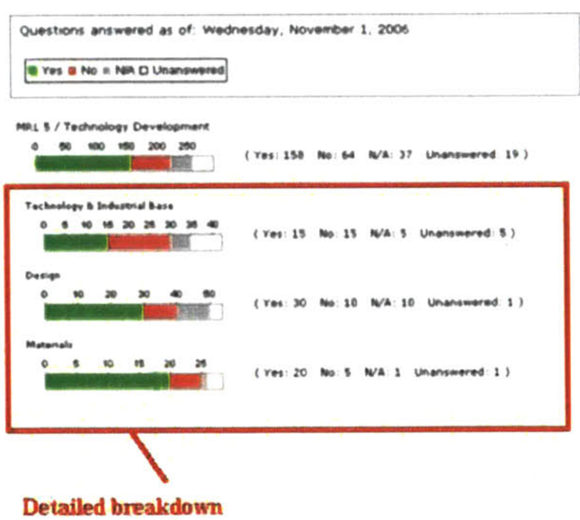
[47] Best Manufacturing Practices/Center of Excellence. MRL Assist Tool User Manual (Version 1.1). February 2007

Figure 13 Examples of MRL Assist Beta Questions/Answers[48]



As the suppliers fill out the questionnaire, program status and scores will be calculated and presented:

Figure 14 Sample Scorecard[49]

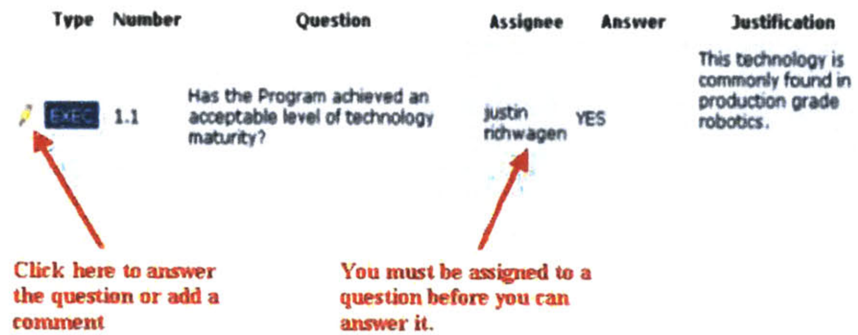


While tools like these seem like good candidates for Raytheon to adopt and use, there were some factors that drove Raytheon toward developing its own version of the MRL assessment. First, the

[48] Best Manufacturing Practices/Center of Excellence. MRL Assist Tool User Manual (Version 1.1). February 2007
[49] Best Manufacturing Practices/Center of Excellence. MRL Assist Tool User Manual (Version 1.1). February 2007

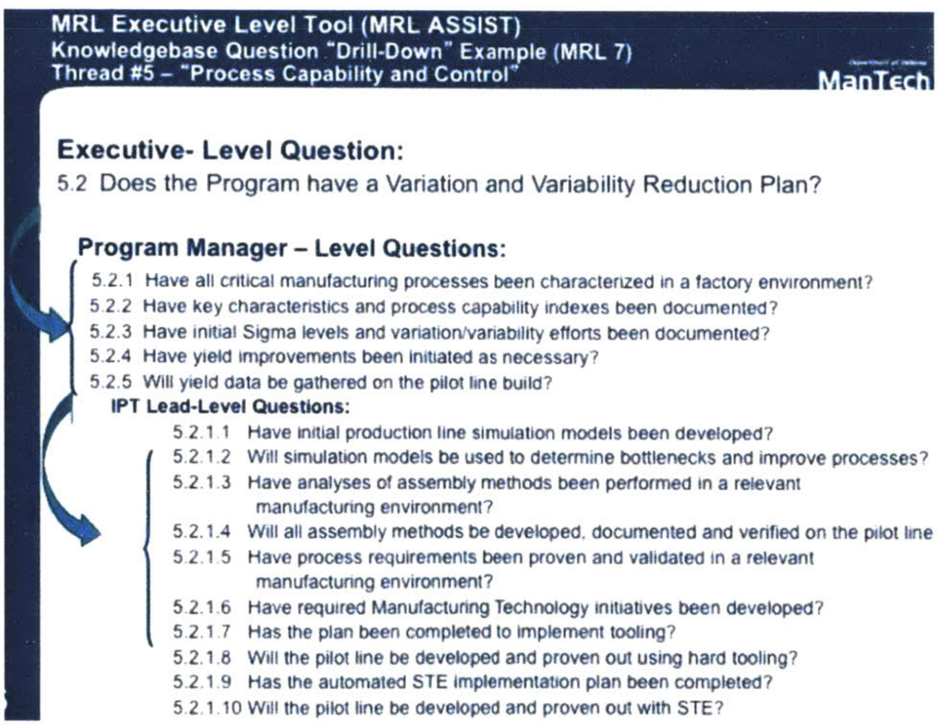
questionnaire format is simply too long and cumbersome. Looking at the example from Figure 14 above, for a MRL5 assessment, there are almost 270 questions to be answered in a YES/NO fashion. For each question answered, justification must be entered as below:

Figure 15 Example of Answers for MRL Assist Beta[50]



Here is another example of the type of questions being asked in the process thread.

Figure 16 Samples of Process-Related Questions[51]



[50] Best Manufacturing Practices/Center of Excellence. MRL Assist Tool User Manual (Version 1.1). February 2007
[51] Best Manufacturing Practices/Center of Excellence. MRL Assist Tool User Manual (Version 1.1). February 2007

Although from a robustness and contractual standpoint this format works, Raytheon did not believe it was the best way to approach suppliers because an audit like this will most likely require suppliers to devote significant amount of man hours to comply, thus disrupting their daily business operations.

The second reason was the scoring algorithm. From Figure 14, it can be seen that scoring is accomplished by simply counting up the number of YESs/NOs and a bar graph is shown as percentage to completion. With scoring like these, each question is weighted equally but in fact it should not be. A good supplier should not be penalized for answering NO on a question that is not relevant. Conversely, a bad supplier might get good scoring because of it answering many YESs on irrelevant questions.

Although Raytheon went ahead and developed its own version of the MRL tool, tools like the MRL Assist Beta provided the team with good insights and great foundations to build upon.

4 ASSESSMENT TOOL DEVELOPMENT

In this chapter, the development of the Raytheon MRL tool will be discussed. While the methodology and the approach taken will be described in detail, it is of the upmost importance to protect proprietary information of Raytheon. Therefore a lot of the data presented will be altered and screenshots will be masked as appropriately.

One of the biggest challenges throughout the project was to find the optimal point between assessment robustness and speed. There are schools of thoughts that insist on leaving no stones unturned but as a result supplier cooperation would be low. Even if the suppliers were forced to comply with Raytheon's request as a contractual agreement, the quality of the assessment at the end would still be affected and Raytheon's philosophy of working with the suppliers and sharing risks mutually would not be realized. Also it was important for Raytheon to show the suppliers that the assessment is really an attempt to help the suppliers to grow and to further develop their own internal processes to better meet the challenges of tomorrow.

4.1 Forming a Comprehensive Data Set

The MRL Deskbook gave the team a great starting point on the kind of questions that need to be answered at each level of the manufacturing maturity. However, Raytheon believed that a thorough assessment will cover beyond what the Deskbook has described in the MRL Maturation Matrix[52].

With this goal in mind, several additional documents were pulled in along with the original MRL Deskbook. Since the MRL assessments have been around since 2005, Raytheon has had to perform assessments on not only internal processes but also certain suppliers to meet program requirements from the Air Force and the Navy. Digging deeper into the questions from the additional documents, it was

[52] See Appendix

revealed that the additional questions are very similar not only in the ways they were asked but also the way the questions progressed as the levels increased.

Complied by the author and another employee from the Supplier Engineering team, a total of 2,500+ questions were absorbed into Raytheon's MRL tool across all 10 MRL levels and within each level the 9 main threads. With the assistance of a senior engineering director, this list was reduced to 1,300+ questions. Great care was taken to identify duplicity across all the questions and if two or more questions are worded similarly, then the question originated from the DoD Deskbook was chosen over the other questions. The chart below illustrates how the questions are populated across the different levels.

Figure 17 Summary of MRL Questions

	DoD	Non-DoD	Total
MRL 1	10	0	10
MRL 2	23	0	23
MRL 3	42	0	42
MRL 4	55	97	152
MRL 5	68	104	172
MRL 6	70	129	199
MRL 7	71	121	192
MRL 8	76	253	329
MRL 9	67	137	204
MRL 10	53	2	55
TOTAL	535	843	1378

With the comprehensive 1,300+ question, this will serve as the foundation as Raytheon's MRL assessment tool. A question arose at this point whether if this was the tool to release to the suppliers to start the assessment programs. However releasing this tool would not have been any different than some of the outside tools that were evaluated with the exception that some of the questions were originated from Raytheon.

4.2 Artifact-Based Approach

One insight gained as the number of the questions was being reduced was that there were primarily two types of questions. The first type of questions only appeared on certain level and the second type of questions appeared throughout a range of levels (for example from level 4 to 6) but was asked differently. Below are some examples:

"Have producibility and manufacturing assessments of key technologies and components been initiated as appropriate?"

This question above is asked in thread B (Design) in MRL5. There are no similar questions asked again in the question bank.

"Have production lines to be modeled been identified?"

"Have production lines been modeled for pilot?"

These two questions above, one appeared in MRL5 and one appeared in MRL6, are treated as type 2. Further insights were revealed that having certain artifacts, processes/documents, in place can adequately give the question the answer of YES. In the first question, an artifact that defines and reviews a supplier's operational capability can answer the question. Therefore, if a supplier is being evaluated for MRL5 and this operation capability artifact is deemed to be mature for the level required, then the question can receive a rating of YES. Since this question only appeared on MRL5, if an assessment was targeted for MRL6, then this artifact will not be required nor will the question be asked.

For the two questions on production line modeling, a common artifact such as value stream mapping can adequately answer the questions. Since these questions appeared on MRL5 and MRL6, an artifact similar to value stream mapping will be required for review for either a MRL5 or MRL6 assessment.

Furthermore, some common artifacts can be used to answer multiple questions across multiple threads and levels. This observation essentially formed the basis for Raytheon's MRL tool. Instead of asking questions that require YES/NO answers, the suppliers will be asked to present various artifacts to demonstrate proven capabilities across various business, engineering, and operation areas. Here are some additional processes/artifacts generally accepted across different industries: EVMS (cost), BOM Analysis (material), Capacity Plan (material), Engineering-Change-Notices Processes (process), Poka-Yoke (process), Non-Conforming Material Policy (quality), and Master Schedule (manufacturing management), etc.

For each artifact reviewed, a numerical score (1-10) will be given. The numbers represent how mature the artifact is according to the MRL Matrix[53]. The supplier will first self-evaluate but the scores will be verified by Raytheon audit team on site. This scale provides objective assessment and common language to be used across all users (Raytheon and suppliers). The maturation of these artifacts will essentially form the basis for a risk mitigation plan that will show the path for a supplier to go from the current state to desired state. It is through the collaborated effort between Raytheon and the suppliers that the risks and responsibilities will be shared.

With over 1,300 questions, a focus group approach was taken. There are diverse talents and experiences across the members of the Supplier Engineering team. Eight members were selected and paired up into four teams based on their expertise and knowledge. Each team was responsible for two threads (one team was responsible for three threads) and for each question the team will propose an artifact that will best answer a particular question.

At the end of this effort, a list of 250+ artifacts was created that would address all the questions that were absorbed into the MRL question bank. It was also decided the tool be Excel-based for ease of transmitting between Raytheon and the suppliers as well as across multiple divisions within Raytheon.

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[53] See Appendix

4.3 Supplier Engagement

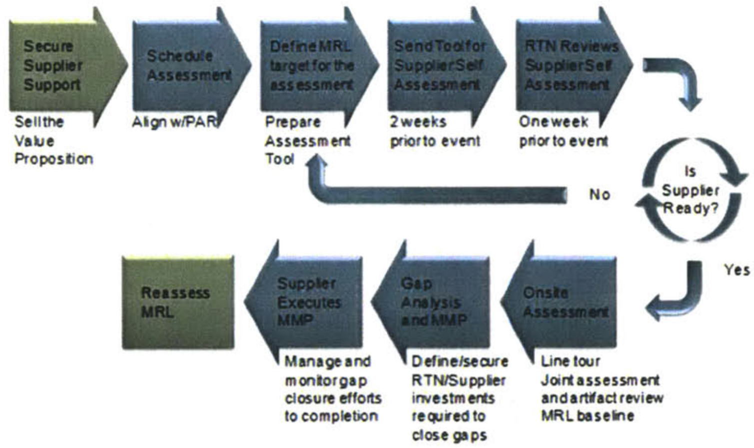
One issue with the current artifact list is that the artifacts were terms that were familiar to Raytheon. As the team releases the tool into the field, how would the suppliers react to the terminologies used? It was decided to release the tool to a supplier who will supply a critical component (that has been identified as a CTE) to a one of Raytheon IDS's radar programs.

There were two main feedbacks Raytheon was particularly interested in. First, will suppliers be familiar with the artifacts Raytheon has identified? If the supplier has an artifact that is similar in nature as the one that has been required, can the supplier submit this artifact instead? Also are the artifacts commonly used by the suppliers for not only program specific purposes but also normal company business operation?

Second, Raytheon was interested in how the supplier deemed the time required to self-evaluate itself and fill out the form. A team from Raytheon was dispatched to the supplier and worked with the supplier management staff to run through the entire list of artifacts and the progression of the maturity expected throughout the entire product lifecycle. At the end of two days, the first version of the MRL assessment tool was fully filled out.

Another invaluable insight gained was how Raytheon should work with the suppliers in order to minimize the time required to do this assessment while achieving the maximum coverage required by the assessment. This flowchart below will demonstrate an ideal MRL assessment effort between Raytheon and its suppliers.

Figure 18 MRL Assessment Flowchart

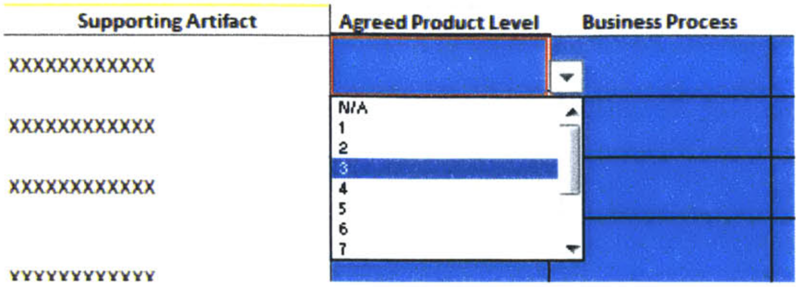


4.4 Method of Data Gathering

In this section, explanation will be given on how data is gathered from suppliers. As mentioned in the previous section, the score for reach artifact is from a scale of 1 to 10. However, there is additional information which the suppliers will need to fill out to be also verified by Raytheon.

For each artifact, a numerical score must be given on two levels: agreed product level and business process. This is essential because Raytheon wants visibilities on the supplier for its current state and its potential for reaching the desired state. For example, on a given program if the value mapping stream artifact is graded to be MRL6 when the desired level is MRL8, then there is a gap. The supplier is more likely to close on this gap if value stream mapping is a business process that the supplier is already engaged in. In this case, the supplier will receive a score of 10, for example, for company-level business process rating. If the supplier does not currently employ value stream mapping or its current value stream mapping process leaves a lot to be desired, then the supplier will receive a score of 8 or below for company-level process rating. When this happens, this gives Raytheon the intuition that it will be less likely for the supplier to mature this artifact to the desired state than it would have been if the supplier already engages in value stream mapping. The altered screen shot below demonstrates how the data would be entered:

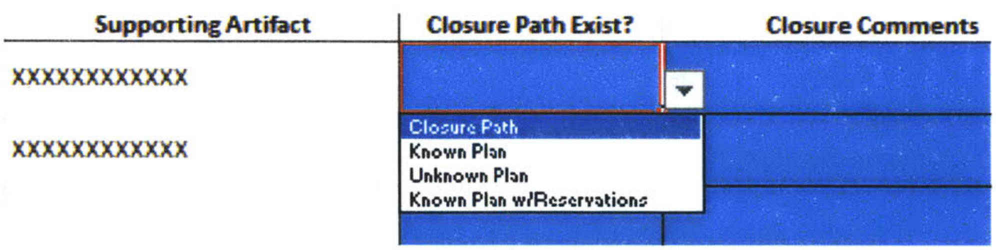
Figure 19 Scoring for Product- & Business-Level Assessments



The pre-determined drag-down selection also restricts users from entering values that are not numerical, thus standardizing inputs and eliminating errors.

There are two additional data points collected for each artifact. If an artifact was scored below the desired state, then it is necessary for the supplier to provide a plan, i.e. closure path, to get to the desired state. The Raytheon audit team will give a qualitative score on the quality of this closure path as illustrated below:

Figure 20 Inputs on Quality of Closure Path



The three possible answers are known plan, unknown plan, and known plan w/reservations. If the supplier has a clear path, known plan, to the desired state for the specific artifact then it is more likely for the supplier to mature the artifact in time versus as if a supplier has no ideas, which in this case the choice would unknown plan. In the cell to right, it provides a space for the supplier or Raytheon team to provide some comments that would be company or program specific.

4.5 Tool Enhancement

Even with buy-ins from suppliers secured (another supplier was introduced to the tool and similar reactions and feedbacks were received), Raytheon wanted to enhance the tool to further increase efficiencies and minimize errors. The first thing that needed to be accomplished was the weighting of the artifacts. In the MRL tool that was evaluated, each question received equal weighting. The problem with this approach was that a good supplier might be unnecessarily penalized for missing some of the less relevant artifacts while a bad supplier might fly under the radar with many irrelevant artifacts meeting the criteria.

Using a qualitative approach commonly used in project management[54], the goal was to give a weighting to each artifact. Again a focus group, enlisting the help from 20+ Raytheon employees, was formed to perform such a task. The artifacts were distributed among the focus group and each member was asked to rank the artifacts in three different aspects: cost, schedule, and performance. The rankings are low/L/1, medium/M/3, and high/H/9 for severity of impacts to the program if this artifact was not able to reach MRLX by the time it was due. The guideline below was given to Raytheon employees to assist them in ranking the artifacts. The criteria have been altered for illustration purpose only:

Figure 21 Guideline for Ranking

SEVERITY OF IMPACT GUIDE			
IMPACT	**COST**	**SCHEDULE**	**PERFORMANCE**
1	(LOW) Program budget impacted by X-Y%.; Minor impact on program success; Development or production cost goal exceeded by X-Y%	(LOW) Schedule would not be impacted if the artifact is not sufficiently mature when the build starts. Non critical path activities might be late. Development schedule goals exceeded by less than 5%	(LOW) Performance goals likely to be met within acceptable limits even if artifact is not sufficiently mature when the build starts. Not likely to impact program success.
3	(MEDIUM) Program budget impacted by X-Y%; Limited impact on program success; Development or production cost exceeded by X-Y%	(MEDIUM) Non critical path activities will be late by XX month or more if the artifact is not sufficiently mature when the build starts. Development schedule goals could be exceeded by X% to Y%	(MEDIUM) Performance likely to be below goal if the artifact is not sufficiently mature when the build starts. Could result in limited impact on program performance.
9	(HIGH) Program budget impacted by X-Y% or more; Program success jeopardized; Development or production cost exceeded by X-Y% or more	(HIGH) Critical path activities will be late by 1 month or more if the artifact is not sufficiently mature when the build starts. Development schedule goals exceed by Y%. Key program milestones would probably be late.	(HIGH) Performance likely to be unacceptable if the artifact is not sufficiently mature when the build starts. Program success would be jeopardized or in doubt.

[54] Amro Elkkad, PMP. Risk-Tolerance Based Schedule and Cost Estimates. 2008

The 1/3/9 scale is chosen over the 1-10 scale for several reasons. First, it was simply easier to use[55] and to communicate to the team. Additionally the non-linearity of the 1/3/9 scale was better at emphasizing the severe risks if an artifact received a rating of 9. This same approach was taken for assigning probabilities which will be discussed in Chapter 5.

Employees themselves were given weights. For example, the engineering director was given a weight of 3 to rank the artifacts in the threads of design and technology while an engineer within the Supplier Engineering group might only receive a weight of 2 for his/her ranking. In addition, each artifact was reviewed and ranked by at least two different employees and the average of their rankings was taken.

The next step was to categorize the artifacts. Based on the needs of the program and the nature of the assessment, perhaps not every single artifact needs to be assessed. Several categories were formed and they are listed below:

- Build-to-Print vs. Build-to-Specification
- Prime vs. Sub-contractor[56]
- Contractual vs. Non-contractual Assessments[57]

Additional filters were added. One of such is previous quality audits performed at the suppliers. Raytheon performs regular quality audits at many of its suppliers. An analysis was done to find the common questions between the MRL tool and the quality assessment. Several of the MRL artifacts were identified that can be adequately answered if certain quality metrics were met in a separate quality audit. Even though the goal was to reduce the number of artifacts, certain special processes (such as plating, brazing, and painting etc.) will often need to be evaluated as part of the contractual requirements. Therefore each special process will need to be added into the MRL assessment as required.

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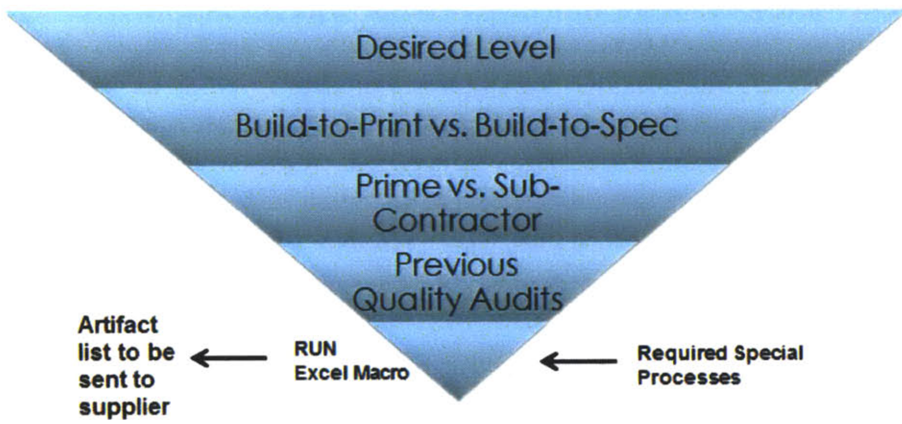
[55] Todd Generotzke CST Consulting PMP, MBA, MPM. A Simple Tool for Risk Management Planning.
[56] We found several artifacts to either fall under the jurisdiction of the Prime contractor, i.e. Raytheon or the supplier will need inputs from Raytheon to prepare the artifacts
[57] Since a particular artifact can answer several questions, if none of the questions that falls under a specific artifact come from the DoD DeskBook, the artifact is a non-contractual artifact

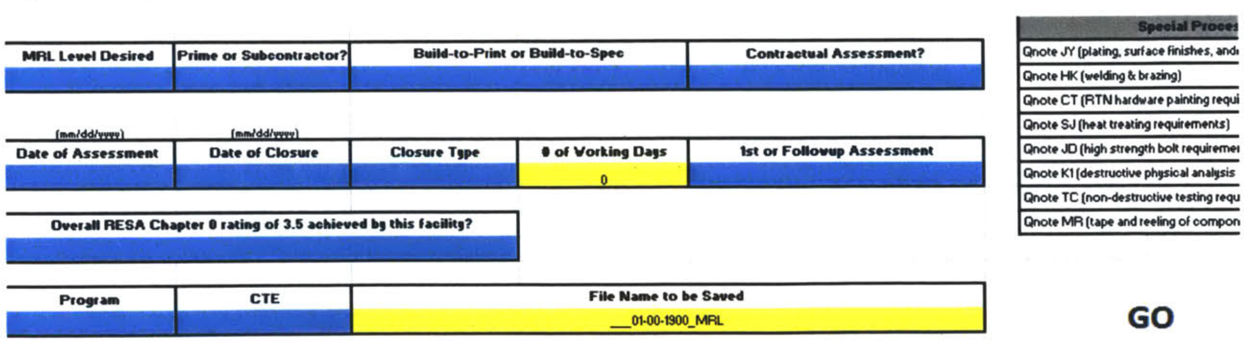
The next step was to automate certain functions of the MRL tool. With the artifacts properly categorized, it is now possible to filter the 250+ artifacts down the ones that are relevant for the particular assessment. Since the tool is Excel-based, a VBA code was utilized to automate the filtering process. The flowchart below demonstrates the various filtering criteria:

Figure 22 Artifacts Filtering Criteria Utilizing VBA



Below is an altered screen shot of the Excel-based tool that allows users to enter different assessment criteria to filter the necessary artifacts.

Figure 23 Sample Screenshot for VBA-Assisted MRL Tool



5 METRICS GENERATION & ALGORITHM CREATION

With the MRL tool able to identify the artifacts and to capture the relevant data to provide visibility of risks, the next step was to quantify the risk. Using an approach similar to ones used in most risk registers, a risk factor will be calculated for each immature artifact as a way to qualitatively measure the risk. The chapter will focus on the calculation for the risk factors, the generation of a scorecard, and the addition metrics calculated from data collected.

5.1 Risk Factor Calculation

Risk factor is defined as **Risk Factor = Impact x Probability**. The impact of each immature artifact has already been defined with the effort of the focus group. The next step was to calculate the probability.

In an ideal world, there would have been statistical data available such that a probabilistic model can be constructed or at least a numerical probability number can be obtained. Unfortunately that was not the case with the MRL assessment. Since this was a pilot project, there were no data as to evaluate the probability of an event. Therefore, a qualitative approach was taken.

In Chapter 4.4, the collected data has been described. There are three main components that are entered by the suppliers for each artifact: program specific rating for MRL, company level rating for MRL, and a qualitative rating for the closure path in the event of an immature artifact. The probability that is being generated here is the probability of this supplier not able to mature the artifact to the desired state given the current state it is in. There is not one factor that can solely determine this probability. Rather, the probability is a composite probability.

This composite probability, of each immature artifact, is made up by 4 probability factors:

- Program maturity, PML
- Business practice maturity, BML
- Time remaining, days-to-close, DTC
- Quality of closure path, CP

Each probability factor has two components, the actual probability and the weight it carries. The actual probability is qualitatively described as L/M/H (10% / 50% / 90%) and the weight of each probability factor must add up to one. A rule was created to assign the L/M/H values:

- For PML, H (PML < MRL-2) , M (PML = MRL-2), L (PML=MRL-1)[58]
- For BML, H (BML < MRL-2), M (BML = MRL-2), L(BML=>MRL-2)
- For DTC, H (DTC<30), M (30<=DTC<=60), L (DTC>60)[59]
- For CP, H (Unknown plan), M (Known plan w/ reservation), L (Known plan)[60]

Value stream mapping will be illustrated here as an example. For the artifact value stream mapping, it has been determined that the desired MRL is 8. On the program specific level, the artifact only achieved a rating of 5 but the value stream mapping is an established process at this supplier, thus it received a rating of 10. The assessment happened on January 1st, 2012 and the supplier must reach MRL8 by February 12th[t], 2012. Although the value stream mapping artifact is immature, the closure path presented by the supplier has been deemed satisfactory by Raytheon. With all these information, the probability of this supplier not able to deliver a mature artifact by February 12th, 2012 can be calculated as:

Weighted Failure Probability = (90% * W%) + (10% * X%) + (50% * Y%) + (10% * Z%)

where W is the weight for PML, X is the weight for BML, Y is the weight for DTC, and Z is the weight for CP. In addition, W + X + Y + Z = 100. For ease of demonstration, the values of W, X, Y, and Z were chosen such that the probability of failure is 40%[61]. The significance of this number, 40%, is not to indicate an actual probability of 40% that this supplier will not be able to mature the value stream mapping artifact from MRL5 to MRL8 in less than 42 days (1/1/2012 to 2/12/2012) given value stream mapping is a common process at this company. Here this 40% simply means, in a qualitative way, that value stream mapping has a higher probability of not maturing to MRL8 than another artifact that has a calculated weighted failure probability of 30%.

[58] If the program specific rating was 4 but the desired level was 6, the failure probability was M (50%)
[59] If the assessment date is more than 2 months away from the closure date, the failure probability was L (10%)
[60] If the supplier does not have a closure plan for the immature artifact, the failure probability was H (90%)
[61] The number has been altered not to reflect actual values used by Raytheon

The next component for the risk factor was severity of impact. As previously mentioned, each artifact was given a score of 1/3/9 in terms of cost, schedule, and performance impact if the artifact was not mature by closure date. Using the same value stream mapping artifact, it has been determined that the artifact carries an impact of 9 for cost, 9 for schedule, and 2.2 for performance[62]. The risk factor can now be calculated as:

Risk Factor = (9 * 40%) + (9 * 40%) + (2.2 * 40%) = 8.08

This calculation can be performed automatically for all artifacts evaluated in the Excel template. Risk factors from individual artifacts are not meaningful at this point, but they form the basis for many of the metrics to be explained later in this chapter.

5.2 Scorecard Metrics

One of the primary outputs required from a MRL assessment is the score of the supplier. This score is required by the customer and must be reported at program milestone reviews. No matter how efficient the Raytheon MRL assessment tool is, it is a failure if the customer (DoD) does not accept the outputs. Therefore great care was taken to formulate an algorithm that will calculate a score.

Even though the Raytheon tool is artifact-based, the customer is familiar to questionnaire-based format. A reverse linking was performed such that for each of the 1,300+ questions in the original question bank, at least one artifact was linked to that question. Since each artifact would carry a score (program level score), each question can now be assigned a score. For example, the question **"Does subtier supplier risk assessment and mitigation plan exist?"** is answered by two different artifacts, one scoring at 6 and one scoring at 8. The MRL score for this question is thus (6 + 8) / 2 = 7. With the individual question scored, it is now possible to score the entire thread. An example of the MRL scorecard to be submitted for customer review is shown in the next figure.

[62] Values have been altered to not reflect actual impact values used by Raytheon

Figure 24 Sample MRL Scorecard[63] (Threads with ratings 2 or more levels below desired state is shown in red)

	MRL Matrix Evaluation Threads	#	MRL Matrix Sub-Thread	GOAL	MRL Baseline
A	Technology & Industrial Base	TRL	Technology Readiness Level (TRL)	7	7
		Tech. Maturity	Technology Maturity	8	6
		A.1	Transition to Production	8	6
		A.2	Manufacturing Technology Development	8	7
B	Design	B.1	Producibility Program	8	8
		B.2	Design Maturity	8	6
C	Cost & Funding	C.1	Cost Modeling	8	7
		C.2	Cost Analysis	8	6
		C.3	Manufacturing Investment Budget	8	6
D	Materials	D.1	Maturity	8	6
		D.2	Availability	8	6
		D.3	Supply Chain Management	8	6
		D.4	Special Handling	8	7
E	Process Capability & Control	E.1	Modeling & Simulation (Product & Process)	8	6
		E.2	Manufacturing Process Maturity	8	6
		E.3	Process Yields & Rates	8	6
F	Quality Management	F.1	Quality Management Including Supplier Quality	8	7
G	Manufacturing Personnel	G.1	Manufacturing Personnel	8	6
H	Facilities	H.1	Tooling/STE/SIE	8	6
		H.2	Facilities	8	6
I	Manufacturing Management	I.1	Manufacturing Planning & Scheduling	8	6
		I.2	Materials Planning	8	6

The scorecard serves two important purposes. First, it communicates to the customer a quick overview of the supplier in current state. Second, more importantly the scorecard provides Raytheon with a method to have a 2-way linkage between the artifacts and the questions, giving Raytheon the validation it needs to promote and defend its artifact-based MRL assessment.

5.3 Percentage to Goal

The metric, percentage to goal, is an internal measure to indicate how far the supplier has to go before reaching the desired state. It is a quantitative measurement based on qualitative data giving the management a visual indication on progress. This section will describe how this metric is generated.

Before the metric, Percentage-to-Goal PTG, can be calculated, the points for each artifact must be explained. For example, an artifact has cost impact of 3, schedule impact of 6, and performance impact of 9. The desired MRL is 8 but the artifact only achieved a level of 7. The artifact should have received 48 points, $48 = 8 * (3+6+9) / 3$ but in reality it only received 42 points, $42 = 7 * (3+6+9)/3$. If there are 5 relevant artifacts within a particular thread, and the point distribution is as follows:

[63] The scorecard utilized altered data and does not represent any specific Raytheon supplier.

Figure 25 Example of Percentage-to-Goal Calculation

	Cost	Schedule	Performace	Assessed	Desired	Actual Points	Desired Points
A1	3	6	6	6	8	30.00	40.00
A2	9	9	9	6	8	54.00	72.00
A3	3	1	9	6	8	26.00	34.67
A4	8	4	2	4	8	18.67	37.33
A5	3	3	3	4	8	12.00	24.00

The Percentage-to-Goal for this thread can be calculated as:

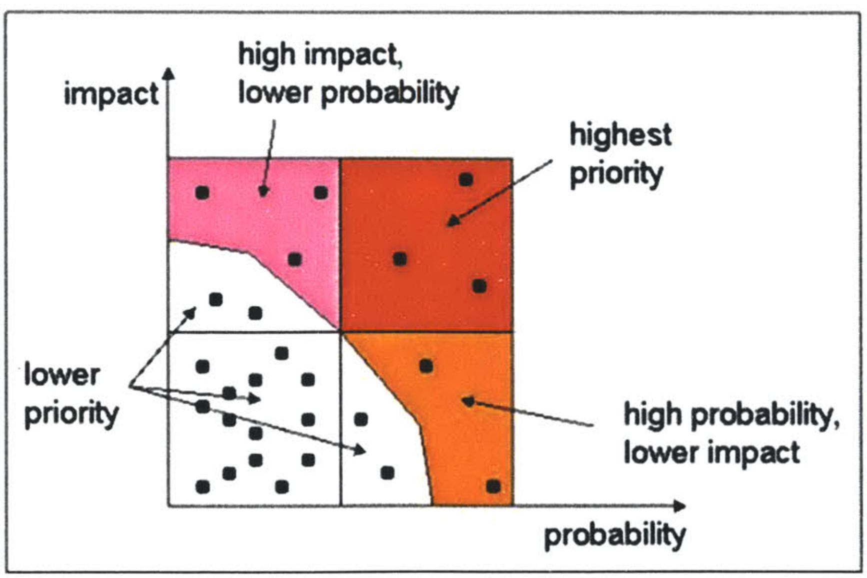
PTG = $\sum$ Actual Points / $\sum$ Desired Points = 140.67 / 208 = 68%

This calculation can be repeated for all 9 threads thus providing the management a visual indication on the supplier in regards to its status in each thread area.

5.4 Risk Mapping

Another metric of interest is the overall risk factors associated with the supplier. Using the risk factor, impact, and probability for each individual artifact as calculated in Chapter 5.1, a risk map can be constructed for as below:

Figure 26 Sample Risk Map [64]



[64] Risk map shown is not an actual map from the Raytheon MRL tool. It is shown for illustration purpose only.

5.5 Summary Report

The final feature of the tool is the ability to provide an instant overview of the assessment results once the data is entered. The Excel-VBA code automatically generates a graph as well as a summary of the assessment. For example, after specifying the following assessment criteria (MRL8, Build-to-Print, Sub-contractor, and required for contractual assessment) and collecting the data from the supplier, a summary is generated:

Figure 27 Assessment Summary[65]

Assessment Target MRL 8	A - Tech IB	B - Design	C - Cost	D - Material	E - Process	F- Quality	G - Mfg. Ppl.	H - Facility	I - Mfg.
Meets MRL 8	0	0	0	0	0	17	1	0	0
Known Closure	7	7	7	43	45	24	7	12	3
Unknown Closure	0	0	2	0	0	0	0	1	1
Total Areas Assessed	7	7	9	43	45	41	8	13	4
Min	6	6	6	6	6	6	6	8	6

It is worth noting that the artifact list is now reduced to 177 from the original 250+. The summary also displays the how many of the areas are not meeting the MRL8 requirements and what percentage of the non-compliant areas has a clear path to closure.

[65] Summary shown for illustration only and does not represent actual data

6 FUTURE ENHANCEMENT & CONCLUSIONS

At the conclusion of this project, the tool was still in its Excel-based format. As the tool evolves and more data points are collected, there are discussions going on about converting the tool into a web portal where suppliers can now evaluate themselves by selecting the appropriate criteria.

The MRL assessment simply addresses the transition-to-production risks but it does not include other risk areas such as finance (outside of cost and budgeting) and geo-political, etc. A follow-on project could be one to form an integrated risk assessment absorbing the MRL scores into an overall risk registrar. Raytheon already has several other metrics on measuring and evaluating suppliers, and it would be an interesting project to evaluate the overall risks with a particular supplier and to come up with a method to quantify the results.

Since the maturation of the immature artifacts forms the basis of the risk mitigation plan for Raytheon to present to its customers, another enhancement would be a proposed integer-programming-based task picking algorithm. In the context of defense acquisition, often all identified risk areas must be mitigated. But what if Raytheon has limited resources to mitigate a high number of risk areas in a constrained time frame? If Raytheon is primarily focused on the schedule impact, then the immature artifacts with the highest schedule impact points can be addressed first. The tool can be modified to include Excel-based integer programming where it will prioritize and pick the artifacts to mature based on the constraints and priority. Here is a conceptual illustration of how this optimization might work:

Figure 28 Illustration of Integer Programming

	Risk Factor			Cost of mitigation		
Artifact	**Cost**	**Schedule**	**Performance**	**Raytheon**	**Supplier**	**Execute?**
A1	2.8	6.39	5.59	$512,635	$563,178	1
A4	1.07	4.68	6.39	$596,791	$244,349	0
A6	3.68	5	8.76	$231,690	$508,665	1
B1	1.69	4.81	6.03	$500,059	$158,022	0
B4	2.92	4.64	4.92	$475,205	$976,245	0
C1	7.68	1.05	3.43	$792,060	$183,701	0
C11	5.89	5.96	1.57	$292,150	$895,748	1
C40	3	7.41	2.6	$567,776	$615,369	1
D1	1.44	6.21	1.92	$612,613	$187,176	0
E23	8.76	6.76	3.79	$649,689	$756,553	0
E44	7.29	5.2	1.77	$976,406	$394,692	0
F1	1.85	4.89	7.46	$304,776	$717,858	1
F2	7.76	5.62	5.64	$746,358	$346,149	0
F3	5.46	5.76	2.94	$61,398	$756,954	1
F4	5.1	7.33	2.19	$635,124	$187,045	0
G10	8.46	1	8.56	$811,193	$694,965	0
H3	6.16	4.37	3.43	$639,271	$382,499	0
H10	3.46	4.93	2.6	$785,580	$381,785	0
H21	4.35	8.22	7	$995,981	$347,458	0
I1	1.93	2.06	5.99	$754,924	$444,875	0
I2	6.33	8.17	8.27	$647,022	$928,637	0
I3	2.14	5.21	5.69	$417,565	$999,291	0
I4	5.84	8.01	7.95	$655,543	$685,649	0
I5	4.07	2.49	7.01	$505,343	$50,958	0
SUM	22.68	35.41	28.92	$1,970,425	$4,057,772	

In the illustration above, 24 artifacts have been identified as being immature and the risk factors have been calculated using the algorithm explained previously. For instance, if Raytheon wants to prioritize on schedule risk, then artifacts A1, A6, C11, C40, F1, and F3 would be picked (in the Execute? column a binary value of either 1 or 0 is assigned). These artifacts are picked to maximize the sum of the schedule risk factors (35.41) while meeting the budgetary constraint of $2,000,000 ($1,970,425 > $2,000,000). Additional constraints can be added such as keeping supplier's cost under a certain amount and this program can be used to pick different task for various priorities.

But for an optimization such as this to work well, sensitivity analysis and uncertainties must be addressed. How sensitive is the optimization to the budget? Would a different set of tasks be picked if the budget was increased to $2,000,100? How certain are the Raytheon's cost for mitigation? As the assessment is currently designed, the Raytheon assessor and the supplier's management would agree on a cost number to mitigate a specific risk. To account for uncertainties, this cost number should really be a range or a distribution and this process would become more of a stochastic optimization. But even with that, data collection is necessary to provide accurate inputs. For example, what was the range/distribution of cost associated with mitigating the risks of immature value stream mapping over the last 50 to 100 assessments for a supplier falling under certain categories? How accurate was the predicted cost versus the actual cost at the end? With the cost incurred, was the mitigation effort successful? This type of data collection is time-consuming and for a project in its infancy such as the MRL assessment, much analysis must be done to study the tradeoffs.

Uncertainties associated with this MRL assessment are the most important issues going forward for Raytheon. Although a guideline was created for Raytheon staffs to assign weights to different artifacts, the accuracy of the assigned weights will need to be proven out in time. As more assessments are carried out, it might be found that the maturation of a highly-weighted artifact in schedule actually does not contribute much to the overall program schedule progress. As of the end of the project, the Excel template was designed so that if the weighting needs to be modified, it can be done if all the stakeholders involved agree on such new ratings.

More importantly, this MRL assessment process must be validated in time. Do the artifacts collected truly answer the questions imposed by the DoD? Even if all the questions are answered and the artifacts are mature, does this mean a supplier is truly at MRLX? For example, there are 40 immature artifacts found after the first assessment at a supplier for MRL8. Over the next 3 months, Raytheon worked with this supplier to mature these 40 artifacts just in time for the program milestone review. Right before the review, a second/follow-up assessment was done and all the immature artifacts are now deemed mature to be at MRL8. The customer (DoD) accepts Raytheon's assessment of this supplier's MRL and the program moves into Low Rate Initial Production. How does the label of this supplier being at MRL8 relate to the program's overall success in terms of cost, schedule, and performance? With the slow moving and long duration of typical defense acquisition process, the validity of a particular assessment won't be clear in a short time. The validation path of Raytheon's MRL assessment process is clear but this proposed methodology will take time to be accepted by the customers and peers.

This first pilot version of the Raytheon MRL assessment tool attempted to address some of the common issues embedded in supplier evaluation and risk management. It provides a compromise between thoroughness and efficiency. It also attempted to provide a common language and objective measurement scale among the different users including Raytheon employees and supplier management staffs. The two-way linking between the artifacts and the DoD questions provided visibility to the customers on Raytheon's method of performing the assessments.

This tool for Raytheon is not only a risk management tool but also a product development template for both internal processes and supplier development. In addition, this template is valuable as a strategic marketing tool. It shows Raytheon as a market leader in the defense industry not only on the technology front but also a first-mover in addressing the new challenges in the defense acquisition programs. It sends a signal to Raytheon's suppliers that Raytheon intends on working collaboratively with the suppliers to share risks and rewards.

No matter how advanced and robust an assessment method is, the human aspect will always be essential. A successful implementation will not occur if the users do not understand the intent of the initiatives. In addition, all stakeholders' interests must be aligned. During this project, a lot of effort was focused on how to engage the various stakeholders and to make sure the tool is marketed to them accordingly.

At the end of the project as of late August 2011, there were efforts at Raytheon to take this template and use it on Raytheon's internal production lines since Raytheon often serves as a first-tier supplier to another defense OEM such as Northrup Grumman. It will be interesting to see how differently Raytheon will be assessed by another defense OEM and whether the artifact-based MRL assessment will gain traction not only with the OEM contractors but also with the customers such as the DoD.

7 APPENDIX (MRL Maturation Matrix)

Table A-1. Manufacturing Readiness Levels for the Technology and Industrial Base Thread

Acquisition Phase		Pre-MSA			MSA	TD		EMD		LRIP	FRP
Technical Reviews		-			ASR	SRR/SFR	PDR	CDR	PRR/ SVR	PCA	-
Thread	**Sub-Thread**	**MRL 1**	**MRL 2**	**MRL 3**	**MRL 4**	**MRL 5**	**MRL 6**	**MRL 7**	**MRL 8**	**MRL 9**	**MRL 10**
–	Technology Maturity	Should be assessed at TRL 1	Should be assessed at TRL 2	Should be assessed at TRL 3	Should be assessed at TRL 4	Should be assessed at TRL 5	Should be assessed at TRL 6	Should be assessed at TRL 7	Should be assessed at TRL 7	Should be assessed at TRL 9	Should be assessed at TRL 9
A – Technology & Industrial Base	A.1 – Industrial base			Potential sources identified to address technology needs. Understand state of the art.	Industrial base capabilities surveyed and known gaps/risks identified for preferred concept, key technologies, components, and/or key processes.	Industrial base assessment initiated to identify potential manufacturing sources. Sole/single/foreign source vendors have been identified and planning has begun to minimize risks.	ICA for MS B has been completed. Industrial capability in place to support manufacturing of development articles. Plans to minimize sole/foreign sources complete. Need for sole/single/foreign sources justified. Potential alternative sources identified.	Industrial capability to support production has been analyzed. Sole/single/foreign sources stability is assessed/monitored. Developing potential alternate sources as necessary.	ICA for MS C has been completed. Industrial capability is in place to support LRIP. Sources are available, multi-sourcing where cost-effective or necessary to mitigate risk.	Industrial capability is in place to support start of FRP.	Industrial capability supports FRP and is assessed to support modifications, upgrades, surge and other potential manufacturing requirements.

Acquisition Phase		Pre-MSA			MSA	TD		EMD		LRIP	FRP
Technical Reviews		-			ASR	SRR/SFR	PDR	CDR	PRR/ SVR	PCA	-
Thread	**Sub-Thread**	**MRL 1**	**MRL 2**	**MRL 3**	**MRL 4**	**MRL 5**	**MRL 6**	**MRL 7**	**MRL 8**	**MRL 9**	**MRL 10**
–	Technology Maturity	Should be assessed at TRL 1	Should be assessed at TRL 2	Should be assessed at TRL 3	Should be assessed at TRL 4	Should be assessed at TRL 5	Should be assessed at TRL 6	Should be assessed at TRL 7	Should be assessed at TRL 7	Should be assessed at TRL 8	Should be assessed at TRL 9
A – Technology & Industrial Base	A.2 – Manufacturing Technology Development		New manufacturing concepts and potential solutions identified.	Manufacturing technology concepts identified through experiments/ models.	Manufacturing Science & Advanced Manufacturing Technology requirements identified.	Required manufacturing technology development efforts initiated, if applicable.	Manufacturing technology efforts continuing. Required manufacturing technology development solutions demonstrated in a production-relevant environment.	Manufacturing technology efforts continuing. Required manufacturing technology development solutions demonstrated in a production-representative environment.	Primary manufacturing technology efforts concluding and some improvement efforts continuing. Required manufacturing technology solutions validated on a pilot line.	Manufacturing technology process improvement efforts initiated for FRP.	Manufacturing technology continuous process improvements ongoing.

Acquisition Phase		Pre-MSA			MSA	TD		EMD		LRIP	FRP
Technical Reviews		-			ASR	SRR/SFR	PDR	CDR	PRR/SVR	PCA	-
Thread	Sub-Thread	MRL 1	MRL 2	MRL 3	MRL 4 A	MRL 5	MRL 6 B	MRL 7	MRL 8 C	MRL 9 FRP	MRL 10
-	Technology Maturity	Should be assessed at TRL 1	Should be assessed at TRL 2	Should be assessed at TRL 3	Should be assessed at TRL 4	Should be assessed at TRL 5	Should be assessed at TRL 6	Should be assessed at TRL 7	Should be assessed at TRL 7	Should be assessed at TRL 8	Should be assessed at TRL 9
B – Design	B.2 – Design Maturity	Manufacturing research opportunities identified.	Applications defined. Broad performance goals identified that may drive manufacturing options.	Top level performance requirements defined. Tradeoffs in design options assessed based on experiments. Product life cycle and technical requirements evaluated.	SEP and T&E Strategy recognize the need for the establishment/ validation of manufacturing capability and management of manufacturing risk for the product life cycle. Draft Key Performance Parameters (KPPs) identified for preferred systems concept. System characteristics and measures to support required capabilities identified. Form, fit, and function constraints identified, and manufacturing capabilities identified for preferred system concepts.	Lower level performance requirements sufficient to proceed to preliminary design. All enabling/critical technologies and components identified and product life cycle considered. Evaluation of design KCs initiated. Product data required for prototype component manufacturing released.	System allocated baseline established. Product requirements and features are well enough defined to support preliminary design review. Product data essential for subsystem/system prototyping has been released. Preliminary design KCs have been identified and mitigation plan in development.	Product design and features are defined well enough to support CDR even though design change traffic may be significant. All product data essential for component manufacturing has been released. Potential KC risk issues have been identified and mitigation plan is in place.	Detailed design of product features and interfaces is complete. All product data essential for system manufacturing has been released. Design change traffic does not significantly impact LRIP. KCs are attainable based upon pilot line demonstrations.	Major product design features and configuration are stable. System design has been validated through operational testing of LRIP items. PCA or equivalent complete as necessary. Design change traffic is limited. All KCs are controlled in LRIP to appropriate quality levels.	Product design is stable. Design changes are few and generally limited to those required for continuous improvement or in reaction to obsolescence. All KCs are controlled in FRP to appropriate quality levels.

Acquisition Phase		Pre-MSA			MSA	TD		EMD		LRIP	FRP
Technical Reviews		-			ASR	SRR/SFR	PDR	CDR	PRR/SVR	PCA	-
Thread	Sub-Thread	MRL 1	MRL 2	MRL 3	MRL 4 A	MRL 5	MRL 6 B	MRL 7	MRL 8 C	MRL 9 FRP	MRL 10
-	Technology Maturity	Should be assessed at TRL 1	Should be assessed at TRL 2	Should be assessed at TRL 3	Should be assessed at TRL 4	Should be assessed at TRL 5	Should be assessed at TRL 6	Should be assessed at TRL 7	Should be assessed at TRL 7	Should be assessed at TRL 8	Should be assessed at TRL 9
B – Design	B.1 – Producibility Program	-	-	Relevant materials/processes evaluated for manufacturability using experiments/ models.	Initial producibility and manufacturability assessment of preferred systems concepts completed. Results considered in selection of preferred design concepts and reflected in TDS key components/ technologies.	Producibility and manufacturability assessments of key technologies and components initiated as appropriate. Ongoing design trades consider manufacturing processes and industrial base capability constraints. Manufacturing processes assessed for capability to test and verify in production, and influence on operations & support.	Producibility assessments and producibility trade studies (performance vs. producibility) of key technologies/components completed. Results used to shape Acquisition Strategy, SEP, Manufacturing and Producibility plans, and planning for EMD or technology insertion programs. Preliminary design choices assessed against manufacturing processes and industrial base capability constraints. Producibility enhancement efforts (e.g., Design for Manufacturing Assembly, Etc. (DFX)) initiated.	Detailed producibility trade studies using knowledge of key design characteristics and related manufacturing process capability completed. Producibility enhancement efforts (e.g., DFX) ongoing for optimized integrated system. Manufacturing processes reassessed as needed for capability to test and verify potential influence on operations & support.	Producibility improvements implemented on system. Known producibility issues have been resolved and pose no significant risk for LRIP.	Prior producibility improvements analyzed for effectiveness during LRIP. Producibility issues/ risks discovered in LRIP have been mitigated and pose no significant risk for FRP.	Design producibility improvements demonstrated in FRP. Process producibility improvements ongoing. All modifications, upgrades, DMSMS, and other changes assessed for producibility.

Acquisition Phase		Pre-MSA			MSA	TD		EMD		LRIP	FRP
Technical Reviews		-			ASR	SRR/SFR	PDR	CDR	PRR/ SVR	PCA	-
Thread	Sub-Thread	MRL 1	MRL 2	MRL 3	MRL 4	MRL 5	MRL 6	MRL 7	MRL 8	MRL 9	MRL 10
–	Tech-nology Maturity	Should be assessed at TRL 1	Should be assessed at TRL 2	Should be assessed at TRL 3	Should be assessed at TRL 4	Should be assessed at TRL 5	Should be assessed at TRL 6	Should be assessed at TRL 7	Should be assessed at TRL 7	Should be assessed at TRL 8	Should be assessed at TRL 9
C – Cost & Funding	C.1 – Production Cost Knowledge (Cost Modeling)	–	Cost model approach defined.	Initial cost targets and risks identi-fied. High level process chart model developed. Technology cost models developed for new process steps and materials based on experiments.	Manufacturing, material and spe-cial requirement cost drivers identi-fied. Detailed pro-cess chart cost models driven by process variables. Cost driver uncer-tainty quantified.	Prototype com-ponents pro-duced in a production relevant envi-ronment, or simulations drive end-to-end cost models. Cost model includes materials, labor, equipment, tooling/(STE, setup, yield/ scrap/rework, WIP, and capa-bility/capacity constraints).	Cost model updated with design require-ments, material specifications, tolerances, inte-grated master schedule, results of system/subsystem simulations and production relevant prototype demon-strations.	Cost model updated with the results of systems/sub-systems pro-duced in a production-representative environment and with pro-duction plant layout and design and obsolescence solutions.	Cost models updated with results of pilot line build.	FRP cost model updated with result of LRIP build.	Cost model validated against actual FRP cost.

Acquisition Phase		Pre-MSA			MSA	TD		EMD		LRIP	FRP
Technical Reviews		-			ASR	SRR/SFR	PDR	CDR	PRR/ SVR	PCA	-
Thread	Sub-Thread	MRL 1	MRL 2	MRL 3	MRL 4	MRL 5	MRL 6	MRL 7	MRL 8	MRL 9	MRL 10
–	Tech-nology Maturity	Should be assessed at TRL 1	Should be assessed at TRL 2	Should be assessed at TRL 3	Should be assessed at TRL 4	Should be assessed at TRL 5	Should be assessed at TRL 6	Should be assessed at TRL 7	Should be assessed at TRL 7	Should be assessed at TRL 8	Should be assessed at TRL 9
C – Cost & Funding	C.2 – Cost Analysis	Identify any manu-facturing cost implica-tions.	Cost elements identified.	Sensitivity analysis conducted to define cost drivers and production development strategy (i.e., lab to pilot to factory).	Producibility cost risks assessed. Initial cost models support AoA and ASR.	Costs analyzed using prototype component actuals to ensure target costs are achievable. Decisions regarding design choices, make/buy, capacity, process capability, sources, quality, KCs, yield/rate, and variability influenced by cost models.	Costs analyzed using prototype system/subsystem actuals to ensure target costs are achievable. Allocate cost targets to sub-systems. Cost reduction and avoidance strate-gies developed. Provide manufacturing cost drivers for "Should-Cost" models.	Manufacturing costs rolled up to system/sub-system level and tracked against targets. Detailed trade studies and engineering change requests supported by cost estimates. Cost reduction and avoidance strategies underway. Update manufacturing cost drivers for "Should-Cost" models.	Costs analyzed using pilot line actuals to ensure target costs are achiev-able. Manu-facturing cost analysis supports proposed changes to require-ments or configura-tion. Cost reduction initiatives ongoing. Update manufac-turing cost drivers for "Should-Cost" models.	LRIP cost goals met and learning curve analyzed with actual data. Cost reduction initiatives ongoing. Touch labor effi-ciency analyzed to meet production rates and elements of ineffi-ciency are identified with plans in place for reduction.	FRP cost goals met. Cost reduction initiatives ongoing.

Acquisition Phase		Pre-MSA			MSA	TD		EMD		LRIP	FRP
Technical Reviews		-			ASR	SRR/SFR	PDR	CDR	PRR/SVR	PCA	-
Thread	Sub-Thread	MRL 1	MRL 2	MRL 3	MRL 4	MRL 5	MRL 6	MRL 7	MRL 8	MRL 9	MRL 10
–	Technology Maturity	Should be assessed at TRL 1	Should be assessed at TRL 2	Should be assessed at TRL 3	Should be assessed at TRL 4	Should be assessed at TRL 5	Should be assessed at TRL 6	Should be assessed at TRL 7	Should be assessed at TRL 7	Should be assessed at TRL 8	Should be assessed at TRL 9
C – Cost & Funding	C.3 – Manufacturing Investment Budget	Potential investments identified.	Program/ projects have reasonable budget estimates for reaching MRL 3 through experiment.	Program/ projects have reasonable budget estimates for reaching MRL 4 by MS A.	Manufacturing technology initiatives identified to reduce costs. Program has reasonable budget estimate for reaching MRL 6 by MS B. Estimate includes capital investment for production-relevant equipment. All outstanding MRL 4 risk areas understood, with approved mitigation plans in place.	Program has updated budget estimate for reaching MRL 6 by MS B. All outstanding MRL 5 risk areas understood, with approved mitigation plans in place.	Program has reasonable budget estimate for reaching MRL 8 by MS C. Estimate includes capital investment for production-representative equipment by CDR and pilot line equipment by MS C. All outstanding MRL 6 risk areas understood, with approved mitigation plans in place.	Program has updated budget estimate for reaching MRL 8 by MS C. All outstanding MRL 7 risk areas understood, with approved mitigation plans in place.	Program has reasonable budget estimate for reaching MRL 9 by the FRP decision point. Estimate includes investment for LRIP and FRP. All outstanding MRL 8 risk areas understood, with approved mitigation plans in place.	Program has reasonable budget estimate for FRP. All outstanding MRL 9 risk areas understood, with approved mitigation plans in place.	Production budgets sufficient for production at required rates and schedule to support funded program.

Acquisition Phase		Pre-MSA			MSA	TD		EMD		LRIP	FRP
Technical Reviews		-			ASR	SRR/SFR	PDR	CDR	PRR/SVR	PCA	-
Thread	Sub-Thread	MRL 1	MRL 2	MRL 3	MRL 4	MRL 5	MRL 6	MRL 7	MRL 8	MRL 9	MRL 10
–	Technology Maturity	Should be assessed at TRL 1	Should be assessed at TRL 2	Should be assessed at TRL 3	Should be assessed at TRL 4	Should be assessed at TRL 5	Should be assessed at TRL 6	Should be assessed at TRL 7	Should be assessed at TRL 7	Should be assessed at TRL 8	Should be assessed at TRL 9
D – Materials (Raw Materials, Components, Sub-assemblies and Subsystems)	D.1 – Maturity	Material properties identified for research.	Material properties and characteristics predicted.	Material properties validated and assessed for basic manufacturability using experiments.	Projected materials have been produced in a laboratory environment.	Materials have been manufactured or produced in a prototype environment (maybe in a similar application/program). Maturation efforts in place to address new material production risks for technology demonstration.	Material maturity verified through technology demonstration articles. Preliminary material specifications in place and material properties have been adequately characterized.	Material maturity sufficient for pilot line build. Material specifications approved.	Materials proven and validated during EMD as adequate to support LRIP. Material specification stable.	Material is controlled to specification in LRIP. Materials proven and validated as adequate to support FRP.	Material is controlled to specification in FRP.
	D.2 – Availability	–	Material availability assessed.	Material scale-up issues identified.	Projected lead times have been identified for all difficult-to-obtain, difficult-to-process, or hazardous materials. Quantities and lead times estimated.	Availability issues addressed for prototype build. Significant material risks identified for all materials. Planning has begun to address scale-up issues.	Availability issues addressed to meet LRIP needs. Long-lead items identified. Potential obsolescence issues identified.	Long lead procurement initiated for LRIP. Availability issues pose no significant risk for LRIP. Availability issues addressed to meet FRP builds.	Long-lead procurement initiated for LRIP. Availability issues pose no significant risk for LRIP.	Long-lead procurement initiated for FRP. Availability issues pose no significant risk for FRP.	Program is in FRP, with no significant material availability issues.

Acquisition Phase		Pre-MSA			MSA	TD		EMD		LRIP	FRP
Technical Reviews		-			ASR	SRR/SFR	PDR	CDR	PRR/ SVR	PCA	-
Thread	Sub-Thread	MRL 1	MRL 2	MRL 3	MRL 4	MRL 5	MRL 6	MRL 7	MRL 8	MRL 9	MRL 10
-	Technology Maturity	Should be assessed at TRL 1	Should be assessed at TRL 2	Should be assessed at TRL 3	Should be assessed at TRL 4	Should be assessed at TRL 5	Should be assessed at TRL 6	Should be assessed at TRL 7	Should be assessed at TRL 7	Should be assessed at TRL 8	Should be assessed at TRL 9
D – Materials (Raw Materials, Components, Sub-assemblies and Subsystems)	D.3 – Supply Chain Management	-	-	Initial assessment of potential supply chain capability.	Survey completed for potential supply chain sources.	Potential supply chain sources identified and evaluated as able to support prototype build.	Supply chain plans in place (e.g. teaming agreements and so forth) supporting an EMD contract award.	Effective supply chain management process in place. Assessment of critical first tier supply chain completed.	Supply chain adequate to support LRIP. Assessment of critical second and lower tier supply chain completed.	Supply chain is stable and adequate to support FRP. Long-term agreements in place where practical.	Supply chain proven and supports FRP requirements.
	D.4 – Special Handling (i.e., GFP, Shelf Life, Security, Hazardous Materials, Storage Environment, and So Forth)	-	Initial evaluation of potential regulatory requirements and special handling concerns.	List of hazardous materials identified. Special handling procedures applied in the lab. Special handling concerns assessed.	List of hazardous materials updated. Special handling procedures applied in the lab. Special handling requirements identified.	Special handling procedures applied in production-relevant environment. Special handling requirement gaps identified. New special handling processes demonstrated in lab environment.	Special handling procedures applied in production-relevant environment. Plans to address special handling requirement gaps complete.	Special handling procedures applied in production representative environment. Special handling procedures developed and annotated on work instructions for pilot line.	Special handling procedures applied in pilot line environment. Special handling procedures demonstrated in EMD or technology insertion programs. Special handling issues pose no significant risk for LRIP. All work instructions contain special handling provisions, as required.	Special handling procedures applied in LRIP environment. Special handling procedures demonstrated in LRIP. Special handling issues pose no significant risk for FRP.	Special handling procedures effectively implemented in FRP.

Acquisition Phase		Pre-MSA			MSA	TD		EMD		LRIP	FRP
Technical Reviews		-			ASR	SRR/SFR	PDR	CDR	PRR/ SVR	PCA	-
Thread	Sub-Thread	MRL 1	MRL 2	MRL 3	MRL 4	MRL 5	MRL 6	MRL 7	MRL 8	MRL 9	MRL 10
-	Technology Maturity	Should be assessed at TRL 1	Should be assessed at TRL 2	Should be assessed at TRL 3	Should be assessed at TRL 4	Should be assessed at TRL 5	Should be assessed at TRL 6	Should be assessed at TRL 7	Should be assessed at TRL 7	Should be assessed at TRL 8	Should be assessed at TRL 9
E --Process Capability & Control	E.1 – Modeling & Simulation (Product & Process)	-	Initial models developed, if applicable.	Identification of proposed manufacturing concepts or producibility needs based on high-level process flow-chart models.	Production modeling/simulation approaches for process or product are identified.	Initial model/simulation (product or process) developed at the component level and used to determine constraints.	Initial model/simulation developed at the subsystem or system level, and used to determine system constraints.	Model/simulation used to determine system constraints and identify improvement opportunities.	Model/simulation verified by pilot line build. Results used to improve process and determine that LRIP requirements can be met.	Model/ simulation verified by LRIP build, assists in management of LRIP and determines that FRP requirements can be met.	Model/ simulation verified by FRP build. Production simulation models used as a tool to assist in management of FRP.
	E.2 – Manufacturing Process Maturity	-	Identification of material and/or process approaches.	Document high-level manufacturing processes. Critical manufacturing processes identified through experimentation.	Complete a survey to determine the current state of critical processes.	Maturity has been assessed on similar processes in production. Process capability requirements have been identified for pilot line, LRIP and FRP.	Manufacturing processes demonstrated in production-relevant environment. Begin collecting or estimating process capability data from prototype build. Process capability requirements refined.	Manufacturing processes demonstrated in a production-representative environment. Continue collecting or estimating process capability data. Process capability requirements refined.	Manufacturing processes verified for LRIP on a pilot line. Process capability data from pilot line meets target. Process capability requirements refined.	Manufacturing processes are stable, adequately controlled, capable and have achieved program LRIP objectives. Variability experiments conducted to show FRP impact and potential for continuous improvement.	Manufacturing processes are stable, adequately controlled, capable, and have achieved program FRP objectives.

Acquisition Phase		Pre-MSA			MSA	TD		EMD		LRIP	FRP
Technical Reviews		-			ASR	SRR/SFR	PDR	CDR	PRR/ SVR	PCA	-
Thread	Sub-Thread	MRL 1	MRL 2	MRL 3	MRL 4	A MRL 5	MRL 6	B MRL 7	MRL 8	C MRL 9	FRP MRL 10
–	Tech-nology Maturity	Should be assessed at TRL 1	Should be assessed at TRL 2	Should be assessed at TRL 3	Should be assessed at TRL 4	Should be assessed at TRL 5	Should be assessed at TRL 6	Should be assessed at TRL 7	Should be assessed at TRL 7	Should be assessed at TRL 8	Should be assessed at TRL 9
E —Process Capability & Control	E.3 – Process Yields and Rates	–	–	Initial esti-mates of yields and rates based on experi-ments or state of the art.	Yield and rates assessment on proposed/similar processes com-plete and applied within AoA.	Target yields and rates estab-lished for pilot line, LRIP, and FRP. Yield and rate issues identified. Improvement plans devel-oped/initiated.	Yields and rates from production-relevant environ-ment evaluated against targets and the results feed improvement plan.	Yields and rates from production-representative environment evaluated against pilot line targets and the results feed improvement plans.	Pilot line targets achieved. Yields and rates required to begin LRIP refined using pilot line results. Improve-ment plans ongoing and updated.	LRIP yield and rate targets achieved. Yields and rates required to begin FRP refined using LRIP results. Yield improve-ments ongoing.	FRP yield and rate targets achieved. Yield improve-ments ongoing.

Acquisition Phase		Pre-MSA			MSA	TD		EMD		LRIP	FRP
Technical Reviews		-			ASR	SRR/SFR	PDR	CDR	PRR/ SVR	PCA	-
Thread	Sub-Thread	MRL 1	MRL 2	MRL 3	MRL 4	A MRL 5	MRL 6	MRL 7	MRL 8	C MRL 9	FRP MRL 10
–	Tech-nology Maturity	Should be assessed at TRL 1	Should be assessed at TRL 2	Should be assessed at TRL 3	Should be assessed at TRL 4	Should be assessed at TRL 5	Should be assessed at TRL 6	Should be assessed at TRL 7	Should be assessed at TRL 7	Should be assessed at TRL 8	Should be assessed at TRL 9
F – Quality Management	F.1 – Quality Management, Including Supplier Quality	–	–	–	Quality strategy identified as part of the TDS and included in SEP.	Quality strategy updated to reflect KC identification activities.	Initial quality plan and quality management system is in place. Quality risks and metrics have been identified and improvement plans initiated. Key Characteristic management approached defined.	Quality data from the production representative environment collected and analyzed and results used to shape improvement plans.	Quality targets assessed against pilot line results feed continuous quality improve-ments. Supplier products have com-pleted qualification testing and first-article inspection. Acceptance testing of supplier products is adequate to begin LRIP. Key Characteris-tics managed.	Quality tar-gets veri-fied on LRIP line. Contin-uous quality improve-ment ongoing. Accept-ance testing of supplier products is adequate to begin FRP. Key Character-istics managed in LRIP.	Quality targets verified on FRP line. Contin-uous quality improve-ment ongoing.

Acquisition Phase		Pre-MSA			MSA	TD		EMD		LRIP	FRP
Technical Reviews		-			ASR	SRR/SFR	PDR	CDR	PRR/ SVR	PCA	-
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G – Mfg Workforce (Engineering & Production)	G.1 – Mfg Workforce (Engineering & Production)	–	–	New manufacturing skills identified.	Manufacturing skill sets identified and production workforce requirements (technical and operational) evaluated as part of AoA. Availability of process development workforce for the Technology Development Phase determined.	Skill sets identified and plans developed to meet prototype and production needs. Special skills certification and training requirements established.	Manufacturing workforce skills available for production in a relevant environment. Identify resources (quantities and skill sets) and develop initial plans to achieve requirements for pilot line and production.	Manufacturing workforce resource requirements identified for pilot line. Plans developed to achieve pilot line requirements. Plans updated to achieve LRIP workforce requirements. Pilot line workforce trained in production representative environment.	Manufacturing workforce resource requirements identified for LRIP. Plans developed to achieve LRIP requirements. Plans updated to achieve FRP workforce requirements. LRIP personnel trained on pilot line where possible.	LRIP personnel requirements met. Implement plan to achieve FRP workforce requirements.	FRP personnel requirements met. Production workforce skill sets maintained in response to attrition of workforce.

Acquisition Phase		Pre-MSA			MSA	TD		EMD		LRIP	FRP
Technical Reviews		-			ASR	SRR/SFR	PDR	CDR	PRR/ SVR	PCA	-
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H – Facilities	H.1 – Tooling/STE/SIE	–	–	–	Tooling/STE/SIE requirements are considered as part of AoA.	Identify tooling and STE/SIE requirements and provide supporting rationale and schedule.	Prototype tooling and STE/SIE concepts demonstrated in production relevant environment. Production tooling and STE/SIE requirements developed.	Production tooling and STE/SIE design and development efforts underway. Manufacturing equipment maintenance strategy developed.	Tooling, test, and inspection equipment proven on pilot line and additional requirements identified for LRIP. Manufacturing equipment maintenance demonstrated on pilot line.	All tooling, test, and inspection equipment proven in LRIP and requirements identified for FRP. Manufacturing equipment maintenance schedule demonstrated.	Proven tooling, test, and inspection equipment in place to support maximum FRP. Planned equipment maintenance schedule achieved.
	H.2 – Facilities	–	–	Specialized facility requirements/needs identified.	Availability of manufacturing facilities for prototype development and production evaluated as part of AoA.	Manufacturing facilities identified and plans developed to produce prototypes.	Manufacturing facilities identified and plans developed to produce pilot line build.	Manufacturing facilities identified and plans developed to produce LRIP build.	Pilot line facilities demonstrated. Manufacturing facilities adequate to begin LRIP. Plans in place to support transition to FRP.	Manufacturing facilities in place and demonstrated in LRIP. Capacity plans adequate to support FRP.	Production facilities in place and capacity demonstrated to meet maximum FRP requirements.

Acquisition Phase		Pre-MSA			MSA	TD		EMD		LRIP	FRP
Technical Reviews		-			ASR	SRR/SFR	PDR	CDR	PRR/ SVR	PCA	-
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I – Manufacturing Management	L1 – Manufacturing Planning & Scheduling	–	–	–	Manufacturing strategy devel-oped and inte-grated with acqui-sition strategy. Prototype sche-dule risk mitiga-tion efforts incor-porated into TDS.	Manufacturing strategy refined based upon preferred con-cept. Prototype schedule risk mitigation efforts initiated.	Initial manufac-turing approach developed. All system-design-related manufac-turing events included in IMP/ IMS. Manufacturing risk mitigation approach for pilot line or technology insertion programs defined.	Initial manufac-turing plan developed. Manufacturing planning included in the IMP/IMS. Manufacturing risks integrated into risk mitiga-tion plans. Develop initial work instructions. Effective production control system in place to support pilot line.	Manufac-turing plan updated for LRIP. All key manufac-turing risks are identi-fied and assessed with approved mitigation plans in place. Work instructions finalized. Effective production control system in place to support LRIP.	Manufac-turing plan updated for FRP. All manufac-turing risks tracked and miti-gated. Effective production control system in place to support FRP.	All manu-facturing risks mitigated.
	L2 – Materials Planning	–	–	–	Technology development article component list developed with associated lead-time estimates.	Technology development part list maturing. Make/buy evaluations begin and include production considerations reflecting pilot line, LRIP, and FRP needs. Lead times and other risks identified.	Most material deci-sions complete (make/buy), material risks identified, and mitigation plans developed. BOM initiated.	Make/buy decisions and BOM complete for pilot line build. Material planning sys-tems in place for pilot line build.	Make/buy decisions and BOM complete to support LRIP. Material planning systems proven on pilot line for LRIP build.	Make/buy decisions and BOM complete to support FRP. Material planning systems proven in LRIP and sufficient for FRP.	Material planning systems validated on FRP build.

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9 ACRONYMS

CDR – Critical Design Review

EVMS – Earned Value Management Systems

FRP – Full Rate Production

LRIP – Low Rate Initial Production

MRL – Manufacturing Readiness Levels

PDR – Preliminary Design Review

TRL – Technology readiness Levels

T/MRA – Technology & Manufacturing Readiness Assessments