Analysis of the Effect of Planning/Design Phase Factors on Rework

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Submitted to the MIT Sloan School of Management and the Engineering Systems Division in Partial Fulfillment of the Requirements for the Degrees of

Master of Business Administration
AND
Master of Science in Engineering Systems

In conjunction with the Leaders for Manufacturing Program at the

Massachusetts Institute of Technology

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ABSTRACT

Over the past several years, Raytheon has experienced great growth in their revenue and sales. One of the contributing organizations to that growth has been the Space and Airborne Systems (SAS) business sector. To continue this growth, SAS has started initiatives to improve their Operations. One of these initiatives is to reduce the amount of rework performed within the manufacturing centers. By reducing rework, SAS will be able to reduce costs, meet aggressive schedules, and continue to satisfy customer's needs.

This paper describes the development of two tools to reduce rework in an attempt to meet Raytheon's goals. One is a manufacturing/Earned-Value Measurement System monitoring tool. The second tool determines the factors during the design and planning phases of a project that affect rework. Developing these two tools will help increase transparency on the manufacturing shop floor and help reduce the amount of rework performed.

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Finally, I'd like to thank my friends and family, and especially my roommate Adriane Faust, for putting up with the countless hours I've spent working on this internship and thesis. I couldn't have done this without everyone's support.

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Biographical Note

Michael Liu was born in Silver Spring, MD. He attended Duke University, where he majored in Electrical Engineering and Computer Science. Upon graduation, Michael worked for Akamai Technologies, an Internet startup founded by an MIT graduate student and professor. After working for Akamai for 2 years, Michael left to work at Northrop Grumman. For 3 years, he worked on multiple aspects of power distribution units for space applications. It was during this time that he developed the versatility in skills, as well as the leadership skills which have served him well at LFM. Also during this time, Michael earned an M.Eng. from the University of Maryland.

Michael is an avid golfer and volleyball player, as well as a chef. Michael looks forward to continuing these pursuits upon graduation from LFM.

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1. Introduction

This thesis covers the work performed during a 7-month internship at the Consolidated Manufacturing Centers (CMC) within the Raytheon Space and Airborne Systems (SAS) sector in El Segundo, CA. Over the last 10 years, Raytheon, and especially SAS, has seen tremendous growth within their industry. The Raytheon stock price has increased from a recent low of ~$20 in 2000 to a current trading price of ~$66[1]. Raytheon revenues have increased from $16B in 2002 to over $21B today, with operating margins varying between 7-11%[2]. In the last year, Raytheon has seen a 7% decrease in operating income, on only a 1% decrease in net sales[3]. As stated by Michael Hammer, "the only way to grow is to take market share … by operating at lower costs that can be turned into lower prices"[4]. To continue growing, Raytheon not only must concentrate on bringing in new sales, but must also focus on reducing their costs to improve their operating margins.

1.1. Problem Statement

The purpose of this internship is to improve Raytheon's operating margins by reducing the amount of rework performed on the manufacturing floor. To meet this goal, this thesis will detail a method for identifying and managing rework, while also developing a forward-looking approach to prevent rework from occurring by identifying important factors during the design and planning phase of a project which drive rework.

1.2. Thesis Overview

The following sections of this thesis document the analysis performed to help Raytheon decrease rework. Chapter 2 will describe the Raytheon environment. Chapter 3 will apply an enterprise architecting framework to changing the state of rework at Raytheon. Chapter 4 will analyze measuring the cost of rework on the manufacturing floor, and describe an approach to

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[1] (Basic Chart for RAYTHEON CO, 2008)

[2] (Financial Statements for Raytheon Company, 2008)

[3] (Q407_Press_Release, 2008)

[4] (Hammer, 2004)

monitoring and managing rework. Chapter 5 will discuss a forward looking approach to managing rework by analyzing the factors during the design and planning phases which effect rework. Chapter 6 will discuss the survey which was performed to determine the most important of these factors. Chapter 7 will discuss the model developed based on the factors from the previous chapter. Chapter 8 will give recommendations for Raytheon, and areas where they have opportunities to improve. Chapter 9 will conclude the thesis.

2. The Raytheon Environment

To improve the operations of Raytheon, an analysis of the company through a three lens analysis (strategic, organizational, culture) was performed. The analysis of the company from these three lenses helped direct the overall analysis on rework.

2.1. Raytheon's Strategic Environment

To meet their challenges, SAS employs a modified version of a matrix organization. As shown in Figure 1, there is a typical matrix organization between Programs and Operations functions. Both of these functions report to the VP of operations, but the Programs group reports to the P&L Business Units as well.

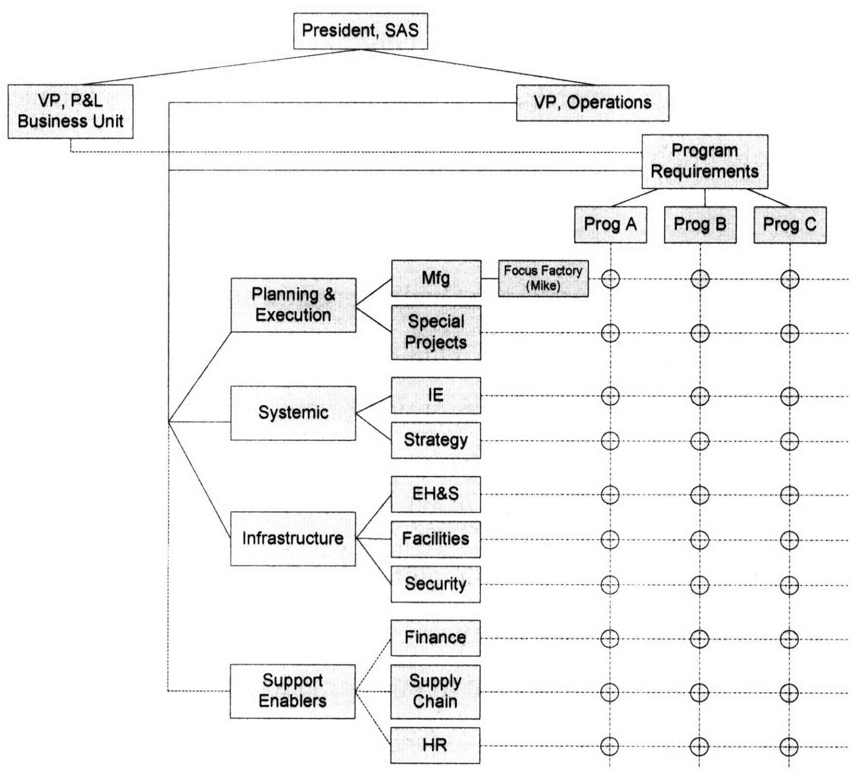

Figure 1: Diagram of Organization Structure

The challenge this structure posed to the project was the need to identify the relevant stakeholders in each of the groups. Rework was a major initiative, which was started by the upper management of SAS. Because of this, almost every group had input into reducing rework.

To be successful, this project had to develop relationships with each of the groups, and gain their support in gathering data and performing studies.

2.2. Raytheon's Organizational Environment

The analysis through the organizational lens shows a misalignment between the different functional groups. One sign of this is within one of SAS's main tools for rework, the Corrective Action Board (CAB). The group is supported by different functional responsibilities: quality, program management, shop floor supervisors, and planning. However, the IT group is not present. A byproduct of IT's lack of inclusion has been a delay in the updating of tools to support the initiatives of the manufacturing shops and the CAB. An initiative was started to reduce the number of non-conformance (NC) codes used on the shop floor. Currently, the unneeded NC codes still appear in the shop floor control software. Having the unneeded codes has led to errors in data reporting, which skews data and requires hours of manual inspection to correct. Any initiative to improve rework will need the support of IT to help with its implementation.

Another observation from this analysis is the Quality organization's role in the rework initiative. Within Raytheon's manufacturing processes, Quality monitors the flow of the product and has the ability to stop it. In fact because of an almost universally schedule driven culture, they seldom exercise their ability to stop product because of rework, but instead simply make sure it is properly documented. Because of this, Quality's role within the rework initiatives has been somewhat marginalized. Quality has the equivalent of an "Andon" cord, which it could pull to stop production, and help signal if there are major issues occurring within the manufacturing floor. However, because of Raytheon's need to push product, this cord is rarely pulled, and everyone just works as hard as they can to keep the product moving. Also, because issues are not being brought to the forefront, this has contributed to a decrease in the feedback loop necessary to prevent further rework. Any rework initiative will need to strengthen this information feedback loop with the Quality organization.

2.3. Raytheon's Cultural Environment

One of the most challenging aspects of this project has been overcoming some of the ingrained culture of Raytheon. One of those characteristics is Raytheon's "Schedule-Driven" culture. Because of this culture, firefighting, "the unplanned allocation of resources to fix problems discovered late in a product's development cycle" [5], is employed to solve issues. Firefighting has reinforcing and viral effects in product development[6]. Once firefighting occurs on one project, it can suck resources from another, which creates a reinforcing loop that spreads throughout the organization. Another reason is the overarching burning platform for SAS to push product. There have been occasions, where the need to push product has led to meeting short-term goals, but a lack of long-term beneficial actions. For instance, there are times when manufacturing will find work-arounds, as opposed to finding the true root cause. Although this will keep product moving, this may not necessarily prevent the issue from occurring again in the future. An example of this is a shop floor worker who kept a jar of screws on his desk. This jar contained all the screws that wouldn't fit in their designated location. The worker would simply throw the screw in the jar and get another out of stock, hoping it would fit. The worker brought this topic to their management, but was told to continue as is. After going through hundreds of screws, a Six Sigma team finally noticed the screws and did a root-cause analysis. By finding the root cause, they found incorrect tolerances on the screw. Fixing the drawing led to a decreased amount of scrap. In the rush to push product out the door, analysis is sometimes skipped. Unless a concerted effort is made to overcome this culture, it will be difficult for any improvement initiatives to succeed.

Another issue within SAS is their tribal culture. Information does not freely flow between groups. Although people are more than happy to discuss their thoughts and share information, it's only after they are approached. This is especially true with the tools that different groups develop. A group could build a really great tool, but the information isn't broadcast to other groups, which can lead to repeated effort of other groups building something similar to what the

---

[5] (Repenning, Understanding Fire Fighting in New Product Development, 2001)

[6] (Repenning, Goncalves, & Black, Past the Tipping Point: The Persistence of Firefighting in Product Development, 2001)

original group has already built. Lines of communication must be developed to keep different groups from repeating the efforts of others.

3. Enterprise Architecting Framework

Before describing the initiatives started to address rework, it is useful to take a look from an enterprise architecting standpoint. Shown in Figure 2 is the framework which shows the seven views from which an enterprise (or in this case an initiative) can be analyzed. By defining the current ("As-Is") state of the enterprise, these views can be used to ensure a smooth transition to the future state of rework at Raytheon.

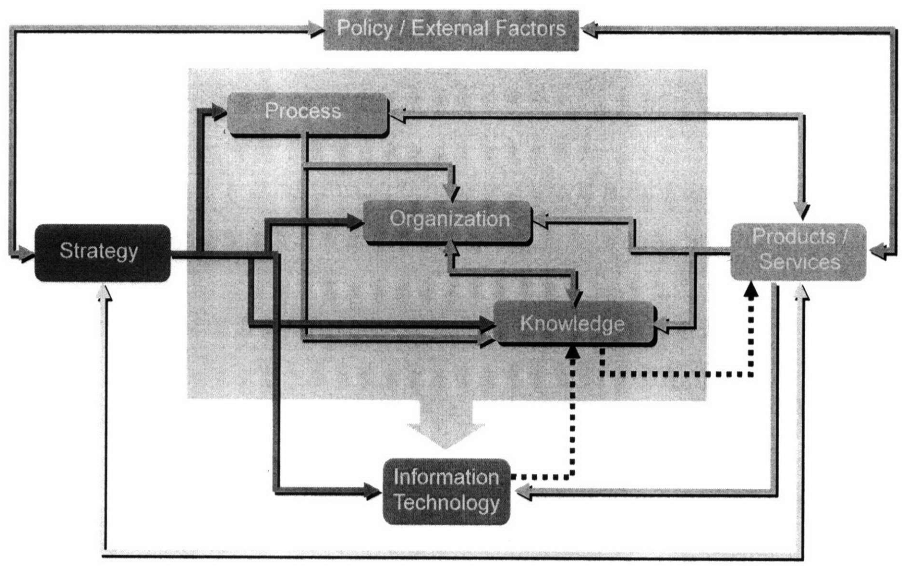

Figure 2: Enterprise Architecting Framework[7]

3.1. Strategy View

Raytheon SAS has thrived on being "a leader in designing and developing advanced, integrated systems for crucial missions"[8]. Because of this, Raytheon has developed a strategy of allowing their engineers to take whatever steps necessary to develop high-performing products. In the future effort to reduce rework, this is an issue which needs to be addressed. A balance will need to be struck between high performance and manufacturability/reliability.

---

[7] (Nightingale, 2007)

[8] (Raytheon Company: Businesses: Space and Airborne Systems)

3.2. Policy View

As a government contractor, Raytheon must abide by fairly strict guidelines on the quality of the product. Raytheon must also deal with the external factor of public opinion. With the current focus on the US Military, any failures by Raytheon products could be exposed to the public and have detrimental effects on the brand. These two factors help reinforce the need for reducing rework.

3.3. Process View

Raytheon is very much a process driven company. There are processes built around every action the company must take, as mandated by many of their contracts. By building an awareness into the existing processes, this will help expand the use of the tools developed during this internship for rework.

3.4. Organizational View

This section was detailed previously in Chapter 2.

3.5. Knowledge View

Raytheon is building a culture of being data-driven. Through lean/six-sigma efforts that Raytheon is performing, it has brought data gathering to the forefront. The amount of data that has been collected can be leveraged to perform the rework model.

3.6. Information Technology View

Over the years, with the many acquisitions that Raytheon has made to grow their business, this has caused Raytheon to develop many different IT systems. This complex system has been a hindrance on Raytheon's drive towards a unified, data-driven company. The company is currently undergoing a unification of their IT systems. By developing new tools with this unification initiative in mind, this will help improve their adoption and usefulness throughout the whole Raytheon rework initiative.

3.7. Service/Product View

Raytheon SAS develops a wide variety of products. Some of the key capabilities that have been developed by SAS are[9]:

- Airborne radars and processors
- Electro-optic/infrared (EO/IR) sensors
- Electronic warfare and precision guidance systems
- Active electronically scanned array (AESA) radars
- Space and missile defense technology
- Intelligence, surveillance and reconnaissance (ISR) systems

By having such a wide variety of expertise, any rework tools and processes that are developed will need to be generic enough to meet the needs of all of these different areas.

[9] (Raytheon Company: Businesses: Space and Airborne Systems)

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4. The Monitoring of Rework

4.1. Initial endeavors

One of the first challenges was assessing the current methods that were being used to approach rework. This was an attempt to avoid the trap of repeating the work other groups had already accomplished. There were many initiatives being headed by different functional groups.

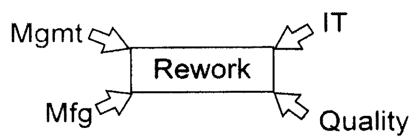


Figure 3: Diagram of Rework Initiatives

4.1.1. Management Initiatives

One of management's primary tools is the four corner diagram. These diagrams highlight how each of the manufacturing centers were performing with regards to rework, what the issues were that the manufacturing centers were experiencing, then would highlight the initiatives that were being taken to address the rework issues and the people responsible for those initiatives.

4.1.2. IT Initiatives

IT has developed many monitoring tools to help track rework. One of these tools helps keep track of NC's, and perform trend analysis on them. It also shows the trends of different performance factors. Along with this, IT has worked on customizing the capabilities within the manufacturing software, Visiprise Manufacturing (VM), to better track the amount of rework performed.

4.1.3. Manufacturing/Quality Initiatives

Quality and Manufacturing are approaching rework through the execution of the CAB's. The purpose of these CAB's is to review what issues have come up in manufacturing during the week. Within some of the manufacturing centers, they have also simplified the problem by grouping the issues that occur in manufacturing within a set of fifteen problem codes. By reducing the number of problem codes, this leaves people with a set of data that is understandable and actionable. The list of problem categories is listed below.

Non-Conformance Category	Description
Testing	Any defects associated with testing
Kit	Any defects associated with parts kitting
Conformal Coat	Any defects associated with conformal coat
Symbolization	Any defects associated with symbolization (markings)
Planning	Any defects associated with planning & VM setup
Eng Dwg	Any defects associated with engineering drawings
Electronic Component	Any defects associated with electronic components
Electronic Solder	Any defects associated with electronic solder
Other	Any defects that you cannot associate with the other categories
Exposed Copper	Any defects associated with exposed copper
Exposed Fiber	Any defects associated with exposed fiber
Lifted pads	Any defects associated with lifted pads
FOD	Any defects associated with Foreign Object Damage
Information	General Information
Wires	Any defects associated with wiring

Table 1: Table of Non-Conformance Categorizations

Along with the CAB, manufacturing also performs daily morning meetings to go over the status of different components. This helps ensure that there is feedback loop of information between manufacturing floor managers, planners, quality and management.

4.2. Cost of Rework (COR)

The cost of rework can have huge implications on the margins of a project. Estimates in the construction world put the cost of rework as high as 12.4% of total cost[10]. And these cost estimates may be conservative. There are many factors which can be considered when determining the cost of rework. The following is a list of some of those factors[11]:

[10] (Love, Edwards, & Smith, A Forensic Examination of the Causal Mechanisms of Rework in a Structural Steel Supply Chain, 2005)

[11] (Williams, Griffin, & Attaway, 2001)

- Reworking and correcting mistakes and problems in the field
- Responses to complaints made to regulatory agencies
- Increased audits and inspections
- Loss of customer trust, goodwill and business
- Effects of negative word-of-mouth among customers
- Increased marketing costs due to customer turnover
- Lost market share due to customer defections
- Wasted materials and supplies
- Unnecessary litigations

While these costs should be considered, the focus of this part of the internship has been with the direct labor costs associated with rework.

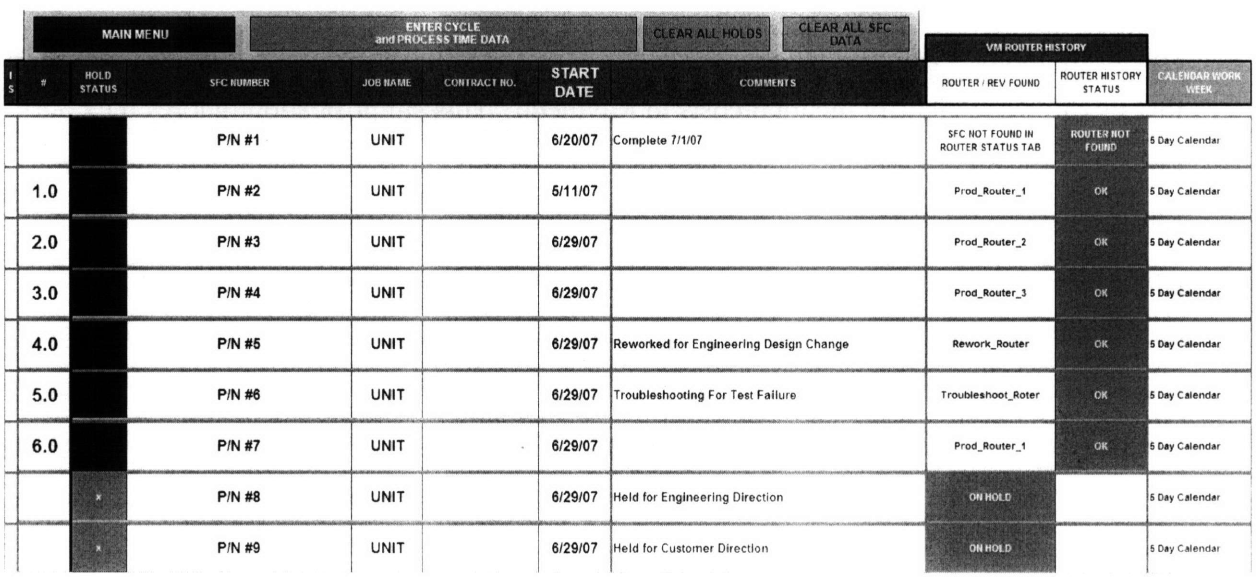
To determine the cost of rework, much time was spent attempting to relate costs to each rework operation performed. The simplest answer to this question was to determine how many manufacturing hours were associated with each rework operation. One of the limitations to this was that it would not identify the total costs to Raytheon. This simplification ignores the hours spent by other functional groups (Management, Engineering, Quality, Planning), or the cost associated with possible scrapped material. Even with this simplification, the task ended up being more difficult than expected. First, rework was not easily designated within the VM system. There were multiple paths that were attempted to approximate the actual rework hours, but in the end, they all ended up fairly fruitless. There were too many exceptions to the rules that made it difficult to collect any sort of usable data. Other groups, including IT, were working on implementing processes to simplify the collection of rework data within the system, but none had been implemented before the completion of this study.

4.3. Earned-Value Measurement System (EVMS) Tool

Because of the difficulties with collecting rework data, time had to be spent working on modifying the EVMS tools, which were already present. By helping to improve these tools to a point where they were more usable, slow-downs in manufacturing could be better detected, which often could illuminate any rework issues.

4.3.1. Manufacturing Summary Tool

One of the first tools to be updated was the manufacturing summary page. This tool gives a quick summary of the amount of product that is flowing through the manufacturing floor, and what the progress of the parts is. If there are issues with any of the products being built, they will be flagged, and a description of the issue, usually followed by an expected resolution time, is noted. A screenshot of the tool is shown in Figure 4. By having this tool, management can quickly see what the progress of the manufacturing floor is, and if there are any systemic issues, they will usually be noted on the multiple copies of the same product that are being manufactured. With these issues being flagged, management can take action to correct the issue, and flow down any information back to the planning/engineering groups.



I S	#	HOLD STATUS	SFC NUMBER	JOB NAME	CONTRACT NO.	START DATE	COMMENTS	ROUTER / REV FOUND	ROUTER HISTORY STATUS	CALENDAR WORK WEEK
			P/N #1	UNIT		6/20/07	Complete 7/1/07	SFC NOT FOUND IN ROUTER STATUS TAB	ROUTER NOT FOUND	5 Day Calendar
	1.0		P/N #2	UNIT		5/11/07		Prod_Router_1	OK	5 Day Calendar
	2.0		P/N #3	UNIT		6/29/07		Prod_Router_2	OK	5 Day Calendar
	3.0		P/N #4	UNIT		6/29/07		Prod_Router_3	OK	5 Day Calendar
	4.0		P/N #5	UNIT		6/29/07	Reworked for Engineering Design Change	Rework_Router	OK	5 Day Calendar
	5.0		P/N #6	UNIT		6/29/07	Troubleshooting For Test Failure	Troubleshoot_Roter	OK	5 Day Calendar
	6.0		P/N #7	UNIT		6/29/07		Prod_Router_1	OK	5 Day Calendar
		×	P/N #8	UNIT		6/29/07	Held for Engineering Direction	ON HOLD		5 Day Calendar
		×	P/N #9	UNIT		6/29/07	Held for Customer Direction	ON HOLD		5 Day Calendar

Figure 4: Page of Parts on Manufacturing Floor

4.3.2. Manufacturing Progress Tool

The second tool developed for this project was the manufacturing progress tool. This tool breaks down each product to its individual manufacturing operations, and tracks the progress that is made each day. The key feature of this tool is that it allows management to follow the progress of each operation, and if any of the products start falling behind in their progress, they will be flagged, and management can take any corrective action as necessary. A screenshot of the tool is shown below in Figure 5.

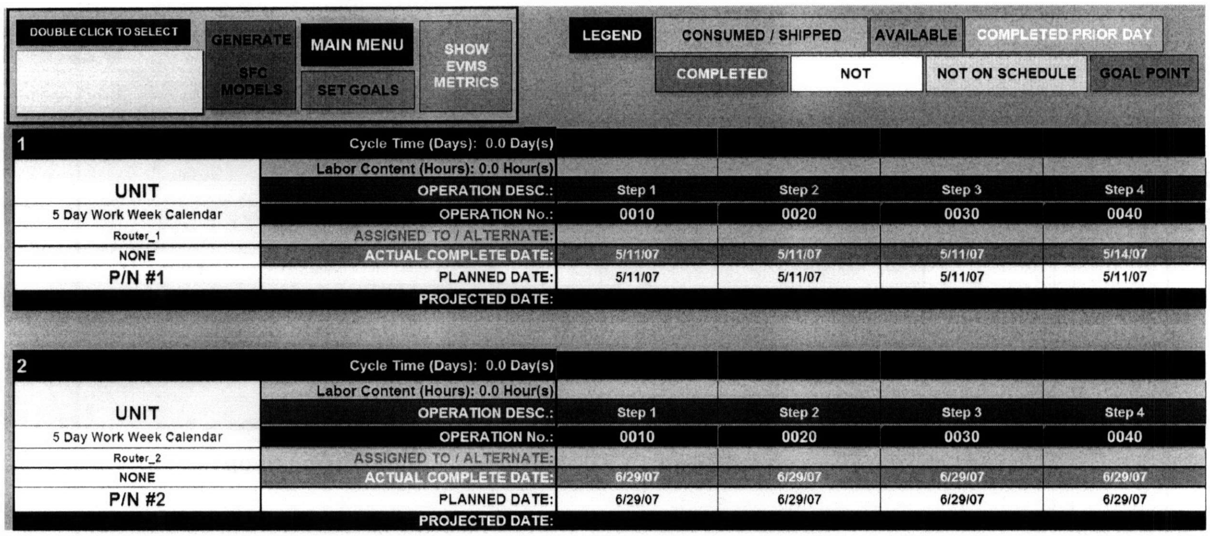


Figure 5: Progress of Parts on Manufacturing Floor

4.3.3. EVMS Metrics Tool

The final piece of the tool suite written for this study is the EVMS metrics suite. This tool tracks the EVMS metrics for each of the products flowing on the manufacturing floor, both current and historically. Two of the primary metrics are the Cost Performance Indicator (CPI) and the Schedule Performance Indicator (SPI), detailed in Appendix A. These metrics give management the ability to assess the productivity of the manufacturing floor, and also show if manufacturing is slipping on one of its products. If the CPI begins to decrease, this will show management that the product is slipping in regards to the expected hours spent. The slippage could be the result of improperly budgeted hours for the operations, or could signify unexpected problems occurring. Either way, management attention is needed to correct the issue. A screenshot of the tool is shown below in Figure 6.

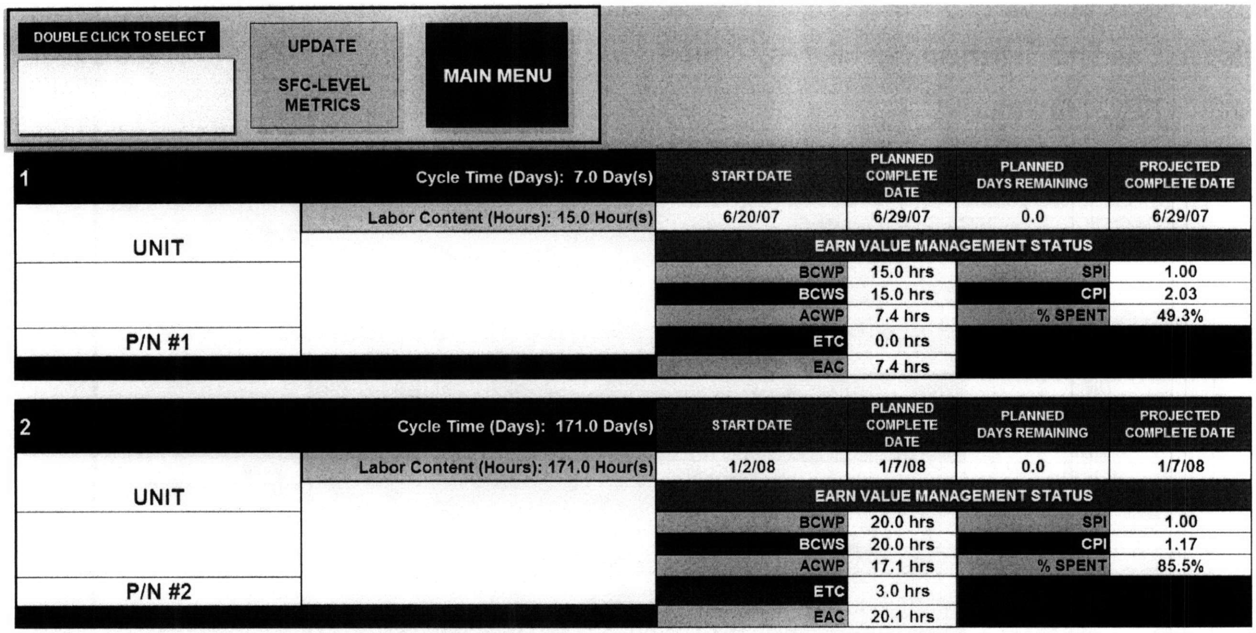


Figure 6: Summary Page of EVMS Status of Manufacturing Shop

4.3.4. Next Steps

By implementing the changes and improving the performance of the system, it made for a more workable system. However, there is still room for improvement. One major area for improvement is in the sustainability of the system. Currently, for this suite of tools to update its data, a report is sent to a person, who must use the import tools within the system to update the data. By having a person in the process, this reduces the reliability of the system. It is also a tedious task, which makes it less likely that the person assigned the task will be excited about performing the task each day. Also, because a person is involved, if that person is out of the office, then there was usually a scramble to find someone who had access to update the data. For the next revision of the tool, it should be implemented using an automated data pull. There is a system in place that will allow programs to programmatically pull data, thus removing the need for a person.

Another drawback of the system is the amount of resources it consumes. There are two reasons for this. One is the fact that there is an individual instance of the tool for each program that is being worked on in the manufacturing floor. Because of this, there are multiple copies of the tool floating around which use up disk space, as well as administrator time. Whenever an update is needed to the system, the administrator must manually update each copy of the tool. Secondly, there is not a strong archival system set up within the tool. Therefore, multiple copies of the tool are kept at different time periods for archiving purposes, also a waste of resources. Finally, the tool was originally built with the wrong architecture. If a database backend had been used, many of the previous issues would have been resolved.

4.4. Conclusion

This tool helped improve the transparency of the manufacturing floor. By watching the metrics shown in this suite of tools, management had the information and opportunity to reduce rework. By catching problems as soon as they happened, solutions could be put in place to keep other products from having the same issues. But with the current state of the tools, there are still many areas that are lacking, which could be improved to help the usability of the tools.

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5. The Rework Factors

5.1. *Motivation*

As important as it is to deal with rework on the manufacturing floor, it can be very expensive to take care of it there. The most cost effective solution to rework is to prevent it from happening. As stated by Love *et al.*, "Delays in defect identification increase the cost of rectification, especially if work activities have already been completed"[12]. To do this, the next phase of this project looked at the design and planning phases. At this point, because the hardware has not been built, making corrections is usually a matter of identifying the required change in the design, performing the required analyses, and updating engineering and manufacturing documentation, as opposed to documenting a fix and making changes to production hardware. This part of the internship attempted to determine what factors during the design and planning phase were contributing most towards the amount of rework performed.

5.2. *Methodology*

Much of the remaining research performed follows a study conducted by Dr. Peter E.D. Love *et al*[13]. While Dr. Love's research was centered on the construction industry, much of the reasoning and methodologies can be applied to Aerospace manufacturing. The first step is to develop a broad set of categories which will encompass the factors. Following that, within the areas, the major factors were developed. Next, a survey was given to relevant parties to assess the importance of each of the factors. While the survey from Dr. Love's group used a five-point Likert scale, the survey for this internship was reduced to choosing only the five most important factors, and not a ranking of all of the factors. Finally, the data was used to develop a model of total rework cost. Love's model is based off the results from their survey, while the model of this internship is intended to be based off of historical Raytheon data.

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[12] (Love & Edwards, Determinats of Rework in Building Construction Projects, 2004)

[13] (Love, Irani, & Edwards, A Rework Reduction Model for Construction Projects, 2004)

5.3. Rework Areas

There are many factors during the design and planning phases which can contribute to rework. Love *et al.* propose poor communication, lack of information-flows, and decision-making as strong contributors[14]. Another factor is the amount of Concurrent Engineering (CE) that is performed during the initial phases of a project. Figure 7 illustrates this complexity:

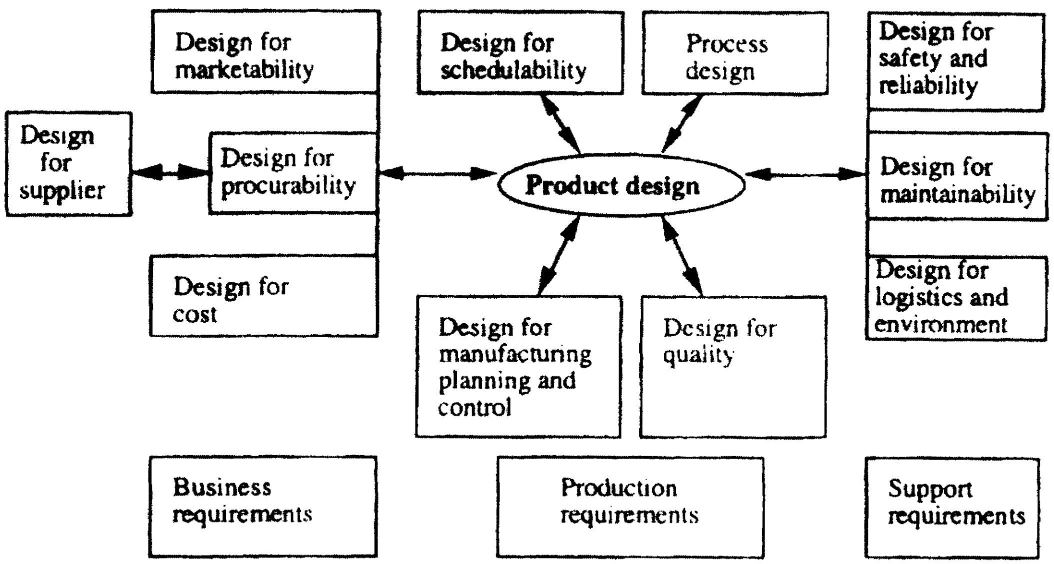

Figure 7: The role of functional areas in a CE environment[15]

As stated by Dowlatshahi, "Design decisions made in the early phases of product design and development will have a significant impact upon future manufacturing and support activities"[16].

By combining the factors discussed by the supporting references with the environment of Raytheon, seven major areas of study were developed: Gating, Engineering, Supplier Selection, Requirements, Manufacturing, Planning and Materials Complexity. Interviews with most

[14] (Love, Edwards, & Smith, A Forensic Examination of the Causal Mechanisms of Rework in a Structural Steel Supply Chain, 2005)

[15] (Dowlatshahi, 2001)

[16] (Dowlatshahi, 2001)

functional groups were performed to develop the list of rework factors. The following sections describe the factors investigated.

5.3.1. Gating Factors

At Raytheon, there is a gating process which is used throughout the development of a product. There are ten gates which a product must pass through to reach delivery to a customer. From the interviews performed, these are the factors that were identified for the gating process:

- Management Best Processes
- Number of Design Reviews
- Operations Involvement During Design Reviews

The theory behind these factors is that if the design reviews for each gate are performed properly with the appropriate groups in attendance, then they will be able to find any issues with the product, anywhere from the contract to the design to the manufacturing plan.

5.3.2. Engineering Factors

One of the most important aspects of a product is the engineering that goes into it. In this area, there were many opportunities for improving a factor and reducing rework. Here is the list of factors that were assessed:

- Engineering Designer Experience
- Engineering Hours Bid vs. Program Management Office Hours Bid
- Engineering Actual Hours Spent vs. Scheduled
- Engineering Module Produced
- Number of Engineering Change Order
- Percentage of Testing Performed at Different Assembly Levels
- Early Involvement of Advanced Manufacturing Engineering
- Early Involvement of Manufacturing Shops/CMC's

These factors break down to a couple of main areas. One of those is the ability of the engineers. The amount of experience they have may affect the quality of the product developed. Another area is the bidding of the engineering work. The program managers and the engineering managers need to bid the hours correctly such that the engineers doing the design have the correct amount of time to complete the designs. If they have not, it is possible that this could be causing undue stress resulting in the engineers making mistakes. The engineers may take shortcuts in an attempt to meet the difficult schedules they are assigned. Conversely, they may be gold plating the designs to fill the amount of the time they are given. In addition, the program management may try to save money by not building an engineering module (prototype), which could drive rework higher. There was also a concern around whether the testing was being developed correctly. Tests being performed may not be catching problems at their lowest level possible. If this is the case, a lot of extra work could be done on a product that in the end needs to be taken apart anyway. By driving more of the testing at lower levels, there is an opportunity for reducing rework. Finally, as proposed by Adler, the management of the design / manufacturing relationship (DMR) has become a key competitive variable in the timely delivery of product[17]. By involving manufacturing and AME early and often during the design process, this can improve the manufacturability of the product.

5.3.3. Supplier Selection Factors

Another area of concern is the selection of suppliers. These are the factors which were investigated:

- Range of Bid Values
- Number of Subcontractors on a Project
- Number of Supplier Assessments Performed
- Percentage of Commercial Products Used

The choice of supplier can play a major part in the design. Because so many parts are custom, and require tight tolerances, by selecting the wrong supplier, rework could be increased. If effort

[17] (Adler, 1995)

is not put into validating the abilities of the suppliers, then they may fall short of the designer's needs. Also, with the goal of driving down costs, using commercial off the shelf (COTS) components, this could lead to using parts which do not have the reliability or tolerance levels needed to build the sophisticated products of Raytheon.

5.3.4. Requirements Factors

One of the most important parts of the product development cycle is the development of the requirements. These can have wide ranging effects. If the requirements are not developed correctly, then this can have a great effect on rework. The product may not meet the customer's needs, which could require costly redesign and rework of the product. These were the quantifiable factors which were investigated:

- Number of Requirements
- Number of Requirements Document Revisions
- Maturity of Product

Paying more attention to these factors could end up reducing the amount of rework performed.

5.3.5. Manufacturing Factors

The actual manufacturing of the product can have large effects on the amount of rework performed. Thus, there are a large number of factors to be investigated:

- Maturity of Processes
- Statistical Process Control Used
- Operator Experience
- Planned Production Rate
- Support Budgets

Some of the factors investigated are more a measure of the complexity of the product, as opposed to its rework issues. These factors can have a direct effect on the product being produced. By having a mature process, it is more likely that the product will have already flushed out any rework issues that may occur. Support budgets play a factor in that if there is not enough money for support, then equipment may not get serviced as often as it should, or the design and test engineering groups may not be able to spend as much time on the manufacturing floor, thus slowing down the resolution time for issues which may occur.

5.3.6. Planning Factors

Planning is the phase of production where the assembly instructions are developed. The following is the only factor that was investigated.

- Number of Planned Production Routers

This factor ends up being more a measure of the complexity of the product than anything else. Its direct tie into rework is debatable, but was included to show the importance and difficulty of finding factors during the planning phase. Overall, the group knows that planning plays an important part in rework, but it is difficult to enumerate the actual factors.

5.3.7. Materials Complexity Factors

The final area of study is in the complexity of the materials. The following are the factors which were investigated:

- PCAT Complexity Estimate
- Part Novelty
- Material Re-Use Utilization

The idea behind these factors is that Raytheon's ability to estimate the cost of the product could be a good measure for how much rework will need to be done. Also, if the part is very different than anything else that has been developed, then it might also be a factor in rework. Finally, if the design is building on previous designs and using components from those parts, then possibly that could also drive rework.

6. Rework Survey

To begin assessing these rework factors, a first pass at reducing the number of factors was performed. Two criteria were used for this first reduction: personal experience from the author, and ability for the factor to be quantified. From the first reduction, these are the factors which remained:

- Program Management Best Practices
- More Detailed Design Reviews
- Early Involvement of Advanced Manufacturing Engineering
- Early Involvement of Manufacturing Shops/CMC's
- Design Team Involved Through Low Rate Initial Production(LRIP)
- Increasing Engineering Designer Experience
- Reducing the Difference Between Engineering Bid and PMO Bid
- Reducing the Difference Between Bid Delivery Date and Actual Delivery Date
- Reducing Engineering Model (EM) Development Overlap w/ Production
- Selecting Suppliers Based on Supplier Assessment Data along with Price
- Reducing the Percentage of Commercial Components Used
- Increasing the Percentage of Requirements Tested at Lower Level
- Increasing % of Budget Allocated to Manufacturing Support
- Increasing Manufacturing Equipment Maintenance Budget
- Increasing Design Re-Use
- Improving Planning
- Improving Operator Training
- Reducing Manufacturing Operator Turnover

Once the factors were reduced, a survey to be taken by a wide range of employees throughout different functional groups was produced. The survey is shown in Figure 8-10.

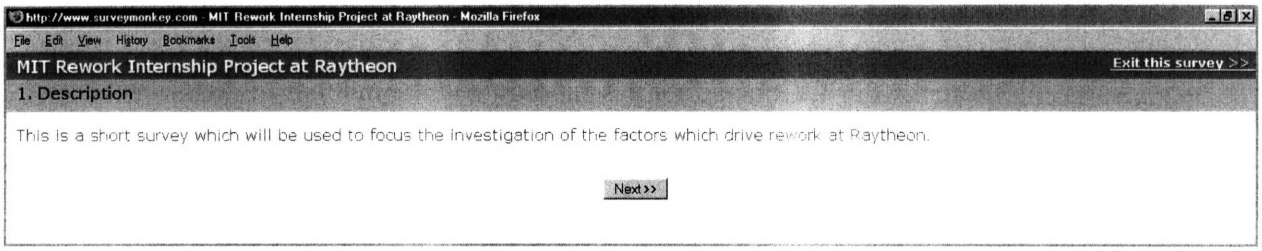

Figure 8: Survey Page 1

This first page of the survey is a brief introduction to the survey.

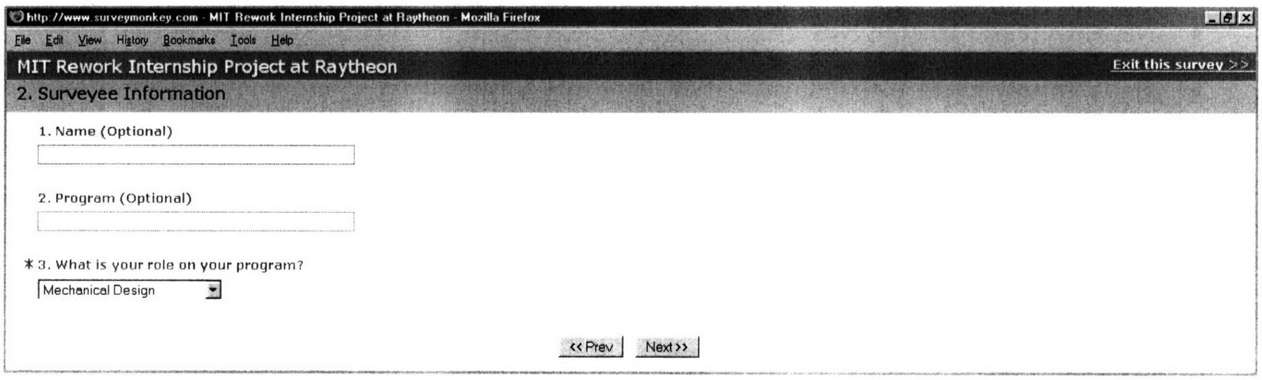

Figure 9: Survey Page 2

The second part of this survey is intended to obtain some metrics on the people answering the survey. Especially important is the role the person plays.

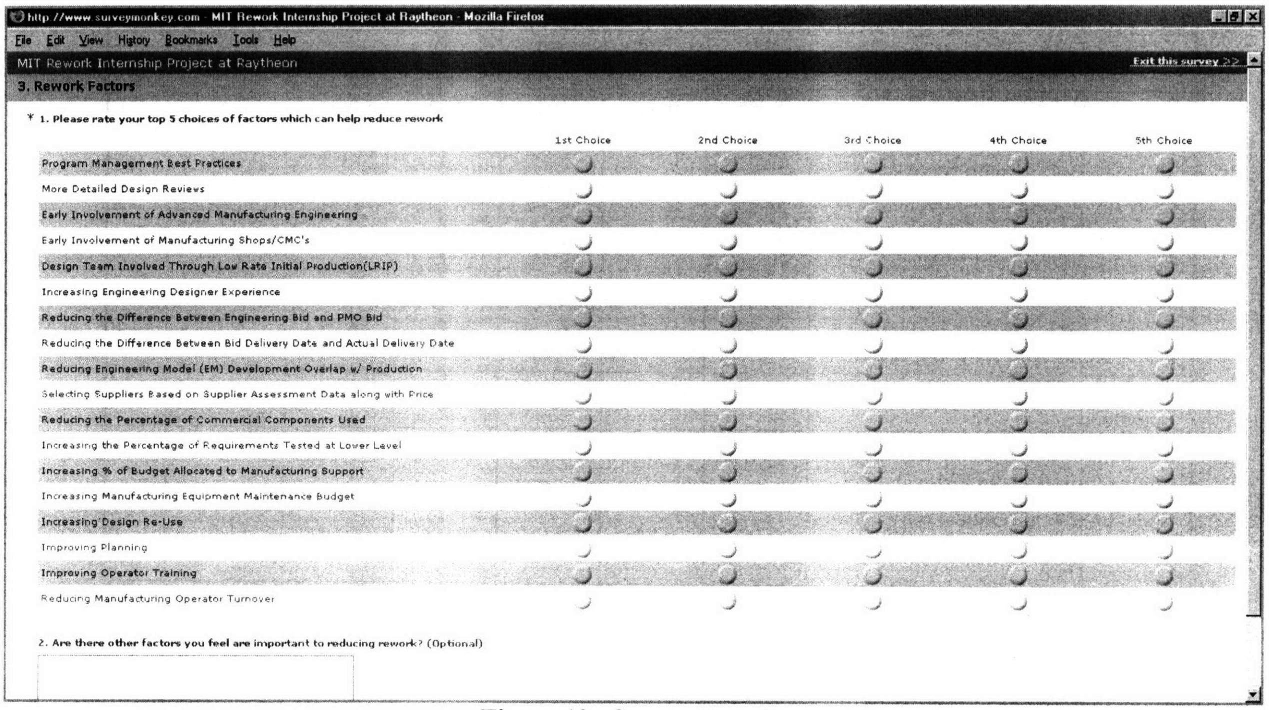

Figure 10: Survey Page 3

The final page of the survey asks the person to choose their top five choices of factors which can help reduce rework. There is also the opportunity to give a free form response as to their opinion on factors which may have been missed.

6.1. Survey Results

There were a total of 35 responses to the survey, spanning 9 different functional groups. Table 2 summarizes the results of the survey.

	1st Choice	2nd Choice	3rd Choice	4th Choice	5th Choice	Rating Average	Score
Program Management Best Practices	20.0%	0.0%	0.0%	20.0%	60.0%	2	10
More Detailed Design Reviews	66.7%	0.0%	16.7%	11.1%	5.6%	4.11	74
Early Involvement of Advanced Manufacturing Engineering	26.3%	36.8%	21.1%	10.5%	5.3%	3.68	70
Early Involvement of Manufacturing Shops/CMC's	10.5%	26.3%	26.3%	31.6%	5.3%	3.05	58
Design Team Involved Through Low Rate Initial Production(LRIP)	16.7%	41.7%	16.7%	8.3%	16.7%	3.33	40
Increasing Engineering Designer Experience	21.4%	28.6%	28.6%	14.3%	7.1%	3.43	48
Reducing the Difference Between Engineering Bid and PMO Bid	25.0%	25.0%	0.0%	25.0%	25.0%	3	12
Reducing the Difference Between Bid Delivery Date and Actual Delivery Date	0.0%	0.0%	25.0%	0.0%	75.0%	1.5	6
Reducing Engineering Model (EM) Development Overlap w/ Production	33.3%	0.0%	33.3%	16.7%	16.7%	3.17	38
Selecting Suppliers Based on Supplier Assessment Data along with Price	7.1%	21.4%	21.4%	28.6%	21.4%	2.64	37
Reducing the Percentage of Commercial Components Used	0.0%	0.0%	0.0%	0.0%	100.0%	1	2
Increasing the Percentage of Requirements Tested at Lower Level	0.0%	33.3%	0.0%	33.3%	33.3%	2.33	14
Increasing % of Budget Allocated to Manufacturing Support	0.0%	22.2%	22.2%	33.3%	22.2%	2.44	22
Increasing Manufacturing Equipment Maintenance Budget	0.0%	0.0%	0.0%	50.0%	50.0%	1.5	6
Increasing Design Re-Use	0.0%	20.0%	0.0%	60.0%	20.0%	2.2	11
Improving Planning	10.0%	20.0%	40.0%	10.0%	20.0%	2.9	29
Improving Operator Training	14.3%	7.1%	14.3%	21.4%	42.9%	2.29	32
Reducing Manufacturing Operator Turnover	25.0%	50.0%	25.0%	0.0%	0.0%	4	16

Table 2: Survey Results

A weighted scoring system for each factor was used to develop the score:

$$Score = 5 * \# \, of \; 1st \; Choice + 4 * \# \, of \; 2nd \; Choice + 3 * \# \; 3rd \; Choice + 2 * \# \; 4th \; Choice + \# \; 5th \; Choice$$

From this scoring system, these were the top five responses:

- More Detailed Design Reviews
- Early Involvement of Advanced Manufacturing Engineering
- Early Involvement of Manufacturing Shops
- Increasing Engineering Designer Experience
- Design Team Involved Through Low Rate Initial Production (LRIP)

Later sections will go into more in depth analysis of each of these rework factors.

6.1.1. Other Suggested Factors

From the survey conducted, many other factors were suggested. They are listed here:

- End to end system engineering ownership
- Not just operator training, but training in general
- Don't start designing without architectures and requirements defined
- Minimizing changes to the existing design
- Design For Six Sigma
- Make sure Design For Manufacturing and Assembly (DFMA) is done on each product.
- Take time to follow our defined processes.
- Involve Manufacturing Engineering in supplier selection process
- Working as a true cross-functional Integrated Product Team (IPT) to determine rework causes and priorities instead of assigning one or two support functions to work it.

All of these factors certainly play a role. One of the conclusions is that Raytheon should focus much of its attention on DFx. Some of the benefits of DFx are that it "forces the development team to think about the production process; it brings representatives from different disciplines into the same room, and it forces a consideration of several alternative detail design strategies"[18].

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[18] (Ulrich, Sartorius, Pearson, & Jakiela, 1993)

By building DFx processes around the design process, this could lead to better designs with less rework. Another suggestion was better teamwork. Employees realize the need to create more cross-functional teams with end to end ownership of the product as a key to reducing rework. All of these suggestions are valid, and could be researched in future Raytheon efforts around rework.

6.2. The Key Factors

Looking at the key factors found by the survey, they correlate with the research performed by Palaneeswaran *et al.* From their research, some of the areas of interest were[19]:

- Avoiding design errors, omissions and other non-conformances (e.g. through appropriate design reviews, independent checking arrangements and relevant quality management systems)
- Reducing design changes and adversarial conflicts (e.g. through better briefing, enhanced stakeholder interactions and their early involvements, improved scope definitions including freezing from further changes, etc.)
- Hiring suitable design team members and moreover, keeping commitment of the key personnel throughout e.g. for essential design tasks and main design management roles

This section goes into more detail on each of the key factors as highlighted by the survey.

6.2.1. More Detailed Design Reviews

This factor was by far the factor that groups felt was driving rework on the manufacturing floor. One concern here is that within Raytheon's gating process, there is a bit of ambiguity. Some gates can be skipped depending on certain parameters, which can lead to crucial design reviews being passed over. Secondly, there is a concern that design reviews don't go far enough to ensure the manufacturability of a product. A testament to this is the fact that recently Raytheon

[19] (Palaneeswaran, Ramanathan, & Tam, 2007)

made a change to their process, which will now include a group who will focus on manufacturability of products.

6.2.2. Early Involvement of Advanced Manufacturing Engineering

The Advanced Manufacturing Engineering (AME) group is responsible for the development of the planning package which instructs manufacturing on how to produce the product. There is a concern that because the AME's are not involved in the early stages of a design, that they will not be familiar enough with it to produce proper assembly instructions. Without proper documentation, this can lead to ambiguity on the manufacturing floor, which could lead to damage of the unit, or slow down of the manufacturing floor as they attempt to clarify the planning. By involving AME early, many of these issues can be avoided.

6.2.3. Early Involvement of Manufacturing Shops/CMC's

Along with the AME's, there is a need for the manufacturing shops to be involved with designs early on. There's a common belief that by all functional groups working together during the design phase, this will help generate a greater bond between the manufacturing and design groups. That way, they can collaborate on designs, ensuring that they meet the needs of the customer, while also taking manufacturability into consideration.

6.2.4. Increasing Engineering Designer Experience

Another important factor is the experience of the design engineers. Young, inexperienced engineers may not have the foresight to see where issues might be in their design. This could lead to the development of products which cannot easily be manufactured. By increasing the experience of engineers, there's a hope that this will reduce the amount of rework performed on the manufacturing floor.

6.2.5. Design Team Involved Through Low Rate Initial Production

The last important factor is the involvement of the design team through the low rate initial production phase. Typically, Raytheon will run through an initial phase of low-rate production to test out the manufacturing processes. Once they are convinced the manufacturing facility has the processes under control, the product will be ramped up to high-rate production. A concern here is that if the design team is not involved during the LRIP phase, there will not be the feedback loop necessary to prevent the issues found during LRIP from occurring again in the future. By including the designers during the LRIP phase, they can learn from the mistakes that were made and apply those lessons learned to future products.

7. The Rework Model

As the last step of this project, the beginnings of a mathematical model to correlate the rework factors and the number of rework hours performed were developed. Upon its completion, this model will help determine the relative importance of each factor, and give a program manager tools to help weigh different options.

7.1. Model Definition

The initial plan for the model was to do a linear regression of first and second order effects of the factors to determine their effect on rework. The model would have been of the following form:

$$\# \; of \; rework \; hours \; = \; k_1(Factor_1) + \; k_2(Factor_2) + \; k_3(Factor_1)(Factor_2) \ldots$$

Unfortunately, to develop such a model would have required hundreds of data points for each of the factors across multiple programs, which would have taken more time than allowed by the internship. As the next step, the survey was performed to reduce the number of factors to be focused on. This brought the number of data points down to a more reasonable number of factors. For the five factors that were determined from the survey, the following data would have been used to support them.

More Detailed Design Reviews: Of the five factors, this is the most difficult one to quantify. Possible measures include the number of design reviews performed on a project, or possibly the number of attendees for the design reviews. While these may not be the optimal measures for this factor, hopefully they can give a rough approximation of the utility of the design reviews.

Early Involvement of AME: To quantify this factor, the method used was to associate different charge numbers with a certain product, then by correlating that with the role of the people charging the number, this will tell how long after the first person started charging the project that the AME started charging. The model will use the number of days to quantify this factor. In addition, the estimated length of the project could be used to normalize out the length of the project as a factor.

Early Involvement of Manufacturing Shops/CMC's: This is similar to the AME factor, except the number of employees within the manufacturing shops/CMC's and the length of time each was first charged to a program are counted.

Increasing Engineering Design Experience: As an approximation for this factor, again by starting with the charge numbers, one can determine which engineers worked on a project. This can then be correlated with HR data to determine how long they have been working at Raytheon, which gives an approximation of the engineer's experience. Ideally, this data would be based off an engineer's career experience, but this data may not be within the Raytheon systems and would be more difficult to identify. By using the number of hours an engineer charged to a project, a weighted average can be calculated to determine the average engineering experience on the project. Again, to normalize, this average can be divided by the duration of the project to develop a ratio.

Design Team Involved Through Low Rate Initial Production: This factor can simply be a binary value of whether the design team was involved or not. One method to quantify this factor could be through looking at the budget plan of the project. Another method could be through an analysis of the charged labor hours. If engineers are charging to the project during the LRIP phase, this could be an indication of their continued participation with the program.

7.2. Obstacles

As useful as this model would have been to develop, in the end there were too many obstacles to overcome to complete this part of the project. One of the difficulties encountered during this portion of the project was the accumulation of data. While Raytheon strives to be a data driven company, there is still a lack of a central data system. Different bits of data reside in different data systems, and can be difficult to track down, especially with Raytheon's history of a tribal culture. While efforts have been made to reduce the number of different data systems, with the difficulty of integrating legacy systems, it will be a while before Raytheon simplifies this problem. Secondly, defining the correct fidelity for the data has been an issue. It has been difficult to determine whether the data should be determined on which level of assembly the data would need to be gathered on. If the data were aggregated at the top-assembly level of the product, this may have been the most effective, but would have required data collection across a large number of programs to develop a data set for a linear regression. But, while trying to take data on a lower sub-assembly, it may have been more difficult to quantify the different factors at the sub-assembly level, such as design reviews which cover multiple sub-assemblies, thus leading to a decrease in the accuracy and effectiveness in the model. Finally, time was a factor in the decision to not pursue the model. While this would have been a useful tool to be used, the difficulties stated above combined with the lack of time led to the rework model not being completed.

7.3. Next Steps

Once the full set of data has been collected and the model has been completed, the next step would be to integrate it with the EVMS tool. By building an interface to enter the factors into the EVMS, the tool could use the model to predict the rework hours for the manufacturing of the product. Also, assuming that the identification of rework is improved within VM or another data system, a rework metric, possibly Rework Performance Index (RPI) which would be similar to CPI, could be used to track rework performance. By implementing this feature, the EVMS tool would be a more complete tool for tracking the status of the manufacturing floor.

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8. Areas of improvement/Recommendations

For Raytheon to improve their operation, these are the key areas they need to improve.

8.1. Sharing of Software Tools

One of Raytheon's current impediments is the sharing of software tools. Different groups develop individual toolsets within their silos. By implementing a centralized system to keep track of the different tools being developed would go to great lengths to reduce overlap of tools. This would also create another communication channel between different groups. By one group having the ability to see the work of another group, they can talk with them to suggest improvements which would improve the software. This could also create a greater environment of collaboration between groups, hopefully aligning their goals of reducing rework.

8.2. Reduction of "Schedule-Driven" culture

One of the biggest challenges to Raytheon is its "Schedule-Driven" culture. Because of the organization's focus on the issues at hand, it is difficult for them to spend time dealing with other issues. By taking precautionary actions, such as completing the model of the rework factors during design and planning proposed by this thesis, as opposed to focusing on the issues of today, Raytheon will have the opportunity to see large gains in their operations.

8.3. Continued Focus on Rework

With the work that Raytheon has done, they can't lose track of their initiative. They must persevere and continue funding such projects as this internship to insure that they do not lose out on the gains they have found.

8.4. Improved Cross-Communication

As a last suggestion, from the results of the survey and interviews, there is a strong need for Raytheon to foster more cross-communication between the functional groups. In many ways, Raytheon is still very much an engineering driven company. By encouraging communication between design, manufacturing, quality, and others, this will help create a more collaborative team, who will have the ability to design better, more producible products.

9. Conclusion

Raytheon has made great strides in improving its operations. By bringing the need to reduce rework to light, the company has undertaken many initiatives to reduce rework. From their introduction of CAB's, to the development of different IT tools, to the focus of management on the issue, Raytheon has taken many of the right steps to ensure its continued growth.

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Appendix A – EVMS Metrics[20]

Earned Value (EV) or Budgeted Cost of Work Performed (BCWP) – the total cost of the work completed/performed as of a reporting date.

EV = Baselined Cost * % Actual Complete

Actual Cost (AC) or Actual Cost of Work Performed (ACWP) – the total cost taken to complete the work as of a reporting date.

AC = Hourly Rate * Total Hours Spent

Planned Value (PV) or Budgeted Cost of Work Scheduled (BCWS) – the total cost of the work scheduled/planned as of a reporting date.

PV = Hourly Rate * Total Hours Planned/Scheduled.

Cost Performance Index (CPI) – an index showing the efficiency of the utilization of the resources on the project.

CPI = EV / AC = BWCP / ACWP

Schedule Performance Index (SPI) – an index showing the efficiency of the time utilized on the project.

SPI = EV / PV = BCWP / BCWS

[20] (Earned Value Management - Overview)

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Appendix B – Definitions and Acronyms

AME – Advanced Manufacturing Engineering, Raytheon group responsible for developing planning packages for the manufacturing of products

CAB – Corrective Action Board

CE – Concurrent Engineering

CMC – Consolidated Manufacturing Center

COR – Cost of Rework

COTS – Commercial off the Shelf

CPI – Cost Performance Index

DFMA – Design for Manufacturing and Assembly

DFx – Design for Excellence, the practice of accounting for assembly, cost, manufacturing, test, logistics, performance, and others during design

DMR – Design/Manufacturing Relationship

EM - Engineering Model, a first-run unit for engineering use to finalize designs

EVMS – Earned-Value Measurement System

LRIP – Low Rate Initial Production

NC – Non-Conformance

RPI – Rework Performance Index

SAS – Space and Airborne Systems, a business unit of Raytheon

SPI – Schedule Performance Index

VM – Visiprise Manufacturing, software system to assist the manufacturing floor

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