Design and Analysis of an Enterprise Metrics System

By

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B.S., Mechanical Engineering, University of Houston, 1992

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Abstract

Enterprise metrics systems are intended to align the behavior and incentives of the organization with management's strategic goals. In designing such a system, it is critical that the cause and effect relationships between performance drivers and outcome measurements be well understood. This understanding is difficult to achieve due to the complex nature of modern manufacturing enterprises, which can exhibit non-linear behavior that is exceedingly difficult to predict and control by standard management methods based on linear models.

This thesis examines the manufacturing process for an air-to-air missile from initial order receipt to final product delivery, and develops a general methodology based on this case to understand and manage complex manufacturing processes. The methodology is based on the integration of balanced scorecard metrics principles with the analytical tools for complex systems found in system dynamics. The methodology is iterative, where an initial computer based model of the manufacturing process is developed, checked against reality, and any differences are then corrected in the model. Based on the understanding from the model, metrics can be designed to improve operational control of the system and identify metrics that would best align individual and organizational incentives.

The thesis provides general recommendations for the development of an enterprise wide process modeling and metrics development program designed to improve management control and business process understanding. Specific recommendations are also provided for the air-to-air missile program to improve its financial and operational performance by reducing variability in key areas. Cash flow is the specific focus of the program recommendations and the tools developed by applying the methodology are used to improve the financial process capability of the manufacturing system.

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I would like to thank and acknowledge the rest of the MIT and especially the LFM community for their dedicated work over the years, which allowed me to as Sir Isaac Newton would say: “See further, but only because I stood on the shoulders of giants.”

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1 Introduction

It is not possible to manage a process that is not well understood. The pilot of an aircraft is required to understand how wings generate lift, how the engines produce thrust, and most importantly how the aircraft controls transform inputs into aircraft speed and direction. The aircraft manufacturer must understand the flight process even more intimately to design an aircraft that will operate reliably, efficiently, and safely anywhere within its flight envelope and over many years of operation. Indeed, aircraft flight is now so well understood, that engineers are able to build simulators capable of reproducing real flight with near perfect fidelity. Use of these simulators has greatly improved pilot training, since emergency situations can now be routinely practiced within the safety of a simulator. The proactive use of simulation as a tool to improve process understanding is at the core of modern flight training programs.

Analogously, manufacturing is a process like any other, and can be described in terms of equations, parameters, and controls. However, the manufacturing process is significantly more complex due to the many and simultaneous interactions of the various players along the supply chain. The complexity of the problem is best evidenced by the fact that there are no “management flight simulators” at anywhere near the same level of fidelity as commercial flight simulators. The fact that these management simulators do not exist should be of even greater concern to corporations, since senior managers often have many more lives under their responsibility than a commercial airline pilot. The present lack of comprehensive manufacturing management simulations was one of the motivating factors for this thesis.

There is, however, a large body of knowledge related to analytically describing individual pieces of manufacturing systems. One of the first to analyze manufacturing systems was Frederick Winslow Taylor [1] who in the late 1800’s described basic parameters such as cycle time, throughput, and cost. These were important first steps, but the organizational complexity of apparently simple systems was not well understood. Today's more enlightened companies understand that along with the basic parameters of manufacturing system performance there are other interrelated measures of equal importance such as safety, employee satisfaction, and innovation. These companies realize that although the structure of a company may be simple to explain in terms of the material flows, labor organization, and financial systems; the interaction between these elements can lead to very complex dynamic behavior that defies simple explanation.

Further complicating the problem for management is the fact that no quantity can ever be known with infinite precision. There is uncertainty associated with every measurement, and even more so in terms of manufacturing systems, where productivity, delivery times, test yields, and all other variables are subject to significant variability. The management difficulties caused by this uncertainty compounded with the complex dynamics of even simple systems are a significant reason for the current interest in developing simulation methods to help guide business decisions and identify appropriate metrics and management control systems.

Fortunately, tools exist to develop these systems such as the tools used in this thesis, system dynamics and statistical uncertainty analysis. System Dynamics[2] specifically deals with dynamic complexity by applying the notions of classical control theory to analyze the effect of time delays, non-linearity, and feedback loops in the business world. Statistical uncertainty analysis deals with the analysis of variable data to extract the actual bounds over which a given parameter may vary and to understand how that variability propagates through a series of calculations such as cash flow estimates derived from sales forecasts.

An example of a company living with dynamic complexity is Raytheon Missile Systems (RMS) in Tucson, Arizona. The current company was formed in 1997 after a series of Raytheon acquisitions that included the defense operations of Hughes Electronics, the defense operations of Texas Instruments, and the missile division of General Dynamics. The new company is the premier tactical missile products company in the world, accounting for over 40% of the worldwide tactical missile market. However, the integration of these acquisitions combined with structural changes in the defense industry have created the need for significant changes to the business strategy and processes, particularly in terms of measurement and control. Meeting financial goals on time, every time, is one of these key goals given the financial pressures created by the debt from acquisitions and declining defense budgets.

Management at Raytheon recognizes the need to better understand and codify the business processes of the newly created organization. The need to develop tools to improve the understanding of the missile production systems was one of the key drivers behind the internship assignment described in this thesis. There are currently programs underway to adapt their measurement and control systems to the new financially focused business conditions, including a pilot project to design a set of enterprise metrics for the production and operations group. This pilot project will rely in part on the balanced scorecard [3] concept pioneered by Robert S. Kaplan and David Norton of Harvard Business School. The idea is to define the business strategy in terms of a small set of key metrics organized around 4 areas: customer, process, organization, and innovation. The organization should then know not only what the enterprise strategy and goal is, but also how to measure the impact of their everyday activities towards the enterprise goals. Also, as the organization's processes mature, the expectation is that managers will develop an understanding of how each of the variables, such as cash flow, relate to each other. This is another way of saying that all parts of an enterprise are interrelated and it is not possible to affect a single variable without significant impact on other areas. Dynamic complexity again!

This thesis focuses on developing tools to document and analyze enterprise production processes, and to generate robust metrics systems from the understanding of their dynamics. This is an iterative process, where an initial model of the manufacturing process is developed, checked against reality, and any differences are then corrected in the model. Based on the understanding from the model, metrics can be designed to improve operational control of the system and generate additional data for the model. The belief is that a company determined to go through several iterations of this process will obtain a robust and deep understanding of the capabilities, dynamics, and financial performance of their manufacturing systems, and this understanding will already be codified in the model for managers to readily test the effects of business decisions. This process is represented in Figure 1-1.

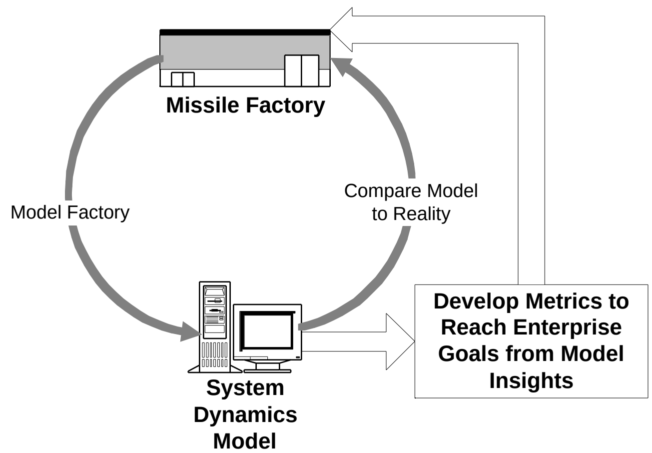

Figure 1-1 Metrics and Process Model

In the model developed for this thesis, cash flow is specifically analyzed to ensure internal policies and processes are aligned with the strategic cash flow goals of the enterprise. The specific case used to demonstrate the development of the tools and apply the analysis is Raytheon’s AMRAAM air-to-air missile. For this program, cash flow and working capital are cast as functions of the other variables in the balanced scorecard, a framework for analysis is created, uncertainty bounds are placed around cash flow and working capital, and recommendations are generated to allow for better control of cash flow and working capital.

Chapter 1 provides a background of the company, the research in the field to date, and summarizes the motivation for the project.

Chapter 2 provides the relevant background information. The current vision and strategy of Raytheon Missile Systems taken from publicly available documents is described as a basis for analyzing the appropriateness of the metrics system. The current metrics system is analyzed in terms of the Raytheon metrics maturity model. A brief discussion of the relevant system dynamics and uncertainty analysis topics is also included.

Chapter 3 describes the current enterprise measurement system and places it within the context of the air-to-air missile program. A survey of Raytheon metrics systems and past initiatives are discussed.

Chapter 4 chronicles the development of the analysis tools and the initial results related to the current measurement system. This chapter also summarizes the key results from the application of the tools to the AMRAAM air-to-air missile program and provides a discussion of the required six sigma initiatives associated with the results.

Chapter 5 describes the uncertainty analysis associated with the enterprise metrics system and provides some results.

Chapter 6 provides recommendations for based on initial model results and provides a set of additional metrics to improve management control.

Chapter 7 provides a summary of the methodology developed and provides general conclusions and guidelines.

2 Background

This chapter is intended to provide the necessary background information on the company, the internship, the problem to be addressed, and the tools used. References are given in the bibliography section to sources with greater detail in each area, particularly the tools used. The problem addressed is how to maximize cash flow while minimizing variability. This is an important problem for Raytheon due to the pressing need to pay down debt and the shift in focus in the defense industry from semi-unlimited government funding to commercial practices. In order to address this problem we needed to find a way to generate an analytical function for cash flow in terms of the other enterprise variables, such as: cash flow = f(critical path lead time, productivity, customer satisfaction, yield, etc.). This function could then be maximized to find which variables most affect cash flow and the total cash flow uncertainty could also be calculated in terms of the uncertainty of the other variables. The tools selected to address the problem are system dynamics, balanced scorecard, and engineering uncertainty analysis. The development of a method to apply these tools to understanding a production process and developing a complementary metrics system is the primary novel contribution of this thesis.

2.1 Current Enterprise Vision and Goals

The following is paraphrased from the Raytheon Missile Systems Vision, Values, and Goals[4] presented to outside investors.

- **Overall Vision:** To be the supplier of choice, be #1 in market share, and a leader in financial performance
- **Financial Goals:** Achieve 100% of the enterprise commitments, meeting financial forecasts every time in terms of cash, sales, earnings, and bookings (contracted sales).

- **Operational Goals:** Meet or exceed customer expectations, become agile in the utilization of resources and processes, capitalize on portfolio breadth in programs and technologies, improve cycle time and processes through six sigma programs, and adopt a common product and process development platform.
- **Organizational Goals:** Work together to break organizational silos and barriers, focus on people development, maintain clear and open communication throughout the enterprise, create a safe work environment, embrace change, and value all aspects of diversity in the workplace.

The emphasis on achieving financial goals is apparent. The management problem then becomes how to meet the financial goals without sacrificing the other dimensions of the enterprise such as innovation, employee satisfaction, safety, and customer satisfaction. To improve financial performance, one of the first areas that must be addressed is the integration of the myriad individual program resources to prevent duplication of effort. However, a tool to clearly understand what variables really affect the individual program's financial performance is necessary before proceeding to re-distribute enterprise resources. This is the tool developed in this thesis.

2.2 Company Description

Raytheon Missile Systems is a business unit of Raytheon Corporation focusing on serving the needs of the worldwide tactical missile market in the primary categories of air-to-air, projectiles, land combat, surface Navy air defense, advanced programs, ballistic missile defense, and precision strike. The missiles unit had sales of US$3.1 billion in 1999 [4], primarily to the US Department of Defense, which must approve all sales. The business unit is internally organized around product categories, and individual programs within each of these categories. The program focus means individual program managers and their organizations have significant authority since the programs hold profit and loss responsibility and are the primary point of contact with the customer. Other organizations such as manufacturing, business, and logistics are seen as support for the programs. This strong program focus is in part historical, but primarily due to the rapid acquisition by Raytheon of the defense operations of Hughes Electronics, General Dynamics, and Texas Instruments. The integration of these groups into a single Raytheon organization is not complete and was a primary motivation for the development of a single enterprise metrics system. Table 2-1 shows each of the missile unit's business categories, the individual programs, their sales, and their corporate heritage.

Category	Programs	Corporate Heritage	1999 Sales (US$ Million)
Air-to-Air	AMRAAM ASRAAM BVRAAM AIM-9M AIM-9X Sparrow	Hughes / Raytheon Raytheon Raytheon Hughes / Raytheon Raytheon Raytheon	$917
Strike	Tomahawk Maverick JSOW Paveway HARM ACM	Hughes TI TI TI TI Hughes	$631
Land Combat	Stinger TOW Javelin BAT	Hughes Hughes Raytheon Hughes	$417
Projectiles	ERGM XM982	TI TI	N/A
Surface Navy Air Defense	Standard Missile RAM / SEA RAM Phalanx ESSM LASM Navy TBMD	GD GD GD Raytheon Raytheon Raytheon	$743
Ballistic Missile Defense / Other Programs	EKV Other Programs	Raytheon TI, Hughes, Raytheon	$325

Table 2-1 Summary of Programs and Corporate Heritage

2.2.1 Product

The products built by the Raytheon Missile Systems Business unit cover the entire missile market. Each missile category covers a wide range of programs from very complex and leading edge weapons such as the AMRAAM air-to-air intercept missile to relatively simple systems such as the TOW wire-guided anti-tank missile. In general all products fall into the generic missile layout shown in Figure 2-1.

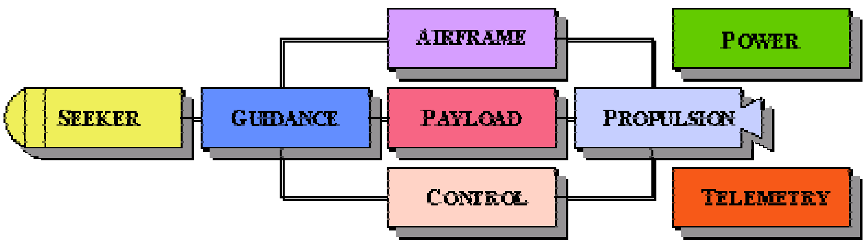

Figure 2-1 Generic Missile Layout

Many of the components used in the missile are procured from external suppliers, which implies that the financial performance of the company is significantly tied to the performance of the suppliers. A description of the components and their source is given in Table 2-2.

Component	Description	Source
Seeker	Provides sensing capability in infrared, visible, radar, or other spectra.	Primarily built at internal factories, but a few specialty items are sourced from suppliers
Guidance	The electronics that interpret the sensor signal and provide instructions to the control unit. May contain an inertial reference unit, and other electronics to determine current position and needed adjustments to target	Programming is internal, but electronics are sourced externally in terms of components. Some board assembly is performed by other Raytheon business units
Airframe	The actual body of the missile housing all of the components and providing structural frame for attachment	A mix of internal and external, but trend is to external suppliers
Payload	The warhead or sensor suite that the missile is to deliver	Primarily external, except for sensor suites

Control	The control system to provide fin actuation, and other flight path changes in response to guidance section inputs	A mix of internal and external, but trend is to external suppliers
Propulsion	The rocket motor or min-jet that provides the thrust to the missile	Primarily external
Power	Typically a battery to run the electronics and power the actuators during flight	Primarily external
Telemetry	Data links over radio, infrared, wire, or other means back to the launch vehicle.	A mix of internal and external.

Table 2-2 Generic Missile Components and Sources

Each of the components in the generic layout is required in some form in every missile. The complexity and type of each component varies according to the missile's intended mission. Due in part to the advanced technology requirements of the first generations of missiles and also to the defense security concerns the fabrication of the majority of components was done in house. With the advent of the commercial electronics industry, this changed substantially, and today many components are sourced from external suppliers whose products are often on the critical path for the assembly of missile products. Thus, variability in supplier delivery times is one of the key factors that management must control to reduce cash flow variability.

2.2.2 Value Chain

The typical value chain workflow starts with the placement of an order from a client, typically through one of the programs. If the program is already in production, the process will move towards material and resource planning. If the program is new, there will be an initial product development phase including prototyping, testing, and manufacturing system design. The product development part of the work flow is not considered here. The value chain continues to long lead item procurement, where items on the critical path are ordered. All of the material and production resources are scheduled according to a traditional Materials Requirements Planning (MRP) system. Due to the long-lead times of the critical path components, which can be up to a year, most of the actual assembly is compressed into a relatively short time towards the end of the schedule. The final step in the value chain being considered is delivery and final acceptance by the customer. The conceptual value chain is shown in Figure 2-2.

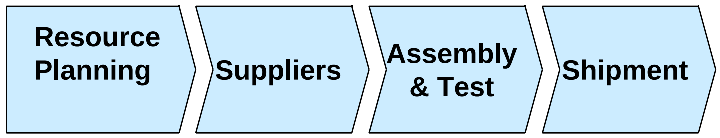

Figure 2-2 Conceptual Value Chain

The final step of product maintenance found in many other value chains is not as significant here since most of the weapons are designed as "wooden rounds", which means that they can be stored with little or no maintenance for years. However, there is some post-sale work known internally as "depot work", and this includes repairs and upgrades. The timeline in Figure 2-3 depicts a long lead program, with the actual timespan between 9 and 30 months from order to delivery. The timeline is conceptual, and does not show the significant overlap that occurs between each stage, but it does show the typical delays associated with each part of the manufacturing process.

Figure 2-3 Typical Missile Manufacturing Timeline

The entire value chain described above is driven by the MRP scheduling system, which contains estimates of supplier and assembly performance. There are some problems associated with relying on these schedule estimates, particularly if they are not updated and validated regularly. Also, the reliance on estimates can introduce significant "padding" by each of the groups in the value chain, which if not accounted for explicitly can add to very significant amount of schedule delay and additional cost. For example, when a department head is asked for a completion date, rarely will it be the average completion date, more likely it will be the expected completion time plus additional buffer time to account for any problems that may arise. The problem is that if everyone does this, it creates an artificial critical path through the system, and makes it very difficult for managers to really know where there is “fat” in a schedule and where the true critical path lies. Figure 2-4 represents the situation.

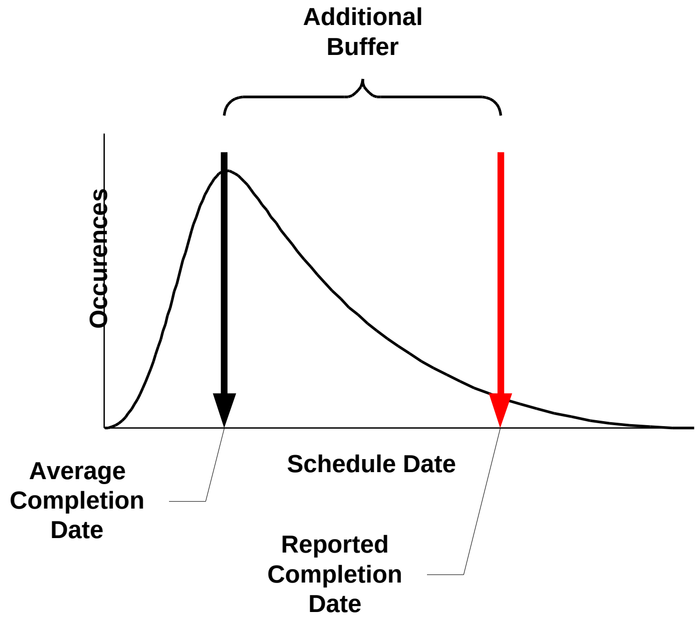

Figure 2-4 Typical Task Completion Time Histogram

The effect of compounding these buffers can be significant, since it is not possible to know what the true original average was. Additionally, the reported completion date that makes it into MRP becomes the target date for the department. This means that the reported date has the danger of becoming a self-fulfilling prophecy in that the organization will shoot for the planned MRP date, without knowledge of the original buffer planned in. The reported date then becomes the average, and additional delays can occur. This situation is shown in Figure 2-5.

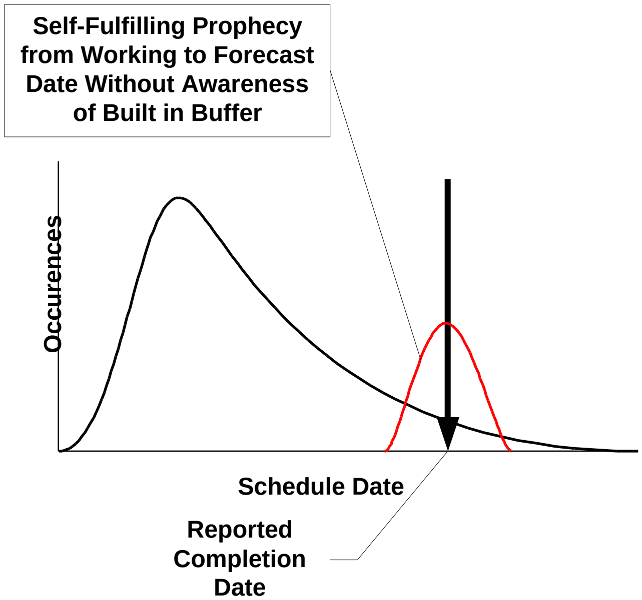

Figure 2-5 Task Completion Histogram Without Managing Buffers

The situation when all of these buffer delays are built into the MRP schedule can be very significant since the buffers will compound and can create a significantly different critical path from the real one. The theory of constraints [5], proposed by E. Goldratt, is of great use here, since it provides a methodology to manage these buffers in a rational way. The theory states that it is better to have zero buffer activities, and a single actively managed buffer at the end of the schedule. However, applying this theory starts in some sense with honesty in the organization, whereby managers are able to report their real expected completion times with the understanding that these are average numbers and the exact duration may be longer or shorter according to a normal distribution. Unfortunately most managers report larger than necessary buffers to minimize the potential reprimands for not meeting schedule. Reporting real durations on the other hand, allows the organization to have visibility of the buffers and to better manage the uncertainty through designed in buffers along the critical path. This situation is conceptually described in Figure 2-6.

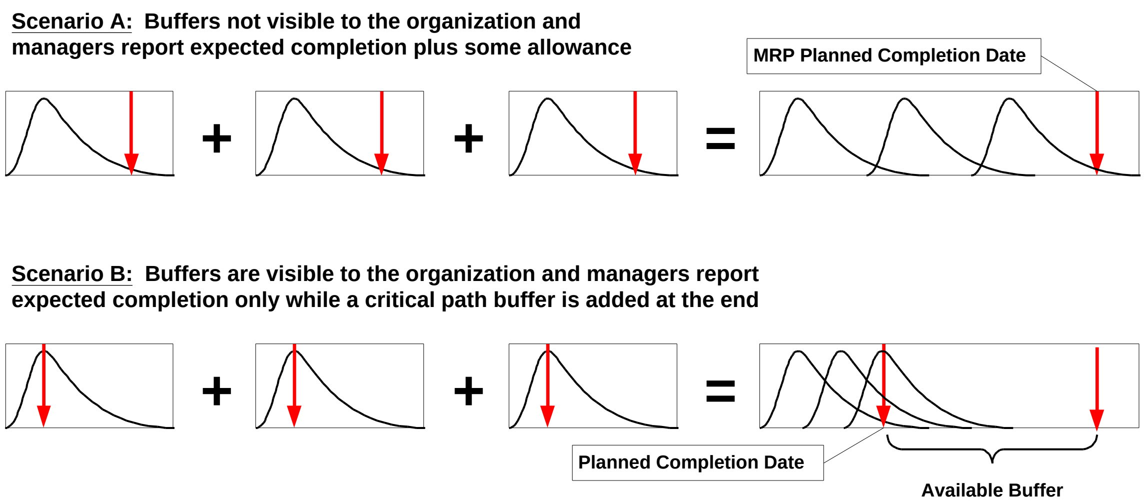

Figure 2-6 Comparison of Visible vs. Invisible Buffers

The MRP system currently in use at Raytheon Missile Systems encourages scenario A in Figure 2-6, since updates are not performed often (once per year) and more importantly there are no benefits to a manger reporting actual completion times, but there is significant downside. The addition of buffers to minimize "punishment" is one of the challenges facing the organization and one that improved metrics should rationally uncover. However, until managers who report accurate schedule times are not punished when they don't precisely meet them, the situation will be difficult to correct. The tools developed here provide a framework for analyzing this over estimation and these concepts will be useful in the subsequent chapters in the thesis, particularly in terms of uncertainty analysis.

2.2.3 Organization

The current management structure is program centered, which can lead to significant sub-optimization of the overall enterprise. This structure exists to best provide for program-centered customers. As individual programs compete for and hoard resources, the ability of the enterprise to balance its workload across all available resources is significantly diminished. The current plan to allow the production and operations group to participate in the management of the enterprise resources is a significant step in the right direction, but aligning the incentives of individual programs with the enterprise goals remains to be accomplished. Developing the enterprise metrics set is another step in that direction, and one that will begin to point out any sub-optimization present due to the program focus. The organization chart in Figure 2-7 is for illustration only, but shows the apparent disconnect between operations and individual programs. This is not to say that this organizational structure is the cause of problems, but it points to the possibility that individual groups can have different goals and incentives than the overall enterprise goals. It also points out the significant possibility for misalignment between the program and manufacturing groups in terms of cost, schedule, and deliverables.

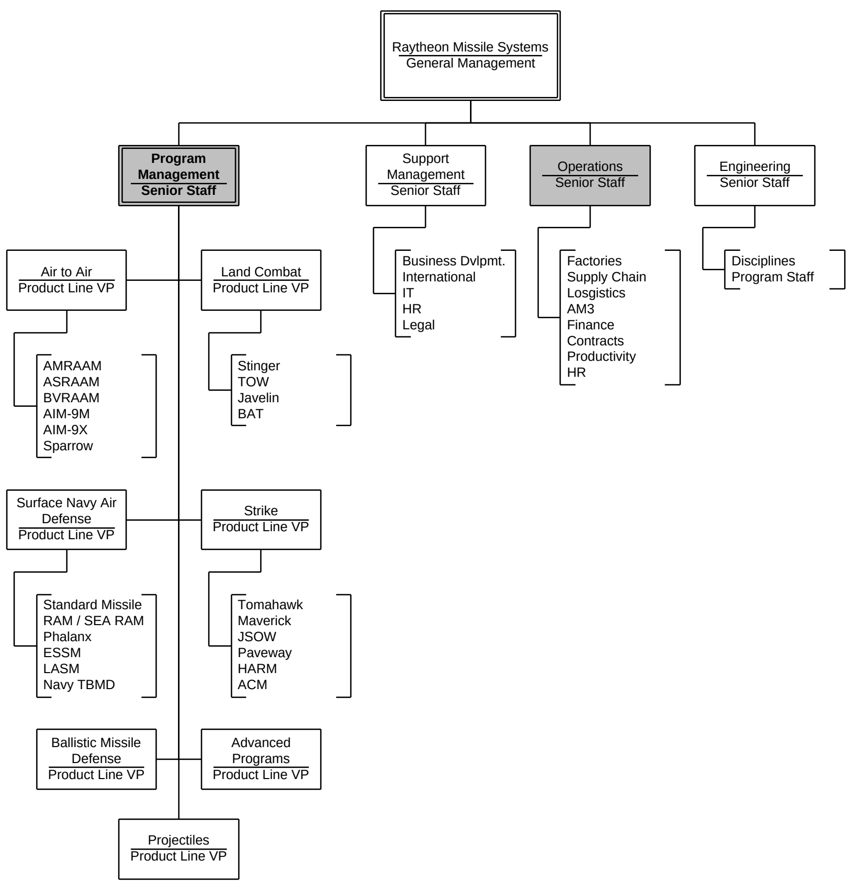

Figure 2-7 Organizational Chart

A goal of the enterprise metrics system is to align the programs and the manufacturing organization to pursue the same objective, to improve the financial performance of the enterprise as a whole. Currently it is possible for a program to look good by meeting deadlines at the expense of higher overtime and delaying the production of other products through key bottlenecks. One of the key objectives of developing the simulation and the metrics set is to provide an enterprise view of the actions of individual programs so that the overall cash flow is maximized and not just one program at the expense of another.

2.3 Metrics Systems

In some form or another, metrics systems have been around from the first trading of resources by primitive tribes, but they are almost always financial in nature. The Egyptians used a form of bookkeeping to facilitate trade throughout their empire. During the age of exploration more complex financial systems were devised to measure profit, such as double-entry accounting by Dutch traders and others. With the Industrial revolution came even greater emphasis on financial performance with the introduction of return on investment (ROI) measures and time-in-motion analysis. However, with the advent of information based companies and the realization that the great majority of the value of an enterprise is in its knowledge, relying exclusively on traditional financial measures is at best misleading. It is much more difficult to quantify the performance of a non-repetitive and intangible task such as R&D into the traditional framework of time-in-motion or cost accounting by activity.

In response, new strategic measurement systems have begun to take hold, which recognize that financial measures are "lagging" indicators that do not necessarily represent the true state of the enterprise. Of these new measurement systems, the balanced scorecard[3] method is the most widely adopted to provide measurement of critical but non-financial dimensions such as employee satisfaction, customer satisfaction, and innovation. The balanced scorecard is presented here because it serves as the foundation for the development of our function for cash flow = f(x, y, z…), where the variables x, y, z, etc., are all the other metrics in the balanced scorecard.

2.3.1 Balanced Scorecard

The balanced scorecard concept is not new. In 1951, Ralph Cordiner then CEO of General Electric, commissioned a study to identify key corporate performance measures. The study recommended that the following general categories must be monitored with equal attention: profitability, market share, productivity, employee attitudes, public responsibility, and the balance between short and long term objectives. Fast-forward half a century to 2001, where companies have deployed systems very similar to GE's 1951 study. The objective is to provide a framework to translate strategy into detailed operational metrics that may be monitored and acted upon. The increasing value of information over physical resources has greatly magnified the importance of the non-financial measures. For example, employee satisfaction at a software company is probably one of the key measures to meet their strategic goals, since it can translate into higher productivity, earlier software release, and ultimately a larger market share. This interrelation between the various parts of the organization is a key reason for the emergence of the balanced scorecard, since it provides data to test cause and effect hypotheses like the one just presented for the software firm.

The balanced scorecard requires that the organization first take a look at itself, define a goal, a strategy to achieve it, and work out the details for how to measure its progress to the goals. This is easier said than done, since it requires that a company profoundly understand its key value drivers and understand how to control them. Once this is achieved, it is relatively easy to design the scorecard, and a typical balanced scorecard diagram is shown in Figure 2-8.

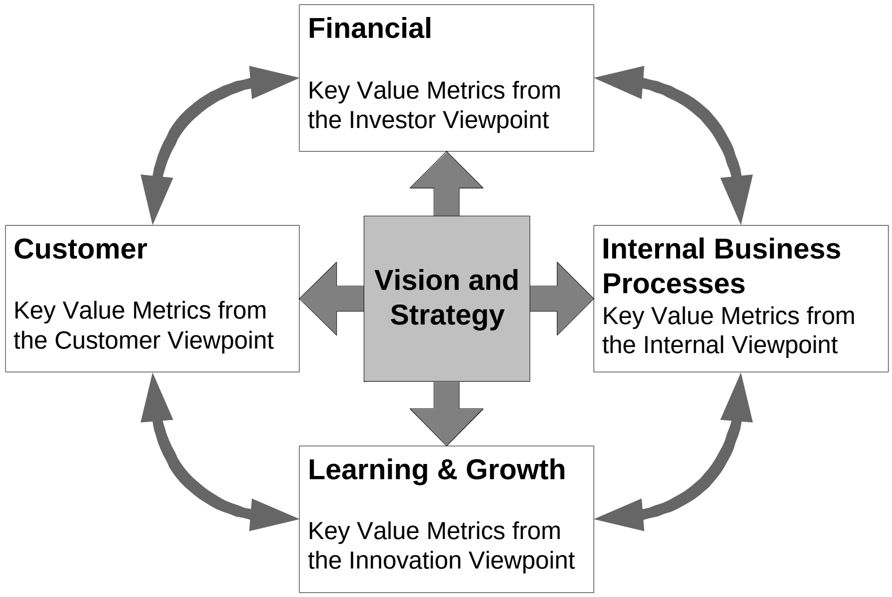

Figure 2-8 The Balanced Scorecard

Note in particular the arrows linking each dimension to the other three. A basic premise of the balanced scorecard method is that linkages should be found between each of the metrics and all of the others. To quote Kaplan and Norton [3]: ***"Balanced scorecards need to be more than a mixture of 15 to 25 financial and non-financial measures, grouped into four perspectives. The Scorecard should tell the story of the business unit's strategy. This story is told by linking outcome and performance driver measures together via a series of cause-and-effect relationships".*** Happily, there are powerful tools to model and understand these cause and effect relationships from the field of system dynamics [2], and it is the combination of these tools with balanced scorecard methods that forms the foundation of this thesis. Again, the objective is to come up with an analytical function to describe cash flow, but in terms of the other dimensions of the enterprise. In terms of the balanced scorecard we are looking for a function that looks like this: cash flow = f(other financial dimension metrics, internal business process metrics, customer satisfaction metrics, and learning and growth metrics). We will use system dynamics as a tool to build this function.

2.4 System Dynamics

The objective of system dynamics is to study the simultaneous interactions between elements of a system. In this sense, system dynamics differs from more traditional scientific methods that attempt to break down a problem into small parts that can be studied individually in great detail. In system dynamics the interaction between parts of the system are the object of study, not the individual parts. The actual mathematical theory is derived from control systems, such as the flight control system of an aircraft which must control a number complex system with several elements such as engine thrust, aileron position, and rudder angle, to direct the aircraft along its intended route. By analogy, business management organizations can be thought of as control systems directing individual parts of the enterprise to operate together in reaching the desired enterprise goal. The first person to explicitly draw this analogy to business systems was Professor Jay Forrester in his seminal book, Industrial Dynamics[6], which showed how to translate many of the concepts from control system engineering, such as feedback loops, and apply them to the analysis of business systems. More importantly for the work performed in this thesis, system dynamics provides a structured framework to analyze cause-and-effect relationships in a business organization and provides a powerful tool to develop the linkages described in the balanced scorecard methods.

2.4.1 Application to Manufacturing Systems

To understand how system dynamics works, it is necessary to go through a few examples that will be Raytheon Missile Systems specific. Let us start with an apparently simple process, such as maintaining the desired inventory of rocket motors to supply the final assembly process. The objective is to maintain a certain minimum desired amount of material on hand subject to consumption rate variability due to quality control rejection variability, changes in the production schedule, and variability in the lead-time for material orders. There are some things we can measure, such as the number of rocket motors we have on hand, the orders we have placed, and the number of units that are required. This can be visualized in Figure 2-9.

Figure 2-9 Material Flow

Orders are placed at a certain rate (units/time), which fills up our "container" of order placed. Orders become delivered rocket motors at the receiving dock according to the delivery rate, and this rate can be thought of as the ordering rate delayed by the lead-time of the rocket motor. The rocket motors on hand are used up according to the actual consumption rate. However, we must keep in mind that the information managers receive is delayed while it is collected, analyzed, and reported. It also takes some time for management to reach a decision once the information is available, and there may be slow adjustments to the consumption rate forecasts that can lead to over or under ordering. These issues are shown conceptually in Figure 2-10.

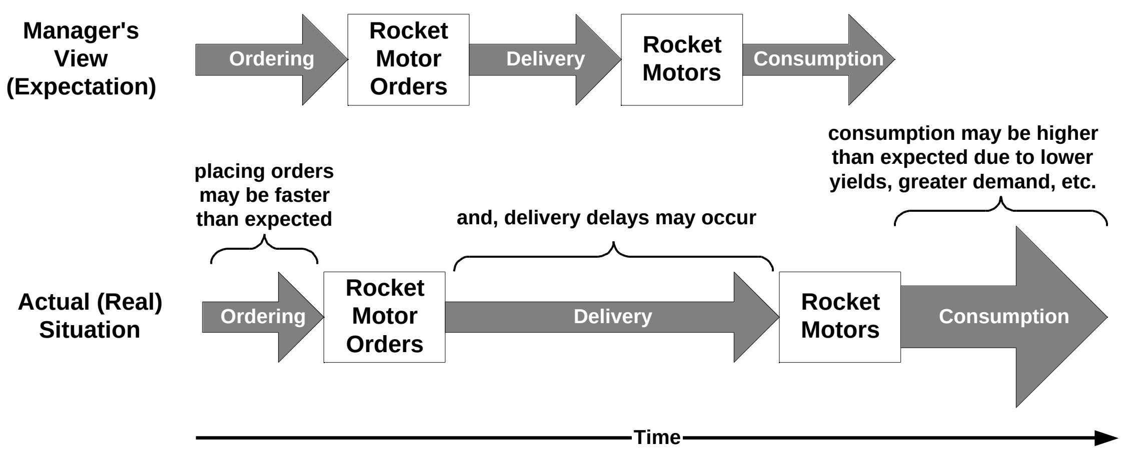

Figure 2-10 Variability in the Material Flow

The top line in Figure 2-10 shows the manager's expectation for the duration and rates of delivery and consumption, whereas the bottom line shows the actual situation where delivery times and consumption rates are significantly larger than expected (forecast). The manager in charge of this process must clearly make some adjustments to ensure the larger consumption rate in the real situation is met, and there are enough orders to fill the now longer delivery supply line due to the delay in delivery. However, suppliers may be reluctant to report the bad news that the rocket motor will be late, it may take time for the procurement department to report the situation once it occurs, and it may take some time for managers to decide what corrective actions to take. Similarly, the consumption rate may increase significantly due to problems with yield, but if the parts are currently in rework this increased consumption rate may not be reported quickly since the parts have not yet been "officially" scrapped. All of this points to the real world business fact that it is difficult to get accurate instantaneous information, and even when the information is available, the system has certain physical and procedural constraints that prevent it from adjusting instantaneously.

System dynamics provides the tools necessary to analyze such problems. Following our example, let's incorporate what management would do to adjust the inventory of rocket motors to the desired level. To correct for the now larger consumption rate and longer lead-time, they would increase the number of orders being placed. This is an example of a goal seeking negative feedback loop commonly found in control systems, as shown in Figure 2-11.

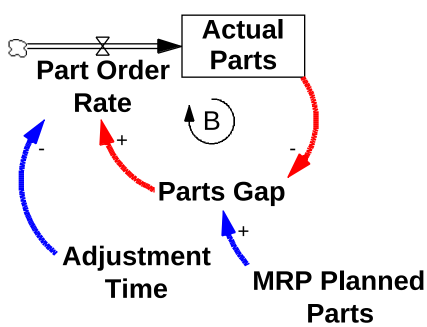

Figure 2-11 Goal Seeking Negative Feedback Loop

It is possible to build more complex structures to explain how management decisions, information delays, and the physical structure of the system may be connected to form control loops. Many other such control loops are possible, including the ones shown below.

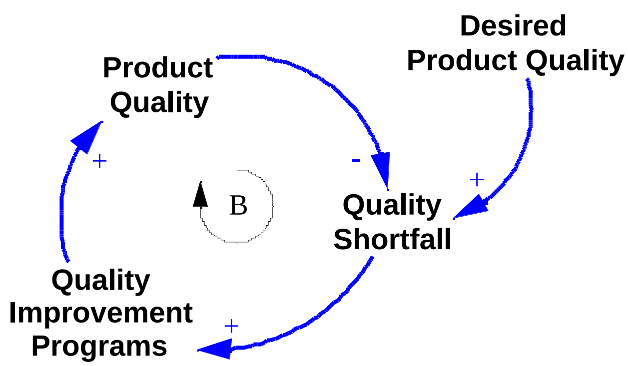

Figure 2-12 Balancing Loop (Negative Feedback) for Quality

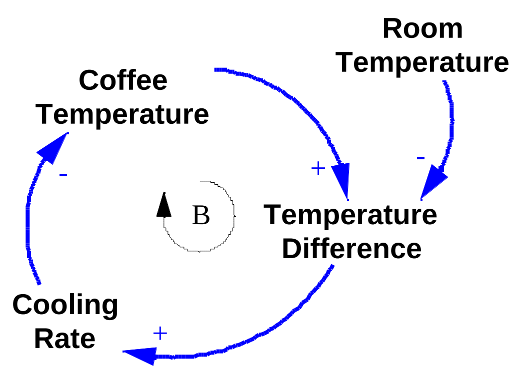

Figure 2-13 Balancing Loop for Coffee Temperature

2.4.2 Applications to the Balanced Scorecard

Comparing the balanced scorecard diagram with causal loop diagrams, the synergies are apparent. Where the balanced scorecard strives to develop linkages between its dimensions, system dynamics can do this analytically. The example in Figure 2-14 shows how traditional balanced scorecard metrics can be represented in terms of system dynamics. The loop below shows a reinforcing loop (i.e. if a variable at the tail end of an arrow increases, so does the variable at the tip.)

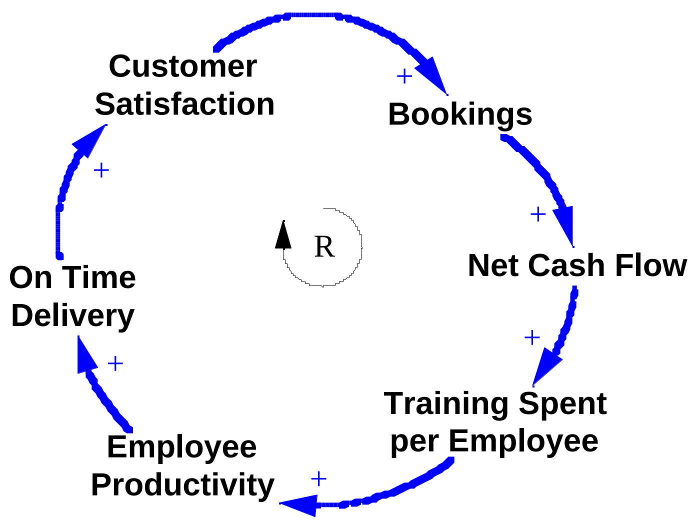

Figure 2-14 Example of Balanced Scorecard Linkage in System Dynamics Terms

2.5 Uncertainty Analysis

Having developed the cause and effect structure using the system dynamics tools, it is now possible to see how the uncertainties propagate through this system. Visualize the system dynamics model as a black box that contains the cause and effect relationships that define the enterprise. Now, consider that each one of the variables in these cause and effect relationships has a certain degree of randomness, or variability. It is then possible to calculate how this uncertainty propagates through the system to higher-level variables. For example, cash flow is a function of the interaction of many variables within an enterprise. Conceptually one may imagine cash flow as a function of these other variables: cash flow = f(x, y, z, ….). These variables may be any key parameter such as lead-time on critical components, worker productivity, etc. Using system dynamics it is possible to develop a model describing the interaction between these variables and obtain an analytical relationship describing the cash flow function. This is explained conceptually in Figure 2-15.

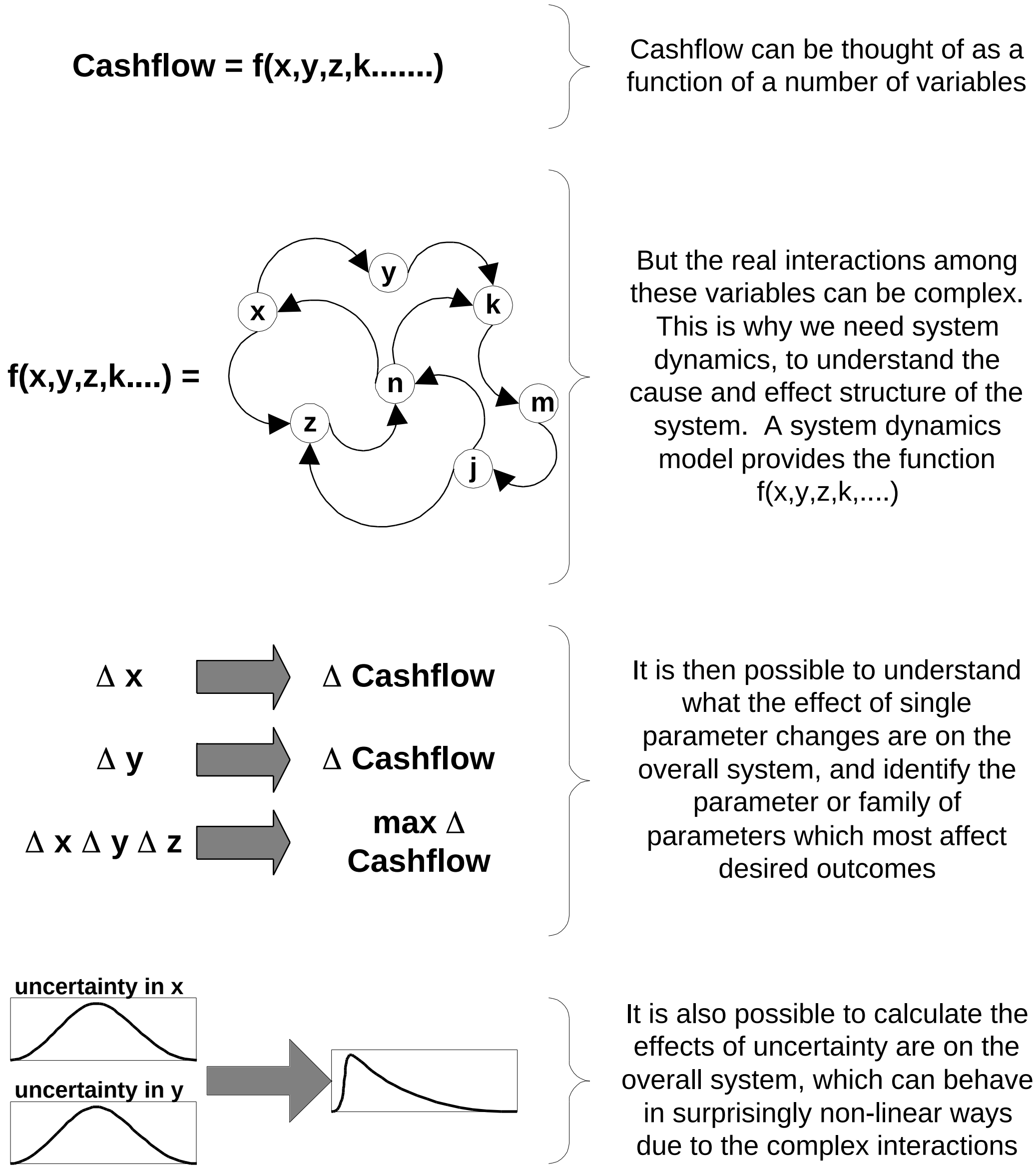

Figure 2-15 The Cash flow Function and System Dynamics

Using this technique it is possible to place uncertainty bounds on the balanced scorecard, and understand in terms of the cause and effect relationships developed using system dynamics to understand the root causes of the variability in a given scorecard variable. For example, cash flow is one of the key balanced scorecard measures, and in a standard scorecard, it is reported as a raw number without any uncertainty bounds. However, the actual cash flow may be based on projections, estimates, and other data with a significant amount of uncertainty. In particular, the cash flow metric may be highly sensitive to critical path component's lead-time, which may have a significant amount of uncertainty. Thus, if the item is delivered early, or on time, the effect on cash flow will be minimal, but if it is delivered late enough to affect production, this will result in late deliveries, increased overtime, and other impacts that will negatively affect cash flow. The premise in this thesis, is that the variability of production variables, such as lead time, cycle time, and others, can be run through a model representing the structure of the enterprise, to understand how this variability truly affects the high level balanced scorecard measures. Armed with this knowledge it is then possible to attack these sources of variability in an organized manner so as to reduce the uncertainty in key enterprise metrics such as cash flow, customer satisfaction, etc.

Once again, it should be emphasized that without explicitly stating and calculating the uncertainty associated with these business measures, the cost of variability is hidden and the ability to use them to manage the enterprise is significantly compromised. For example, imagine that one of the metrics in an enterprise's balanced scorecard is delivery time. The balanced scorecard reports a single average measure, but the variability around this number may be very large, and it may be un-symmetric. There will be a large number of unsatisfied customers on the right side of the curve, although this would not be visible simply from looking at the average number. Similarly, the variability in product delivery time results from variability in a number of lower level processes such as the supplier lead-time variability, quality control variability, and perhaps also labor productivity variability. By explicitly calculating what the impact on product lead time of each of these lower level variables, it is possible to understand which one has the most impact and deploy six sigma improvement resources to attack it. In this way the balanced scorecard can be brought under a much more of a statistical process control methodology using lower level operations variables that can be monitored and controlled.

3 Current Metrics System

As described in the background section, the current Raytheon Missile Systems was created from several different companies, each of which had its own metrics systems. The former Texas Instruments groups were used to Oregon Performance Matrices, where composite measures of enterprise well-being were developed and tracked. The former Hughes groups were in general more comfortable tracking detailed metrics, while officially primarily measuring production variables and some personnel and customer satisfaction measures. A key point is that, all of the organizations measured the balanced scorecard metrics in some form or another, but these metrics were not always regularly collected, reported, or used to change the organization's behavior. Each organization had performed systematic evaluation of their metrics systems prior to their integration into the current company, but due to the challenges of integration there had been no systematic review for several years prior to the pilot program initiated by the production and operations group in September 2000. Before this initiative, each program recorded its own metrics according to its corporate heritage, but also reported metrics as requested by Raytheon management. This leads to doubling of effort, and more dangerously, can cause misalignment of priorities between groups.

3.1 Description

The individual metrics currently used can be categorized along the lines of the balanced scorecard. Here the individual metrics are placed in the following categories:

- Financial: Metrics describing the current financial situation of the enterprise. This includes traditional measures such as cash flow, accounts receivable, and newer measures such as capital turns.

- Production: Metrics describing the operations of the enterprise, such as cycle times, schedules, inventory, quality, etc.
- Customer: Metrics describing the customer satisfaction both internally and externally, such as % of items delivered on time, perceived value, etc.
- Organizational: Metrics describing the state of the organization such as employee satisfaction, safety, community involvement, etc.
- Reporting: Metrics describing the quality and timeliness of the metrics system such as error rates and time to report.

What follows are detailed descriptions of the current metrics in use along with some parameters to describe their effectiveness.

3.1.1 Financial

The current financial measurement system is based on traditional cost accounting. Some efforts were made by Hughes prior to the acquisition to transition to an activity based accounting system, but these efforts were met with significant resistance. The system is organized around individual contracts, and is designed to track direct and indirect charges to these contracts. Direct charges are items like direct labor, material, and a catch-all called ODC (other direct charges). Indirect charges are collected in overhead pools that are charged to individual programs through allocations based primarily on number of man-hours expended. Indirect charges consist primarily of the corporate services to the individual contract, such as business personnel, manufacturing support, etc. Financial forecasts are based on bookings, since the delivery times are very long (9 to 30 months). These revenue forecasts are known with reasonable certainty for contracts already open (i.e. missiles in production). However, for new projects, or missiles where there are substitutes available on the market, the forecasts are calculated based on a probability of win. The labor and material costs are calculated using “standards”, which provide an estimate of the cost represented by completed products. Most of the financial information is tightly held, and very few factory floor or production management personnel have a clear overall picture of the financial impact of various decisions. Table 3-1 is a summary of the key financial metrics in use.

Metric	Description	Frequency	Drives
Bookings	Value of contracts awarded to enterprise (includes firm awards and forecasts)	Annual (some semi-annual)	Baseline for all other planning (manpower, facilities, capital, etc.) Establishes expectations (investors and management)
Sales	Program expenditures plus profit (typically % complete basis)	Monthly	Focus on % complete hides potential rework
Earnings	Sales less Cost of Sales (COS), which is estimated by a process called Estimated Cost at Completion (ECAC)	Monthly	Less day-to-day awareness of costs due to monthly calculation of ECAC and little dissemination to the organization
Cash	Total program receipts less total program disbursements	Monthly	The focus of programs to generate good cash numbers makes some of them hide costs in overhead pools that eventually get charged to the enterprise
Working Capital	The investment in programs (mostly inventories) that is not covered by the customer through progress payments or advances	Semi-Annually	Production and floor personnel have little direct knowledge of the changes in working capital due to their decisions, and there is also no incentive for them to reduce their safety stocks (it is a greater penalty to not meet schedule than to carry too much inventory)
Cost of Goods Sold	Man-hours expended, material	Monthly	The costs are calculated from reported man-hours, and material payments (primarily direct costs)

Table 3-1 Summary of Current Financial Metrics

In general, there is relatively little awareness of financial issues amongst the production personnel, and this leads to some non-optimal behavior. For example, reduction in working capital is a key issue, but the cost associated with keeping inventory on hand, is not explicitly tied to any performance goal within the production organization, which is instead evaluated on schedule performance. Not having any incentive to reduce their inventories, since they are not being measured on this, managers try to keep safety stocks to smooth variability in component deliveries. Tying capital costs to these managers performance evaluations and providing them the data and tools to measure it, would address this problem.

Another problem area is the lack of awareness by production personnel of the opportunity cost associated with their decisions. Taking some of the activity based accounting concepts, currently they do not know the cost of inaction. For example, the additional time a missile spends on the test stand is lost revenue since that missile could be sold, but the current financial metric measures completed products. This metric by itself does not encourage efficient use of resources since the only objective is to get product out the door, not the actual cost of using particular resources to accomplish this. Many of the actual financial measures reported are a combination of the above “raw” measures combined into ratios to produce traditional measures such as return on sales or working capital turnover.

3.1.2 Production

The current production metrics are a mix of carry-overs from individual programs. Several attempts have been made to produce a common set of metrics for all programs to use, but in the past programs simply continued to use their own metrics and prepared additional reports as needed for Raytheon management. The metrics used by the programs are extensive, and typically all of them measure the standard performance criteria such as cycle time, schedule performance, quality performance, budget performance, and some measure of rework. However, most of these measures are prepared as reports to upper management and are not commonly used by factory floor personnel to make decisions. Some of the metrics would be very abstract measures for personnel on the factory floor, but there are no "translational" metrics to allow personnel to guide their behavior. The lack of common metrics has in the past prevented the rational allocation of resources between programs since it is difficult to compare "apples to apples" without common metrics. Furthermore, the lack of common production metrics further encourages personnel to remain in silos within programs, since it is not easy to immediately be productive in another program until the measurement tools are understood.

3.1.3 Customer

Customer satisfaction is measured primarily by the business development organization, partly as a marketing effort to demonstrate interest in the customer. However, few of these measures get sent back to the production organization as feedback to their work. When these measures are sent back, they are primarily in terms of schedule compliance, which is perceived to be the greatest driver of customer satisfaction. Other measures such as ease of use, responsiveness of the customer service organization, and other more traditional service industry measures are largely ignored.

3.1.4 Organizational

There is a very strong emphasis on safety, but it is primarily focused on reducing lost time incidents. No measurements are kept of "near misses" and other lower level components of the now famous DuPont accident pyramid safety methodology[7]. Annual surveys are given to employees to measure their satisfaction, but again the perception is that these measures are largely ignored. There are no public measures of employee satisfaction that can be tracked and acted upon.

3.1.5 Reporting

Due in part to the highly classified nature of the work at Raytheon Missile Systems, most information remains on a need to know basis. This includes financial, operational, and organizational data that in other non-defense industries would be widely disseminated throughout the organization, causing severe lags in reporting times. For example, the time for factory floor personnel to get data on their performance in financial or operational terms may be measured in months, often too late to make any change, or worse, if any change is made to that data, the current situation may be significantly different.

3.2 Raytheon Metrics Maturity Model

In 1998, Raytheon Systems Company (RSC) published an excellent guide [8] to designing and deploying a strategic metrics system. The guide advocates the use of the balanced scorecard to help define business excellence for the business (i.e. what are the goals). The guide also advocates using the performance pyramid model[9] to help define roles and responsibilities within the organization as well as identify appropriate metrics for each level in the organization to have a "clear line of sight" to the enterprise goals. The guide also presents a valuable metrics and process maturity model to classify the state of a given metrics system. The connection between process maturity and metrics system maturity is explicitly described in the guide, the implication being that one cannot exist without the other. A summary of the Raytheon metrics and process maturity model is given in Table 3-2.

	Process Maturity	Level	Metric Maturity	
Process management provides world-class competitive advantage (i.e. agile and forward looking)	Holistic	**5**	Optimizing	Metric-driven actions are simulated during the strategy setting process to ensure organizational alignment before metrics are implemented
Support processes are integrated with and enable core business processes to provide competitive advantage	Enabling Processes Integrated	**4**	Total Alignment	All metrics (process, results, organizational, etc.) align with strategic objectives, provide competitive advantage, and optimize the whole
Common process language and specifications exist. Core processes are integrated to allow a seamless flow of work across process boundaries	Core Processes Integrated	**3**	Horizontal Alignment	Metrics reinforce and leverage activities across all core business processes. Local interests are subordinated for the good of the whole
Business process management, which begins and ends with the customer, is established, in control, and in the conscious thinking of management.	Core Processes Managed	**2**	Vertical Alignment	Process metrics have been added and integrated with result metrics. Metrics are aligned between the strategy and daily activities in the core processes
Little or no process focus. That which exists is primarily directed internally toward local operations	Initial	**1**	Initial	Metrics are ad-hoc and primarily results oriented

Table 3-2 Raytheon Process and Metrics Maturity Model

Using the model it is possible to classify the current state of the Raytheon Missile Systems metrics set. Due to the recent integration of other companies into the current enterprise, Raytheon Missile Systems is necessarily between a 2 and 3 according to the model. In particular, the lack of seamless integration between financial and production processes makes it difficult to currently move past a 3. At level 2, the enterprise is trying to align the entire organization with its strategic objectives, and this is the process that is currently underway. The next step will be to generate horizontal alignment at level 3 between all the organizations in the enterprise and the customer. Breaking the program focus and allowing for more of an enterprise view is critical to achieving this goal. The goal of the current metrics system and strategy is to bring the enterprise from its current 2/3 level to a level 5. Note the comments in the figure above regarding the metrics evolution associated with level 5: “Metric-driven actions are simulated during the strategy setting process to ensure organizational alignment before metrics are implemented”. This was one of the prime objectives of the work associated with this thesis, to provide management the tools to perform these simulations and figure out what the quickest route is to get to level 5.

3.3 Survey Results

In order to evaluate the current perception of the metrics system at Raytheon, a metrics survey was prepared and given to senior operations management staff. There were 14 respondents out of 26 surveyed. The survey was based on the book, “Keeping Score” by Mark Graham Brown [10]. The objective of the survey was to gauge the overall approach to metrics, the quality of individual measures, and the quality of reporting. Table 3-3 contains selected questions from the survey. Darker shading indicates more respondents.

Metrics Survey Question	(1) Strongly Disagree	(2) Disagree	(3) Uncertain	(4) Agree	(5) Strongly Agree
Our metrics are tightly linked to the key success factors that will allow us to differentiate ourselves from our competitors	14%	21%	36%	29%	0%
Our metrics were built with a plan rather than something that just evolved over time	21%	36%	21%	21%	0%
Metrics are consistent across our business units and locations throughout the company	57%	36%	7%	0%	0%
We have a well balanced set of metrics with equal attention paid to each of financial, process, customer, and people areas	21%	36%	29%	14%	0%
Our metrics include hard measures of customer satisfaction such as in-service failure rates, training time for customer personnel, etc.	36%	36%	21%	7%	0%
Individual metrics of employee satisfaction are aggregated into an overall index	21%	57%	0%	14%	7%
Financial metrics are a good mix of short and long term financial success	29%	43%	21%	7%	0%

Metrics Survey Question	(1) Strongly Disagree	(2) Disagree	(3) Uncertain	(4) Agree	(5) Strongly Agree
Financial metrics are consistent across different units/locations throughout the company	14%	14%	36%	29%	7%
The organization has developed a set of 4-6 common operational metrics that are used in all locations/functions	29%	57%	0%	7%	7%
Operational metrics allow us to prevent problems rather than just identify them	29%	36%	29%	7%	0%
The organization has established easily measurable standards (bounds) for all key process metrics	29%	43%	7%	21%	0%
Safety metrics are more behavioral and preventive in nature rather than typical lost time accidents	14%	71%	7%	7%	0%
The organization reports data from all sections of its scorecard in a single report to all key managers	46%	38%	15%	0%	0%
Data are presented graphically in an easy to read format that requires minimal analysis to identify trends and performance levels	31%	46%	8%	15%	0%
Data on innovation, customer and employee satisfaction, are reviewed as often and by the same executives as financial data	46%	31%	15%	8%	0%
The organization understands the relationships between all key metrics in its overall scorecard	38%	46%	8%	8%	0%
Performance data are analyzed and used to make key decisions about the organization's business	15%	38%	38%	8%	0%
The key metrics are consistent with the organization's mission, values, and long-term goals and strategies	15%	23%	23%	31%	8%
The organization continuously evaluates and improves its metrics and methods used to collect and report performance data	15%	31%	31%	8%	8%
Metric collection methods are calibrated on a regular basis to ensure accuracy and reliability	15%	54%	31%	0%	0%

Table 3-3 Metrics Survey Results

There are several trends in evidence in Table 3-3. The survey indicates the current metrics system is not perceived to be world-class, and more likely is perceived as barely functional. Information is not widely available, nor is it standardized across all programs. There is a focus on financial and operational metrics at the expense of other dimensions such as employee and customer satisfaction. The survey had a field available for feedback, and one of the comments received probably best summarizes the current situation:

"The survey questions were revealing and appropriate for a company trying to understand and improve all aspects of its business. The survey made it apparent to me that we have many aspects of our business that we could and should be monitoring but are not."

Anonymous Operations Manager

4 Metrics System Analysis

This chapter chronicles the development of the system dynamics model to generate the cash flow function. The model is first developed for the ideal case with no real world problems such as rework, low yields, or labor constraints. These constraints are then added to the basic structure, which is then repeated to provide the overall structure for the AMRAAM program model. The model was built using specialized software[11] called Vensim©, which greatly simplifies the creation of system dynamics models. This chapter first develops the conceptual structure of the model then delves into the details of the Vensim © model and equations.

4.1 System Dynamics Model

The easiest way to visualize how the model was built is to picture the missile assembly process. The first step is order receipt, which is typically a government contract for a certain number of missiles. This order is then translated into material, personnel, financial, and facilities requirements, which become the basis for the MRP plan. Long-lead items are ordered, and ramp up of labor and facilities is begun. Orders for all other parts are placed according to each part's lead time as entered in the MRP plan. As parts arrive, they are inspected and consumed to form a finished missile. During assembly parts are tested, and a final inspection is performed on the missile. Finally the process is complete with delivery and payment receipt. A conceptual flowchart through the assembly process with its corresponding system dynamics stocks is shown in Figure 4-1.

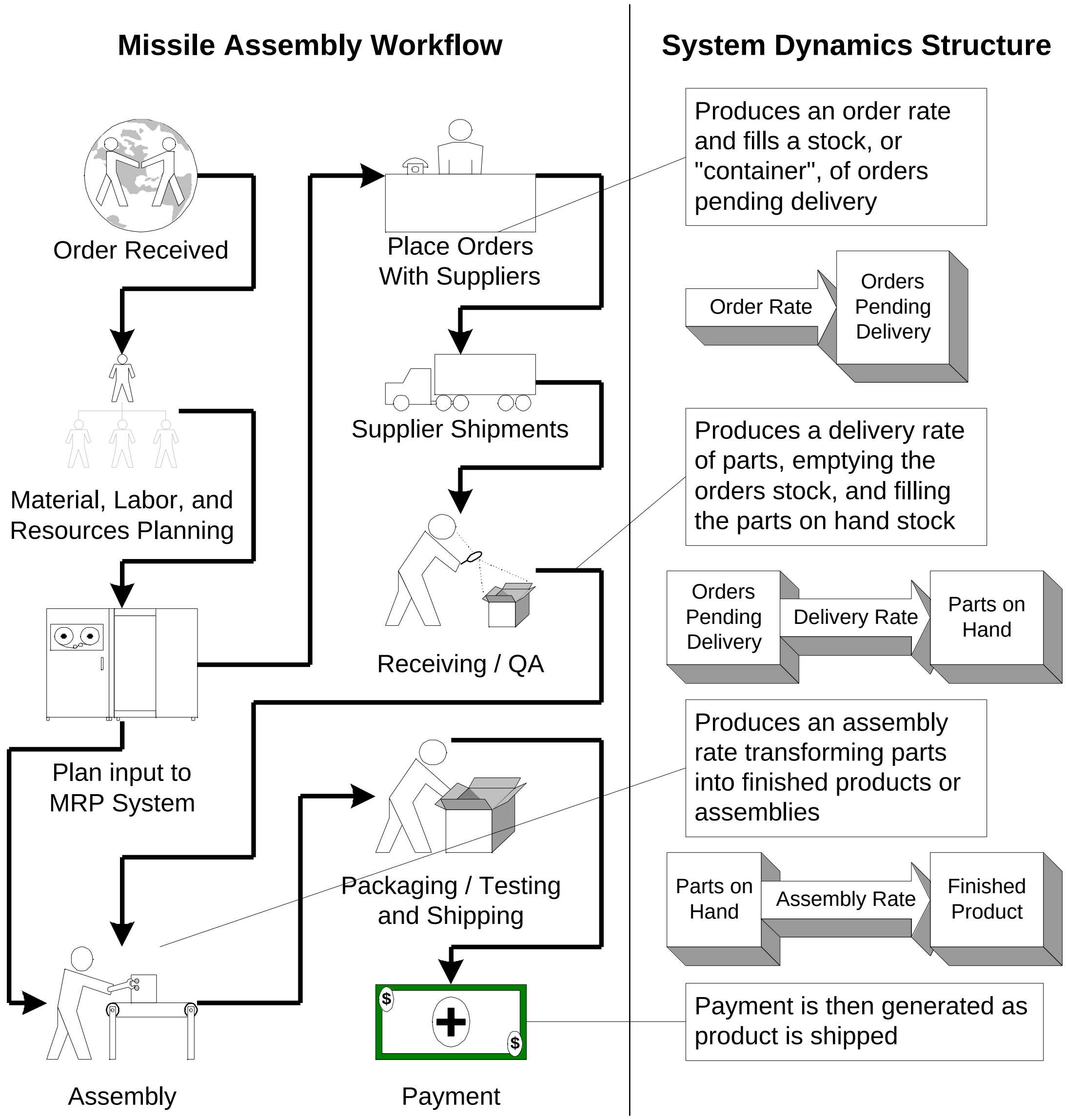

Figure 4-1 Workflow Processes and Corresponding System Dynamics Models

The model is built in a straightforward fashion very similar to the above diagram. The stock and flow diagrams on the right hand side of Figure 4-1 correspond to the structures found in the model. A diagram of the basic structure we will be building is shown in Figure 4-2.

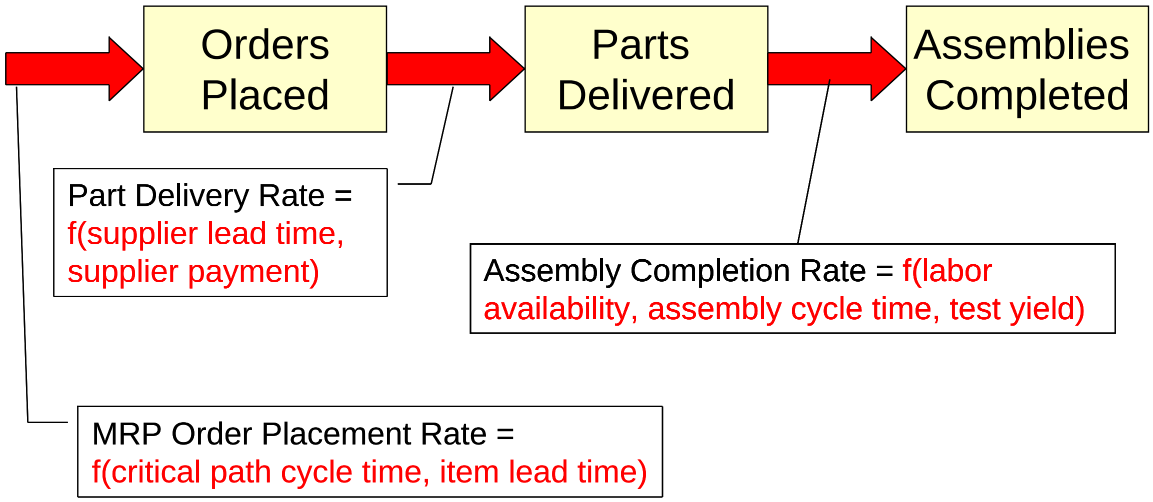

Figure 4-2 Basic Model Structure

We begin by establishing an order rate, which is dependent on the planned (forecast) critical path through the system. The bill of material for the missile will indicate which part needs to be ordered first, second, and so on to satisfy the MRP plan. In the case of the model, the bill of material for the AMRAAM missile was taken and the MRP order lead times are used to back-calculate which part needs to be ordered, in what quantity and at what time. As these orders are placed they form a backlog of orders pending, or stock in the language of system dynamics. A representative bill of material for the AMRAAM air-to-air missile is shown in Figure 4-3. There are many more parts that go into the assembly of an AMRAAM missile, but only the ones on the critical path, or very close to the critical path in terms of lead-time are considered. Thus, each branch in Figure 4-2 is described in terms of the set of assembly steps on the critical path up to that point. Thus, the Chassis 7 part has a certain set of electronic components that must be delivered and assembled, and constitute the critical path in obtaining a complete Chassis 7 part.

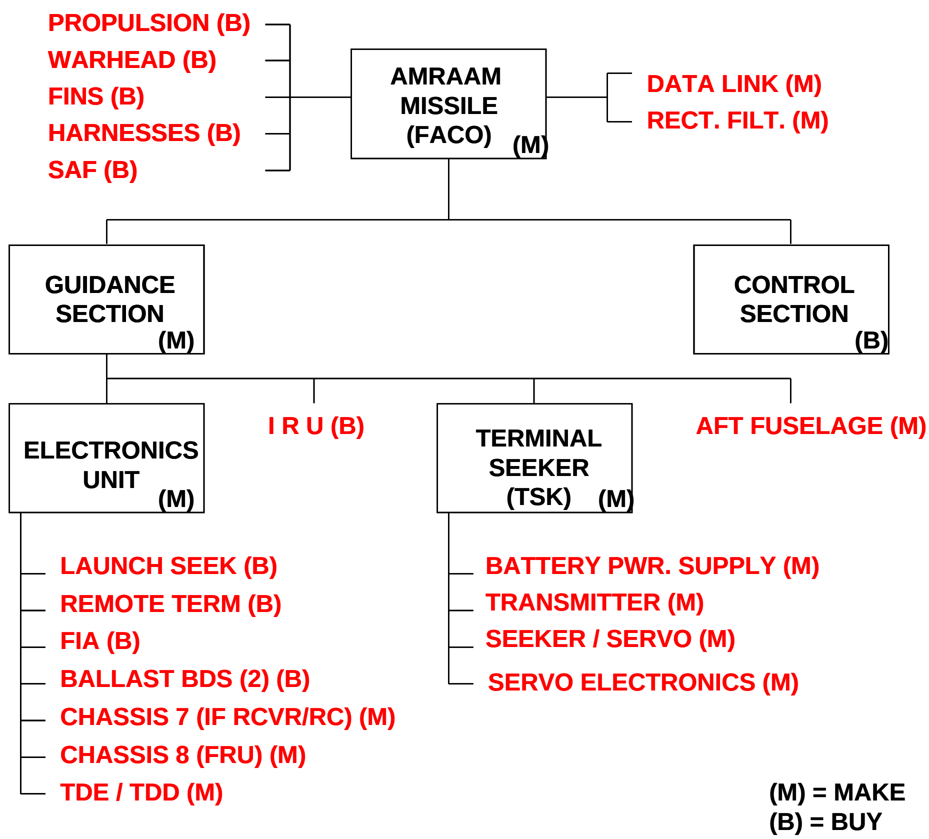

Figure 4-3 AMRAAM Missile Work Breakdown Structure

Imagine that the critical path for the assembly of the missile is through the electronics unit, which itself depends on a number of parts. For the remainder of this example, we will focus only on the electronics unit to show how the model was developed. The parts that go into the electronics unit are shown in Figure 4-4 (B=bought items and M=made items):

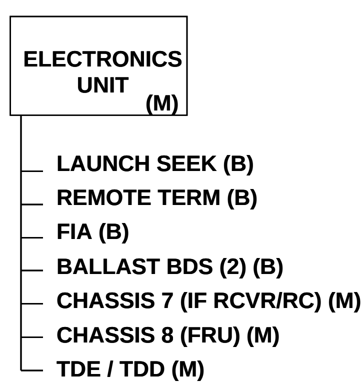

Figure 4-4 Electronics Unit Work Breakdown Structure

If the electronics unit is on the critical path, then one of the lower level components must also be on the critical path, and in this example case it is the RT- remote terminal (the heavy line) which must be ordered first as it has the longest lead time. The other items are ordered according to their individual lead times. To demonstrate how this looks in the model, Figure 4-5 represents a doubling in the production rate and each line represents the order rate for a given component to meet the doubling in demand.

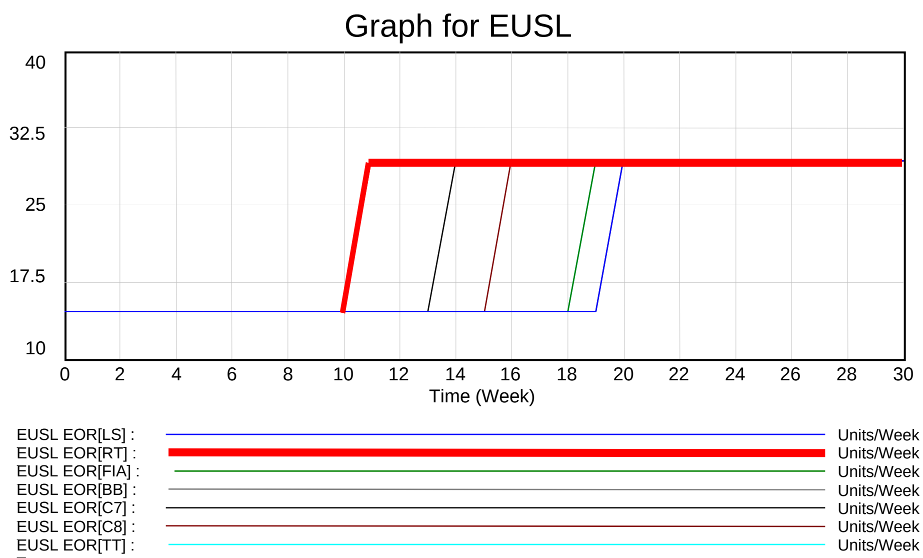

Figure 4-5 Model Output Showing Individual Part Order Rates for Doubling in Production

The graph has a staggered shape because orders are placed according to each individual part's lead-time, and such that all parts arrive simultaneously to satisfy assembly of the electronics unit. The individual lines correspond to each of the items in the electronics unit bill of material, or work breakdown structure (WBS). Note that the model run corresponding to the graph above does not account for any safety stocks. However, each stage of the manufacturing process requires some level of safety stocks to account for variability in the supply chain. Therefore when doubling production rates as has been done here, the higher level assemblies in the work breakdown structure will want to adjust their safety stocks to satisfy the now higher production rate. The model simulates this by adding an additional amount of orders to account for the desired "downstream" safety buffers. This is the reason for the spikes shown in Figure 4-6, they are additional orders for safety stocks at higher level assemblies.

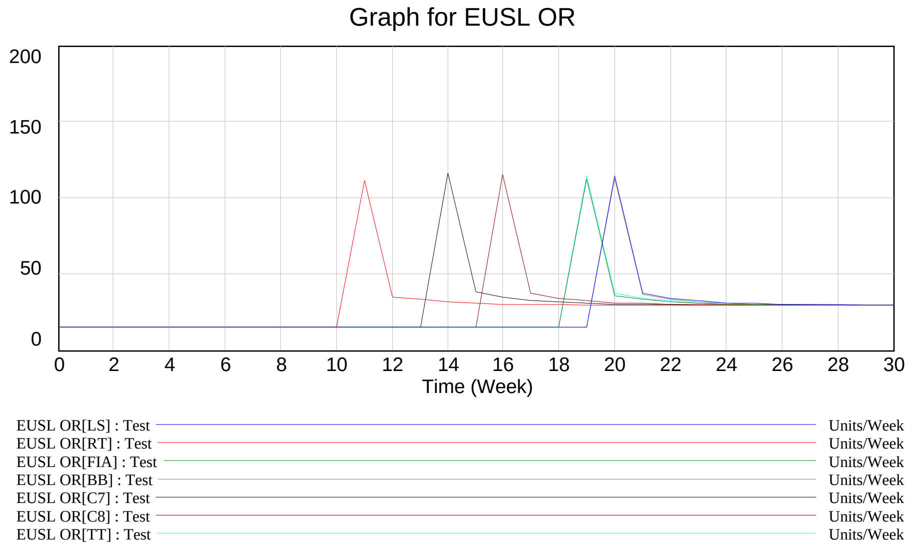

Figure 4-6 Model Output Order Rates Adjusted for Downstream Buffer Requirements

As these orders are fulfilled, they arrive on the loading dock at some rate, which in the model is called the delivery rate and is a function of the average lead time for each part. Therefore an increase in the order rate at time t=0 will cause a corresponding increase in the delivery rate at time t=0 + (average lead time) for the part. The corresponding graph for the delivery rate is given in Figure 4-7.

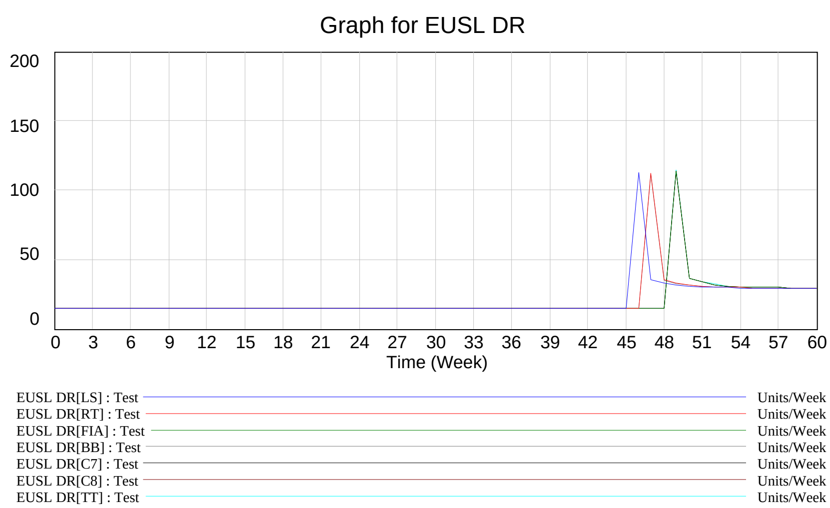

Figure 4-7 Model Output Delivery Rate

Note that this graph is also staggered and "spiked". The staggering in the case of the delivery rate is due to differences in the inspection and stocking time for each of the parts. Therefore parts with shorter inspection and stocking times will show up later in this graph. The spikes are due to the same logic explained previously, that rate increases must also account for larger safety stock inventories upstream.

The next step in the manufacturing process is that parts are assembled in completed electronics units. The assembly rate depends on the availability of the necessary parts and the availability of labor. In the model the availability of equipment is not explicitly modeled, but can be easily incorporated in later versions. Assuming parts and labor are available, the assembly process will be completed within the average cycle time for electronics unit assembly. Thus as in the previous stages, an increase in the part delivery rate will be met with an increase in the assembly rate, but with a delay equal to the average cycle time for assembly, provided that labor is available. Thus, the assembly rate graph is as in Figure 4-8.

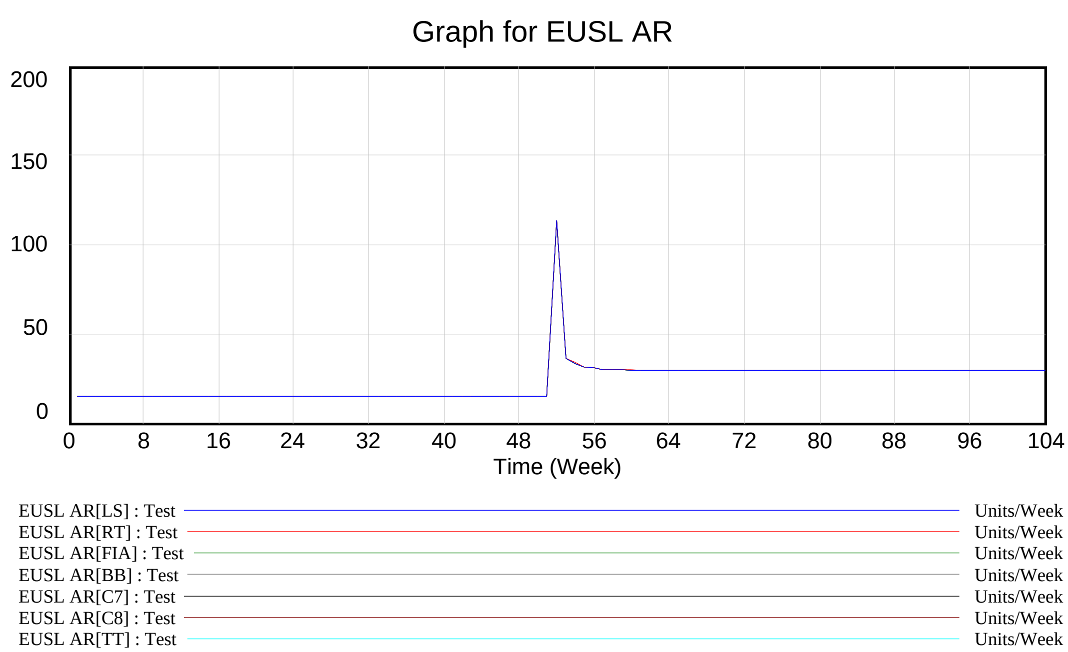

Figure 4-8 Model Output Assembly Rate

Note that the individual assembly rates for each part overlap precisely since they are now modeled as moving together as part of a single electronics unit. The spike represents the need for downstream assembly operations to have a safety stock of electronics units at the now higher production rate. The number of electronics units on hand is shown in Figure 4-9 and represents the numerical integration of the difference between the rate at which electronics units are being produced and the rate at which they are being consumed, plus an initial value.

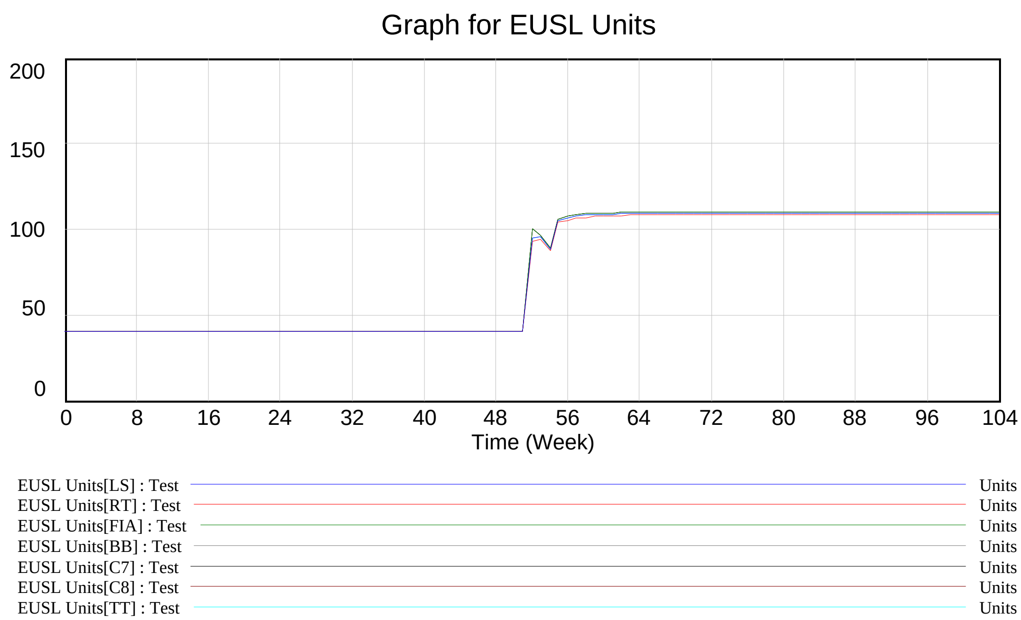

Figure 4-9 Model Output Electronics Unit Supply Line Units On Hand

Note that there is a dip as the downstream assembly processes consume the buffer that is slightly out of phase with the increase since the way the model was built only the assembly process immediately downstream makes the request for additional safety stock at any given time. Therefore, it takes some time for assembly processes two or more steps removed to make the request. If the organization truly has visibility of all safety stocks at any one time, this will have to be changed in subsequent models, although at present this does not seem to be the case. The model does assume that the additional buffer will eventually be requested however, and orders it.

4.1.1 Model Structure

Thus far we have seen an idealized case with no forces pushing the system out of equilibrium. In the previous example, we calculated an order rate, which became a delivery rate delayed by the part lead time. We also calculated an assembly rate which was just the delivery rate delayed by the average assembly time. However, the real world is significantly more complicated in that the part lead times can vary, the assembly time can vary, there may be rework loops, or part failures. This can be added to our original diagram in Figure 4-2 to conceptually show how these problems may be modeled in Figure 4-10.

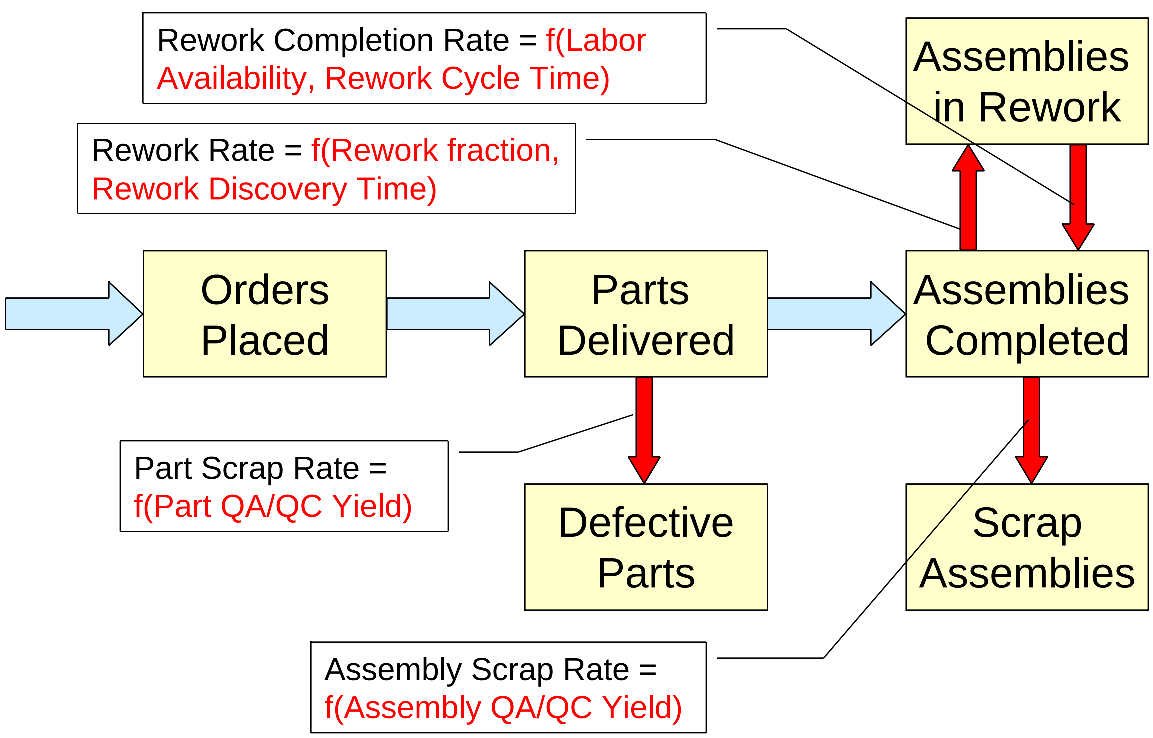

Figure 4-10 Model Structure Including Part Failure Rates, Scrap Rates, and Rework

In addition to our order, delivery, and assembly rates, we now have scrap and rework rates. As parts get delivered a certain fraction will be inspected and found to be defective, this is the part scrap rate as a function of the QA/QC yield. Similarly, the assembly scrap rate is a function of the QA/QC yield through assembly. We then have the rework rate, which is a function of the discovery time (i.e. is the error discovered 10% of the way through or when 90% has been completed) and the rework fraction (the % of reworked parts). The rework completion rate is then a function of the rework cycle time (which may be significantly different from the standard cycle time and the labor availability. These are some of the things that are pushing our system out of equilibrium, and this is why management is needed, to act as a control mechanism to take corrective action and bring the system back into equilibrium.

To model this corrective action, it is necessary to specify the feedback and control mechanisms acting on the manufacturing enterprise. In the structure developed so far, we want to model how management maintains production in the face of changes due to rework, part failures, and variability in the system. One approach is to simply place additional orders to match the parts lost due to failures and those caught in rework. However, due to the long lead times it is very difficult to correct the situation simply by placing additional orders. It is also necessary to maintain a certain safety stock to reduce the production stoppage risk associated with long lead times. This concept is shown in Figure 4-11.

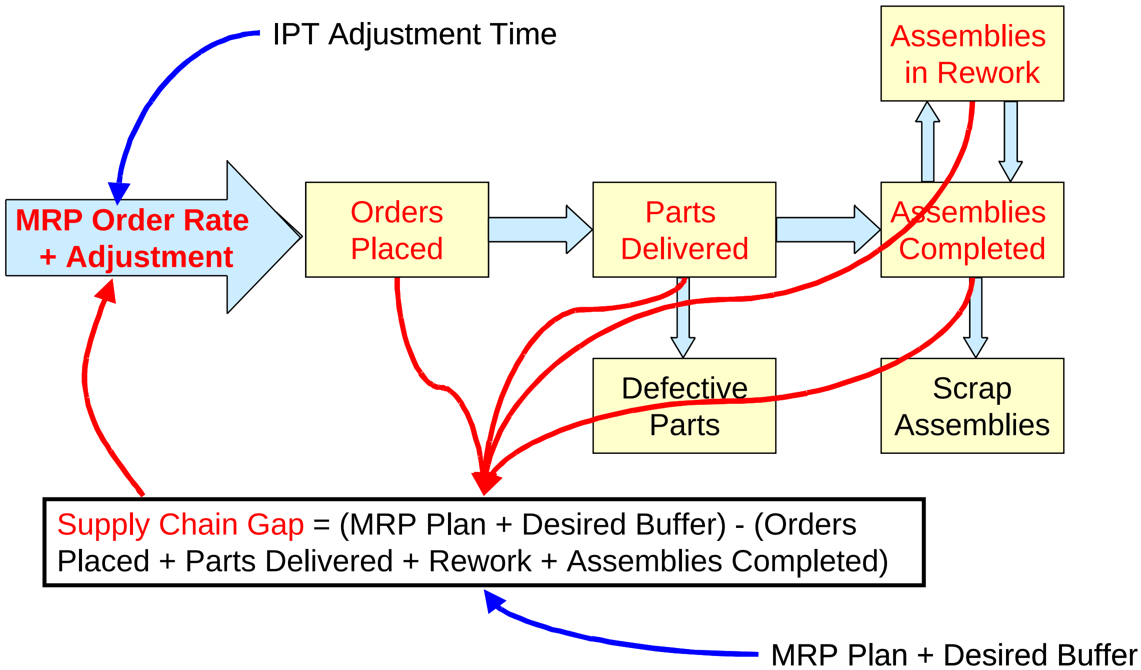

Figure 4-11 Model Structure Showing Material Control Mechanism

Managers are trying to minimize the supply chain gap that arises from the difference between the MRP planned number of units in the supply chain and the actual number in the supply chain. Thus, in the equation above, if all of a sudden a number of parts fail, the number of parts on hand would be smaller, the difference between the planned number of parts and the actual parts on hand would be greater, and the supply chain gap would increase. Managers would seek to close this gap by taking some parts from a safety stock and placing some orders to replenish this safety stock. If the gap is larger than the available safety stock, managers will be forced to place orders and await their delivery. However, this gap is not closed instantaneously. It takes some time for the gap to be noticed, additional time for it to be reported, and another amount of time for the appropriate action to be taken. To account for these delays, the gap is divided by the average delay time, which here is called the IPT adjustment time, and is the time for the Integrated Project Team (IPT) to reach a decision. Thus, the longer the delay time, the smaller the correction that is possible at any given time. The shorter the delay time, the larger the correction in order rate that is possible.

To fully develop these concepts, what is being described here is a first order negative feedback loop to control inventory. Imagine simplifying the system we just described to one where we are only required to maintain 100 parts in a bin from which assembly personnel are drawing. We again use the concept of a gap to show the difference between our planned number of parts and what we actually have. To minimize the gap, we are required to place orders, but it takes some time for us to go get the paperwork, walk to the warehouse, and refill the bin. The structure of this system and its behavior looks something like Figure 4-12.

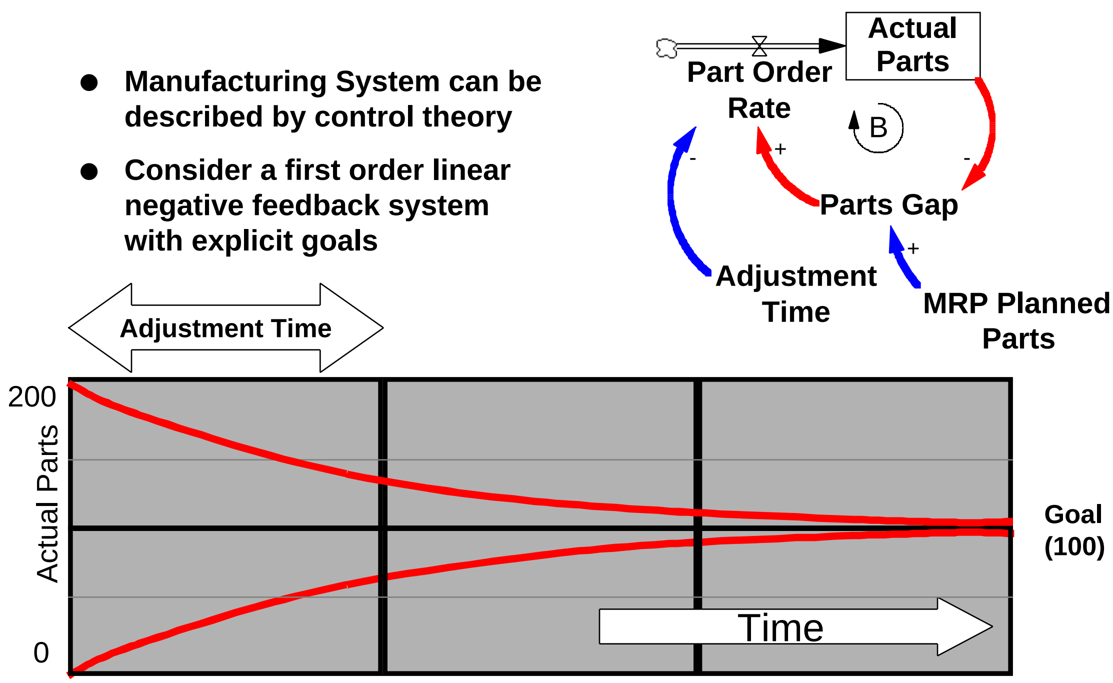

Figure 4-12 Material Control and a First Order Goal Seeking Negative Feedback Loop

If we have too few parts (i.e. starting at 0) we want to increase the amount by 100, but since it takes us some time to get this done, the effective rate at which it happens is something like this: delivery rate=gap/adjustment time. If the adjustment time is very short, the adjustment will be very fast and the effects described here will not be visible. However, if the adjustment time is very long, say a week, then the effects start to be more pronounced and will follow a curve like the one plotted in Figure 4-12.

4.1.2 The Basic Structure Model

We are now able to present the Vensim model structure and detailed equations. The approach taken here is to show annotated portions of the model such that connections between the conceptual model developed previously and the detailed Vensim model can be made, as shown in Figure 4-13.

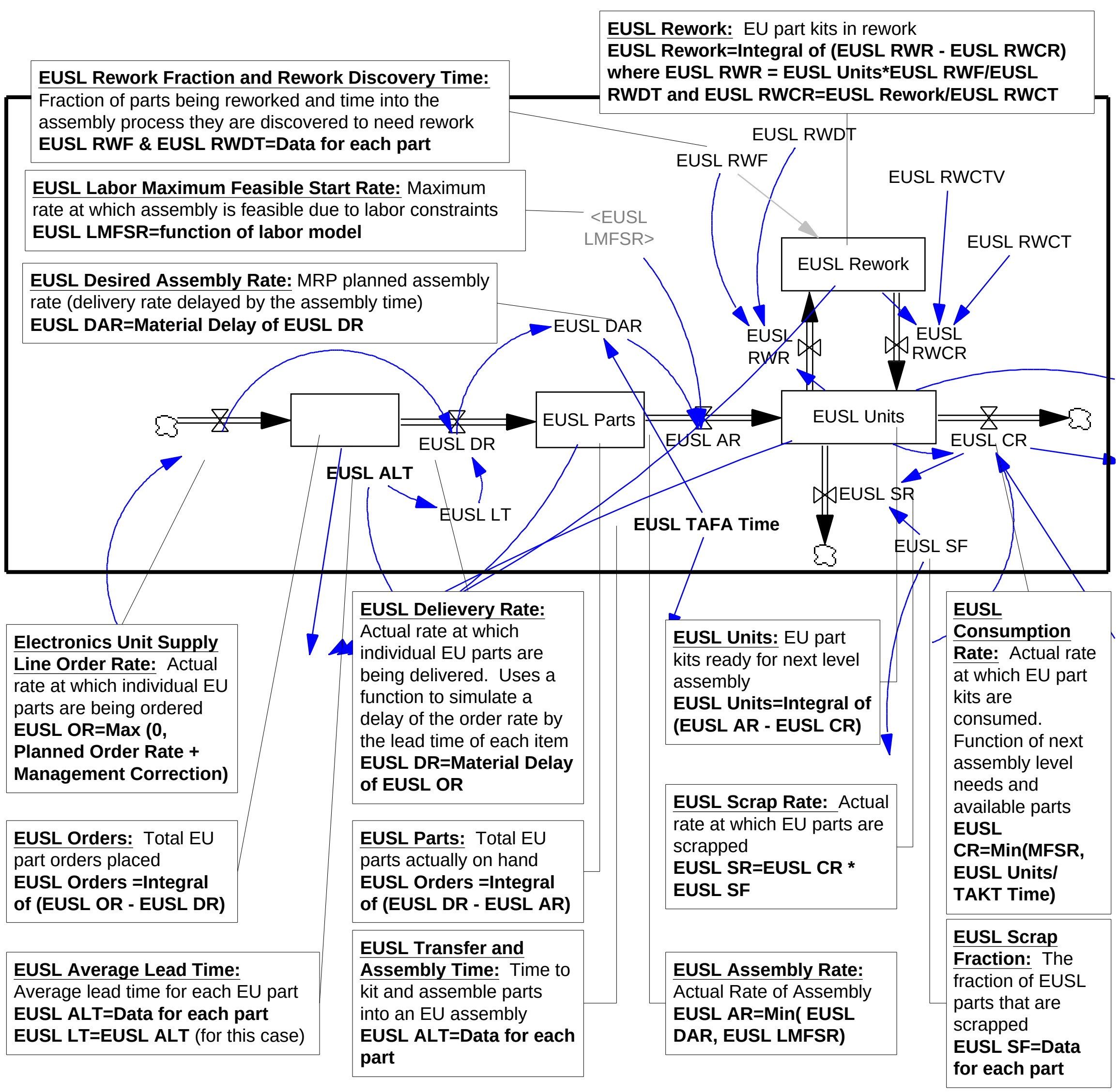

Figure 4-13 Vensim Model Material Flow Structure

The same basic conceptual structure as before is shown in Figure 4-13, however, the additional equations required to build the model are evident. Vensim uses a graphical interface to build the models, but the program is actually evaluating the equations that are entered to generate the analytical relationships between variables. The output of these calculations are the graphs shown in the previous section. The part of the model presented here is the supply chain feeding the electronic unit assembly. This is why all variables have the prefix EUSL, for Electronics Unit Supply Line.

Another nearly identical structure in the model then represents the actual assembly of the electronics unit. The reason for separating the parts from the actual assembly is to capture the work that must be performed on parts before they are placed in kits for the actual assembly of the electronics units. Thus, the EUSL Units that are the last stock in Figure 4-13, are actually kits of parts ready for the next level assembly. Another reason to build the model in this way is to capture the effect of part shortages. Electronics unit assembly can only proceed at the available number of kits, which in turn depend on individual parts being available. In practice, some assembly proceeds without waiting for individual parts that are late, but on average the effect should be similar since higher-level assemblies will eventually be delayed due to a part shortage. The corresponding material control structure is shown in Figure 4-14.

Again the equations may seem significant, but the model control structure is conceptually identical to the simple goal seeking negative feedback loop shown in Figure 4-12, albeit with additional detail to account for the actual policies and manufacturing structure present at Raytheon Missile Systems. In the case of the model the loop's goal is to meet MRP targets in terms of production rate and delivery times.

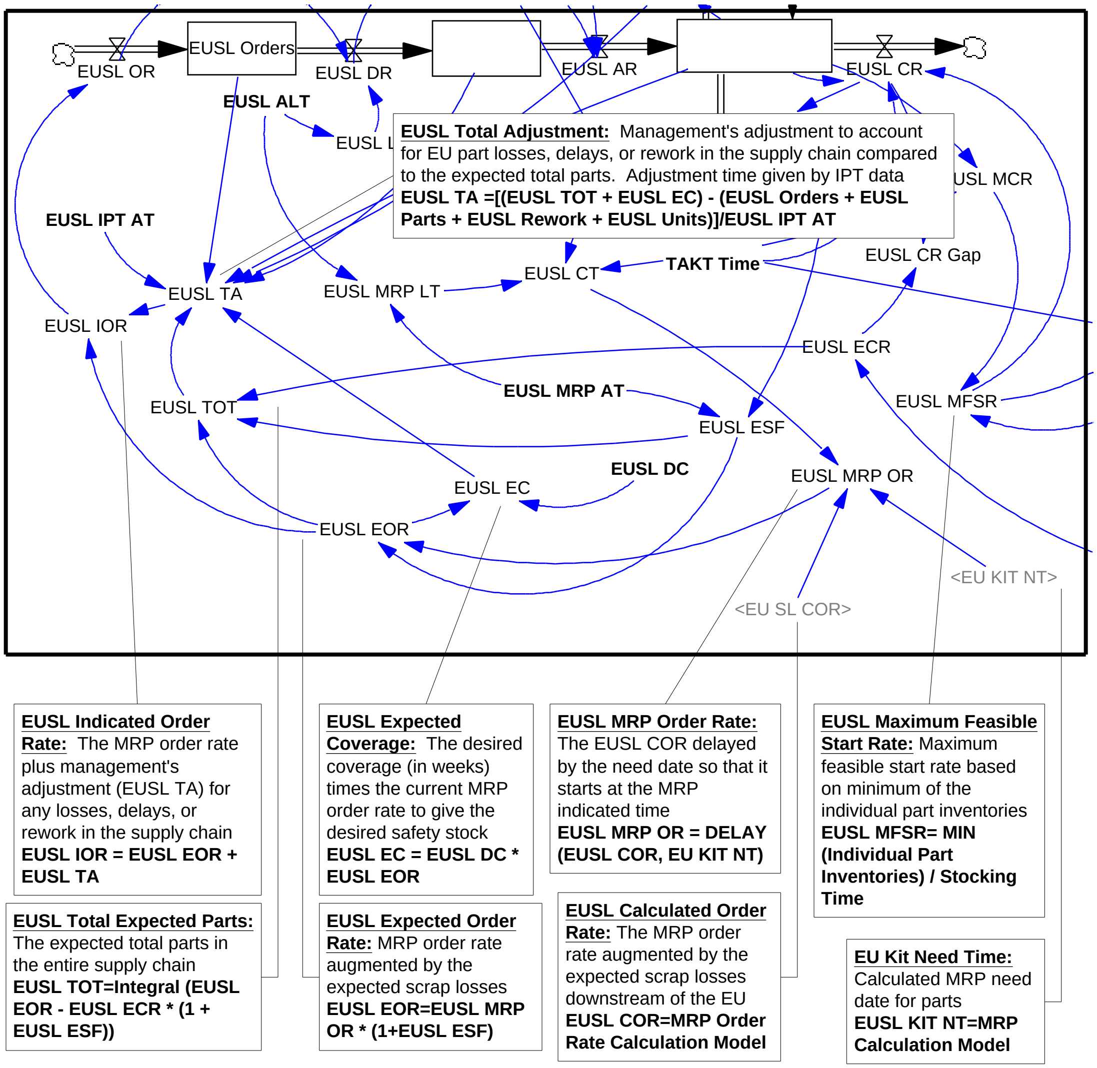

Figure 4-14 Vensim Model Material Control Structure

One of the more important aspects of the control structure is the explicit modeling of actual and expected parameters. For example, at any moment in time there is an actual scrap fraction for parts, i.e. what is actually occurring. However, it takes some time for this information to be collected, reported, and acted on, thus the system is actually operating based on the ***expected*** scrap fraction until the real data catch up. The same is true for other parameters, such as lead time, where the MRP system will have a certain expected value on which it is basing its calculations, but the reality may be significantly different. A supplier may be behind (or ahead) but MRP will continue to plan other material deliveries, labor requests, etc. according to the planned (expected) lead time. This is the reason for explicitly modeling the difference between real and forecast variables since discrepancies between the two can lead to the “self-fulfilling” prophecy problem described in Figure 2-5 and Figure 2-6 in the background chapter.

There is an implicit assumption that material control personnel have a very clear visibility of the entire supply chain. This is shown by the fact that in Figure 4-14 there is a single adjustment for the entire EU supply chain (EUSL TA) that goes into the indicated order rate. This is modeled in this way because there is little variability in demand for missile systems and suppliers are aware of precise order quantities very much in advance. Also, implicit in the MRP system is that there is clear visibility of part and labor needs throughout the assembly process and that things proceed in a deterministic way. This system would show very significant oscillations if this were not the case, and in fact may not be the case for certain manufacturing areas. Addressing this issue is left to the final section under work required to further the model.

The remainder of the model is simply a set of structures identical to the one developed here for the electronics unit supply chain connected in building block fashion to account for the other parts of the AMRAAM work breakdown structure. The only other significantly different structures are the labor supply model and the calculation of MRP parameters such as need times and rates. The labor model is described in further detail in Figure 4-15, but is essentially another goal seeking negative feedback loop trying to meet the MRP labor requirements. Overtime is available to meet the labor requirements, but is limited to 1.5 times the base labor hours. The labor supply part of the model accounts for the delays in obtaining labor since hiring personnel is not immediate but may take several months from the initial requisition. This can place significant constraints on production and hence on cash flow.

The MRP calculation engine in the model is not shown in figure form, but has identical logic to the standard MRP system in calculating the critical path, assigning material need dates, labor requirements, etc. The MRP calculation takes into account the expected failure and scrap rates as product progresses up the work breakdown structure. The lead times, standard hours for assembly, etc. are all included as data tables built into the model, but which could be transferred to Excel for lookup by Vensim in later versions.

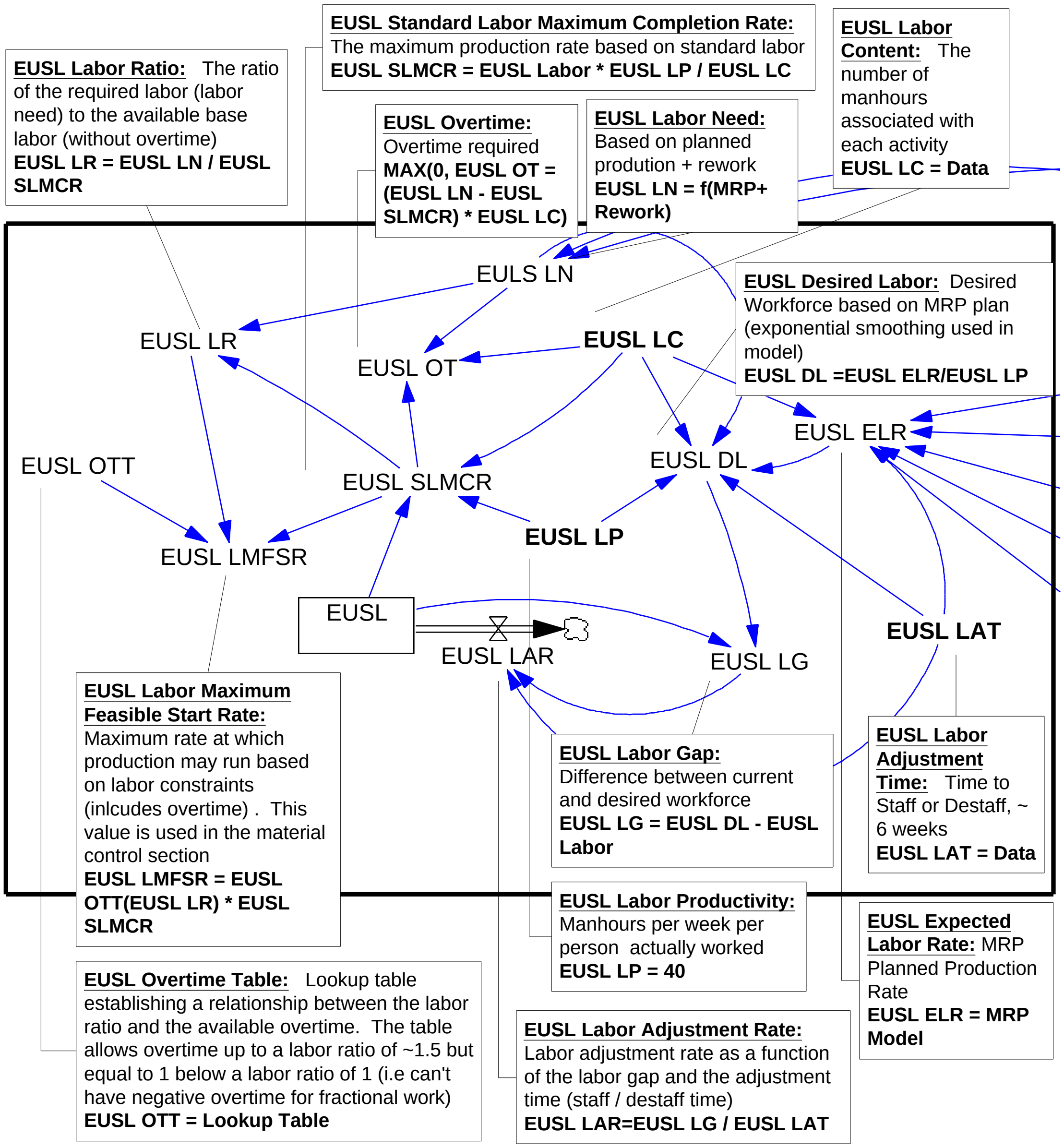

Figure 4-15 Vensim Labor Supply Structure

4.1.3 Putting It All Together

Now that we have our basic building block, we can proceed to build the entire model. Recall the AMRAAM missile work breakdown structure given in Figure 4-3. The model takes each piece in that work breakdown structure and builds a material and labor control structure around each piece and connects them together in the order they are required by the assembly process. Thus, the EU supply chain we developed in the previous section feeds the EU assembly process, which is one of the required parts for the Guidance Section (GS) assembly along with a number of other GS specific parts from the GS supply chain. The overall model structure is shown in Figure 4-16.

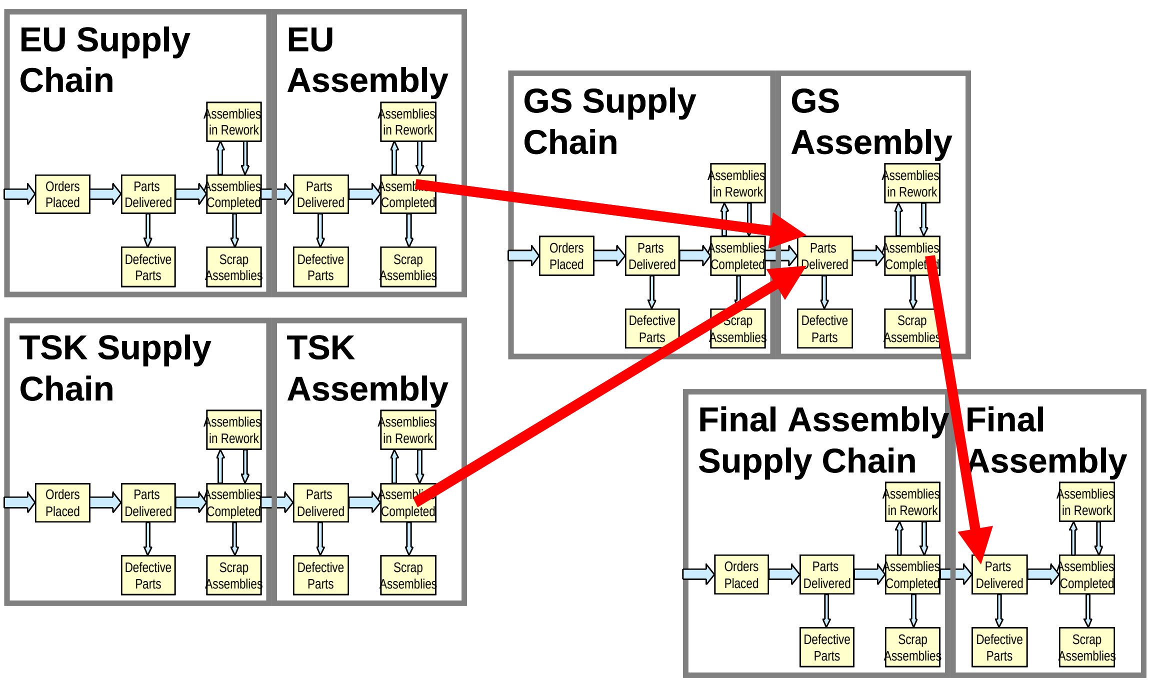

Figure 4-16 Overall Vensim Model Structure

The actual structure as seen on the Vensim screen is very similar to that shown in Figure 4-16, and the actual EU and TSK portions of the model are shown in Figure 4-17, for comparison.

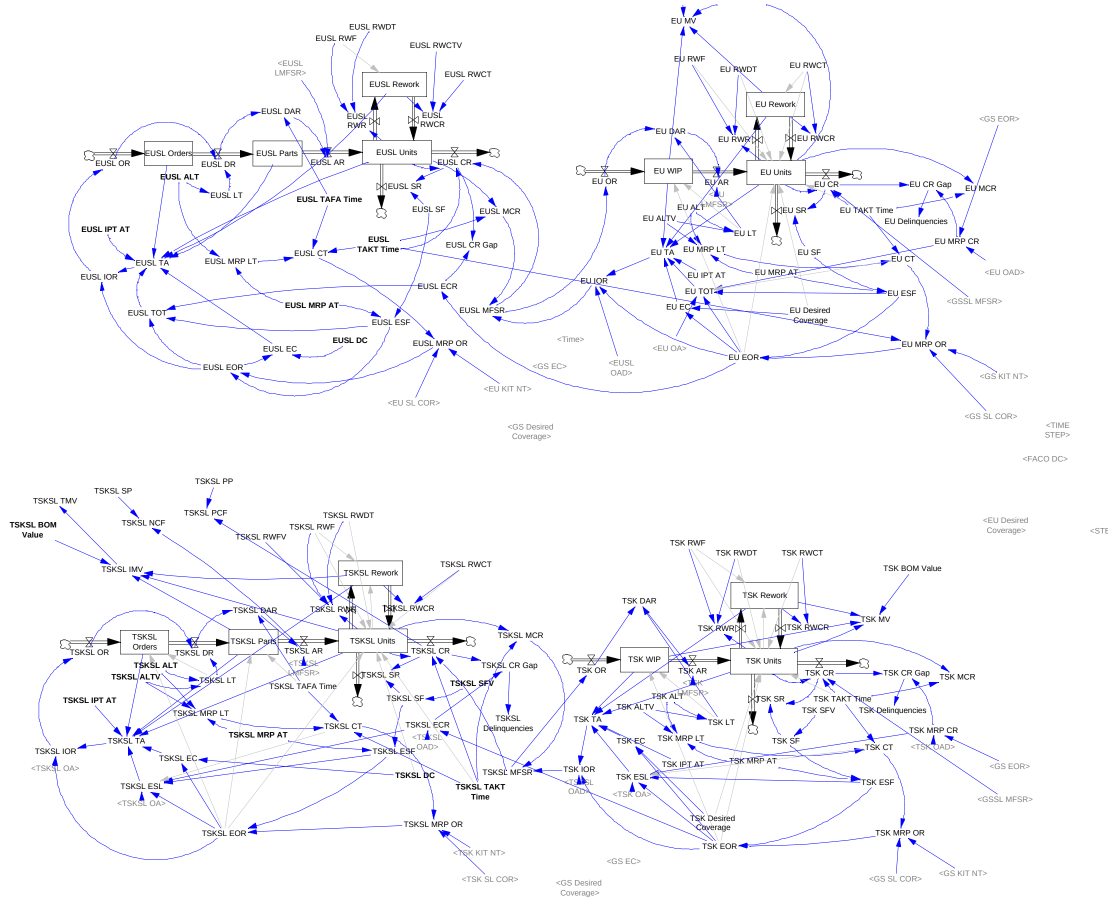

Figure 4-17 Screen View of EU and TSK Material Control Section of the Vensim Model

Once we have this basic framework for the material and labor control loops it is possible to add the financial dimensions such as cash flow that we seek to optimize. In the material control structure, we modeled the delivery of material as a delivery rate into the stock of parts on hand. Now picture what happens financially when the material arrives: 90 days later a payment is made to the supplier, but the material triggers the use of labor immediately to inspect and assemble at a certain hourly rate. We can then simply multiply the delivery rate (EUSL DR) or the assembly rate (if inspection is required before payment) by the individual part's cost and assign it a delay function equal to 90 days. If we do this for all material, and also collect the labor costs based on the number of hours being expended at standard and overtime rates we can establish a close approximation for the cash being consumed in production. To refine our approximation we add a certain base cost for support personnel and overhead based on a support to touch ratio and fixed percentage of cost as overhead. To collect cash from sales we simply multiply the sales price by the delivery rate of completed AMRAAM missiles, and if we had progress payments we could establish cash flow calculations based on intermediate progress as well. The cash flow calculation in the model is then simply the sum of all cash going out (material, labor, and overhead payments) and the cash coming in (delivery payments). This is shown in Figure 4-18.

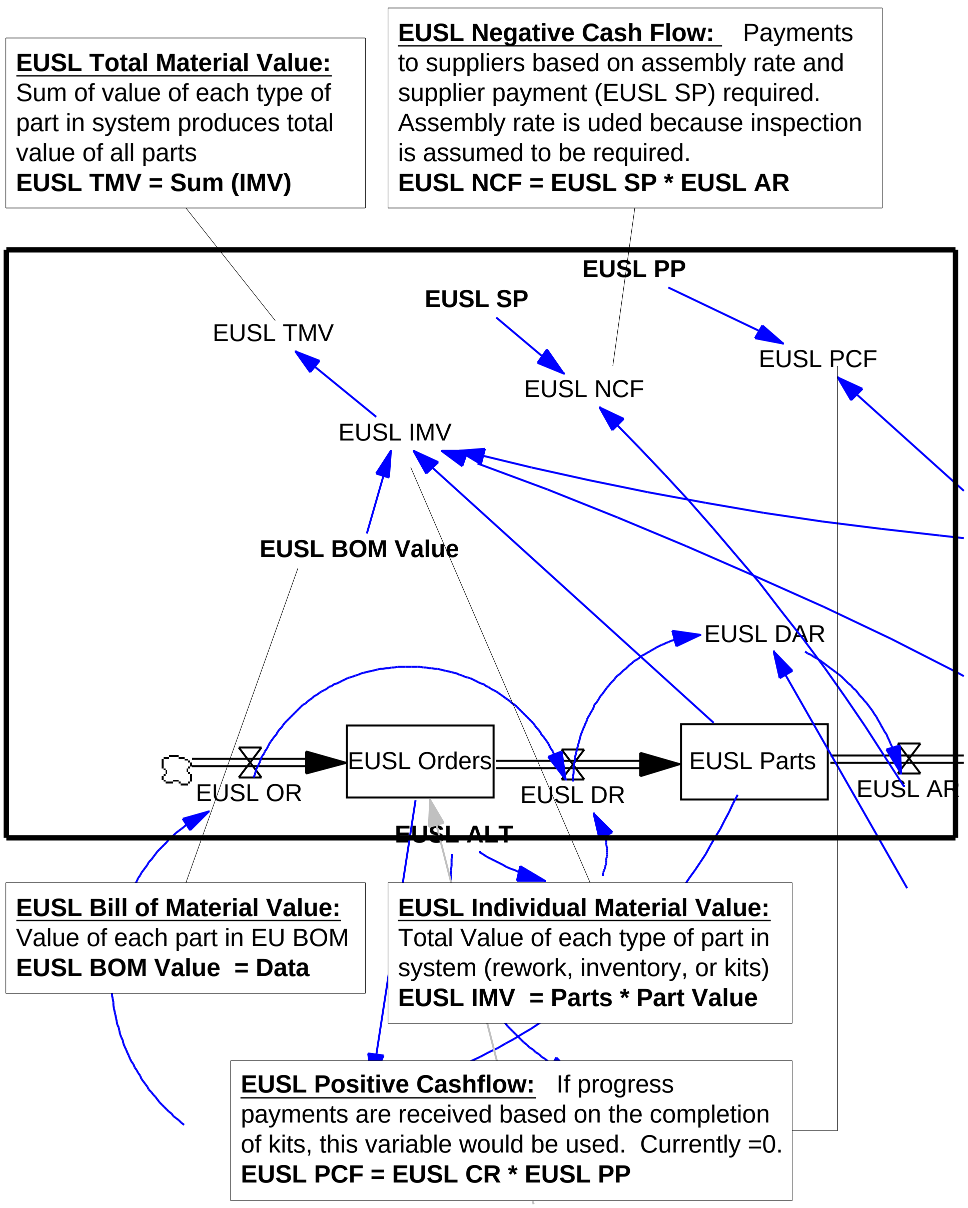

Figure 4-18 Calculation of Supplier Payments in Vensim Model

Figure 4-18 shows how the cash use for supplier payments can be added to the model. The labor and delivery payments are modeled identically to Figure 4-18. The labor calculation takes into account different hourly rates for overtime versus standard work and it is assumed that there is always a certain baseline amount of cost for lights, water, etc. The other overhead costs are modeled as a function of the support to touch ratio as stated previously.

With this final piece of the model we are now able to compute the cash flow function described in the background section. Specifically we are now able to calculate the effect on cash flow from each of the variables we have described in this section, such as rework fractions, scrap fractions, rework cycle times, assembly cycle times, etc. The analysis is developed in the next section.

4.2 Some Model Results

The model allows us to change parameters and identify what the behavior over time will be of cash, material turns, working capital, and a number of other measures on the traditional balanced scorecard. This section shows the effects of varying some of these parameters, with some obvious and not so obvious results. Let's start with a traditional manufacturing improvement example of determining what the effect of reducing the final assembly cycle time is from the current 2 weeks to 1 week. We don't expect a change in the delivery rate since that is fixed by the critical path elsewhere in the system. However, we do expect some improvement in the amount of material contained in the system and therefore also in our inventory turns. Figure 4-19 and Figure 4-20 show the results. Thicker lines are the improvements. The one week improvement translates into a one time savings of $2.2 million, since that amount of inventory no longer needs to be held. In this scenario the work content per missile and delivery rate are assumed to be the same so cash flow is not significantly affected, but the savings in working capital are significant.

A unique feature of the missile market is that sales forecasts are well known far in advance. Except for the odd military conflict, most sales follow congressional appropriations and it is therefore not advantageous to have a large amount of excess production capacity since demand does not fluctuate as significantly as in the commercial world. In the defense business sales are fixed every year, but it is very possible to fail to meet cash flow due to operations execution problems. This is the very thing we would like to manage with this model.

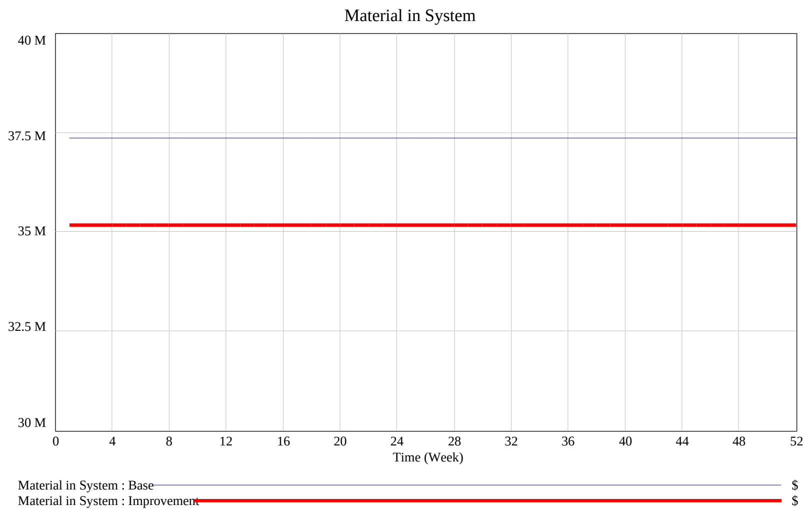

Figure 4-19 Material in System Improvement for 1 week Reduction in Final Assembly Time

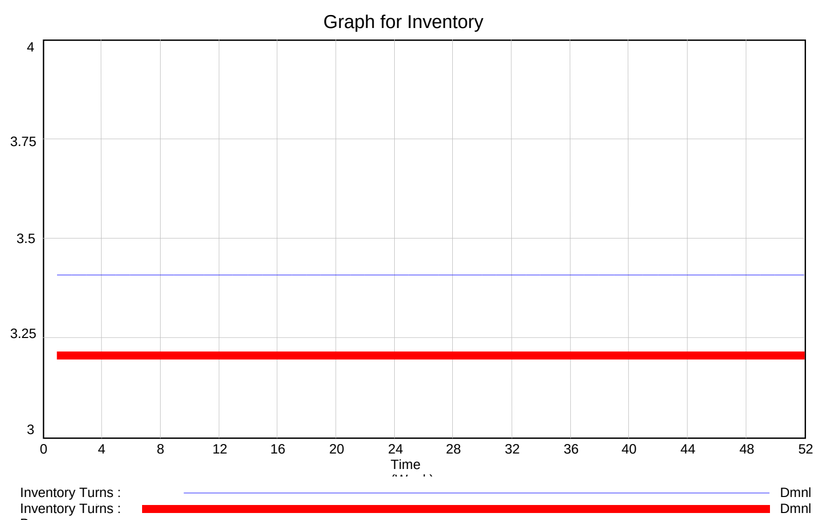

Figure 4-20 Inventory Turns Improvement for 1 week Reduction in Final Assembly Time

Another example of an operational decision is how much safety stock or buffer is required to prevent production stoppages. Using the model we are able to identify not only production stoppages, but also to identify the level of safety stocks required to maintain a certain minimum cash flow subject to potential delays in part deliveries or assembly. Using the model we are able to simulate the effects on cash flow of a delay in material delivery, and what the cost of safety stocks to reduce the impact of this potential delay would be. Figure 4-21 shows the effect on cash flow of a sudden 20 week delay in the Chassis 7 part that goes into the electronics unit. In scenario A (the thin line), there is only a 2 week safety stock for the chassis 7 parts, and the cash flow is severely affected, dropping to a minimum value of negative $2.94 million per week in week 83. In scenario B (heavy line), the safety stock is increased to 12 weeks, and the cash flow is not so severely affected, dropping to a minimum of positive $0.53 million per week in week 87 and recovering quickly thereafter.

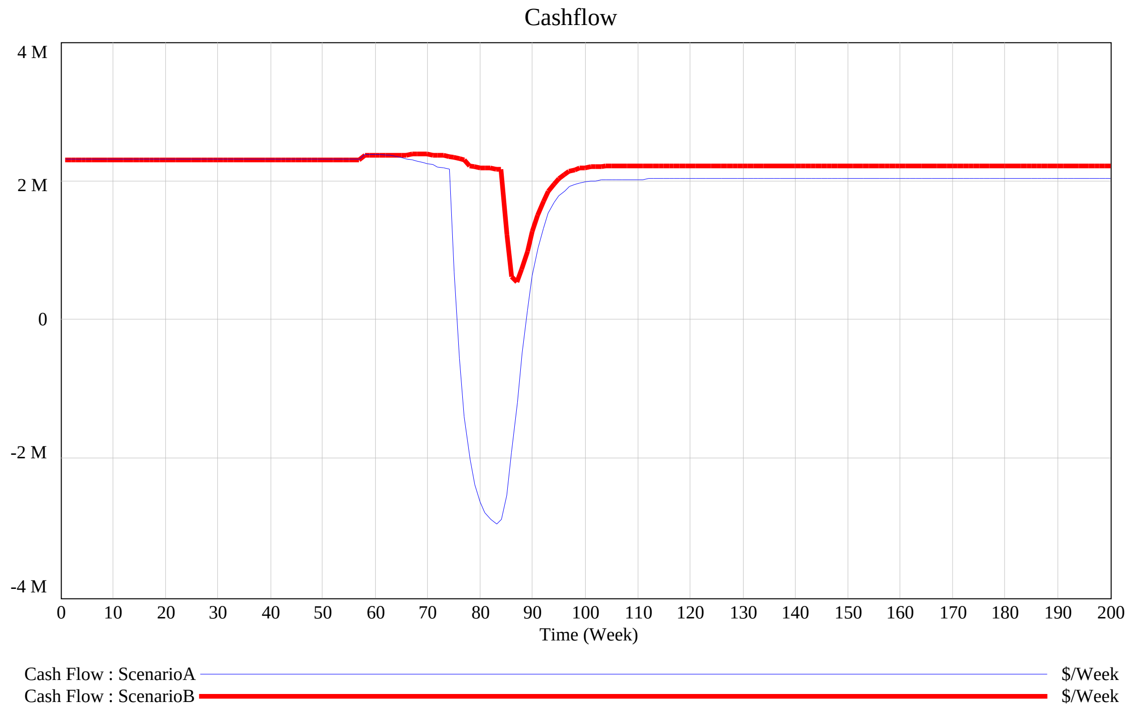

Figure 4-21 Comparison of Model Output for 20 Week Delay in the Chassis 7 Component of the Electronics Unit with a 2 Week Buffer (Scenario A) and a 12 Week Buffer (Scenario B)

Note also that scenario B returns to nearly the same level of cash flow after the delay, but scenario A with less buffer does not. The model assumes that work releases continue according to the MRP plan and thus a certain amount of excess inventory builds up which cannot be used until the corresponding chassis 7 components arrive. The continued work releases consume labor and the additional material inventory also consumes labor since it will produce additional inspection and rework. This assumption may be easily changed in the model to one where all work is stopped until the chassis 7 parts arrive and no excess inventory of other parts is built up while the delay is sorted out, but interviews with production personnel do not justify this assumption.

One of the problems mentioned by production personnel is that although MRP is officially updated on a weekly basis, many of the parameters such as part lead times are updated much less frequently and there is little dynamic re-scheduling to better allocate resources when delays occur. To compensate for this, managers often enter lead times that are very significantly buffered into the MRP system to prevent situations like the one described here. This leads to the situation described in chapter 2 in Figure 2-6 of the propagation of "hidden" buffers through the system. Using this modeling tool to look at the real consequences of problems should allow for a more rational allocation of these buffers and hopefully a reduction in the overall cycle time for production.

Another area of cash flow risk that can be analyzed using the model is the effect of rework. The model examples presented so far have been for illustrative purpose only, using disguised financial data, although the behavior of the system will remain the same. The following rework example includes actual data on rework cycle times, rework fractions, scrap fractions, and lead times, although the cost data remains disguised primarily by an assumed high sales price of $500,000 per missile. Two scenarios are analyzed. The baseline case represents the baseline situation with rework, scrap, based on the data found in Table 4-1 Baseline Model Rework and Scrap Fraction Data .

Time in Days		Scrap Fraction			Rework Fraction			Rework Discovery Time	Rework Cycle Time		
Item	Key	MIN	MRP	MAX	MIN	MRP	MAX	MRP	MIN	MRP	MAX
								40%	200%	300%	500%
AMRAAM Missile	M	0	0	0	***10%***	***15%***	***20%***	2.0	4.0	6.0	10.0
Propulsion	P	0	0	0	0	0	0	2.0	4.0	6.0	10.0
Warhead	W	0	0	0	0	0	0	2.0	4.0	6.0	10.0
Fins	F	***0***	***5%***	***10%***	0	0	0	2.0	4.0	6.0	10.0
Harnesses	H	***0***	***5%***	***10%***	0	0	0	2.0	4.0	6.0	10.0
SAF	SAF	***0***	***5%***	***10%***	0	0	0	2.0	4.0	6.0	10.0
Data Link	DL	***0***	***5%***	***10%***	0	0	0	2.0	4.0	6.0	10.0
Rectifier Filter	RF	***0***	***5%***	***10%***	***10%***	***15%***	***20%***	2.0	4.0	6.0	10.0
Control Section	CS	0	0	0	***10%***	***15%***	***20%***	2.0	4.0	6.0	10.0
Guidance Section	GS	0	0	0	***10%***	***15%***	***20%***	4.0	8.0	12.0	20.0
Inertial Reference Unit	IRU	***0***	***5%***	***10%***	0	0	0	6.8	13.6	20.4	34.0
Aft Fuselage	AF	***0***	***5%***	***10%***	0	0	0	6.8	13.6	20.4	34.0
Electronics Unit	EU	0	0	0	10%	15%	20%	0.0	0.0	0.0	0.0
Launch Seek	LS	***0***	***5%***	***10%***	0	0	0	11.2	22.4	33.6	56.0
Remote Term	RT	***0***	***5%***	***10%***	0	0	0	6.8	13.6	20.4	34.0
FIA	FIA	***0***	***5%***	***10%***	0	0	0	6.8	13.6	20.4	34.0
Ballast BDS (2)	BB	***0***	***5%***	***10%***	0	0	0	6.8	13.6	20.4	34.0
Chassis 7 (IF RCVR/RC)	C7	***0***	***5%***	***10%***	***0.4***	***0.45***	***0.5***	6.8	13.6	20.4	34.0
Chassis 8 (FRU)	C8	***0***	***5%***	***10%***	***0.4***	***0.45***	***0.5***	6.8	13.6	20.4	34.0
TDE / TDD	TT	***0***	***5%***	***10%***	***0.4***	***0.45***	***0.5***	6.8	13.6	20.4	34.0
Terminal Seeker	TSK	0	0	0	67%	70%	75%	1.6	3.2	4.8	8.0
Battery/Power Supply	BP	0	0	0	5%	10%	15%	8.4	16.8	25.2	42.0
Transmitter	T	0	0	0	40%	45%	50%	6.8	13.6	20.4	34.0
Seeker / Servo	SS	0	0	0	55%	60%	70%	6.8	13.6	20.4	34.0
Servo Electronics	SE	0	0	0	0%	5%	15%	8.4	16.8	25.2	42.0

Table 4-1 Baseline Model Rework and Scrap Fraction Data

The second scenario examines the effect of increasing rework cycle times for a single critical path item, such as the terminal seeker assembly (TSK). The terminal seeker has a high rework fraction averaging 70%, however, and although the time to complete the rework (i.e. the rework cycle time is reported to be 1 week), we can use the model to determine the effect on the system of longer rework times. In this scenario, a sudden increase in rework from 1 week to 3 weeks and another from 1 week to 6 weeks is tested. These scenarios are labeled as Shock3 and Shock6 respectively in Figure 4-22. The system is extremely sensitive to rework fraction and rework cycle time increases due to the very long lead times for most components. These “shocks” to the system caused by additional rework are what safety buffers are designed to protect, although the magnitude of the effect can be greatly reduced if rework fractions and times are small to begin with. In the scenarios analyzed here, the program would take a hit of approximately $60.6 million (22% loss) due to the delays caused by the worst case of a sudden increase in terminal seeker rework time from 1 week to 6 weeks with all other variables remaining the same as in the baseline. The system eventually adjusts for this additional delay, but the financial impact is significant as shown in Figure 4-22.

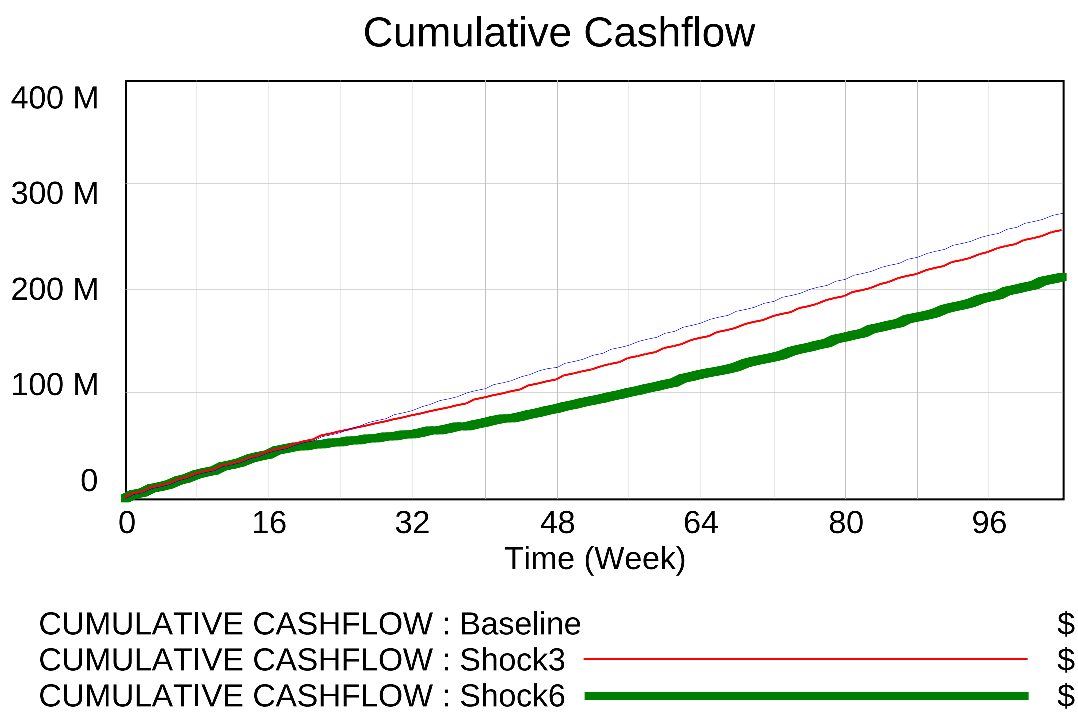

Figure 4-22 Effect on Cumulative Cash Flow of Increasing Terminal Seeker Rework Time

In practice, several variables may change simultaneously over known bounds. For example, the rework fraction of Terminal Seekers has historically been as high as 70%, and the officially reported rework cycle time has been about 1 week. However, any increases in this rework fraction above 70% or rework cycle times above 1 week can potentially stop production and have a huge financial cost to the organization, although the actual cost of the rework may be small. The modeling of this variability in key model parameters is the focus of chapter 5.

4.3 Six Sigma Programs

Another important result from the model is the evaluation of six sigma project benefits. Conceptually, reducing cycle time, inventories, and variability are all good things, but it is sometimes difficult for managers to know which areas should be improved to yield maximum financial benefit especially in a complex manufacturing system like Raytheon. Using the model it is possible to simulate planned six sigma programs and determine their contribution to financial performance. This allows managers to better direct limited six sigma improvement resources to areas that will yield the greatest benefit. Along these same lines, it is also possible to use the optimization routines in the Vensim program to generate what the required improvements in other areas of the enterprise, such as yields, productivity, etc., should be to reach a certain payoff such as a cash flow level.   Table 4-2 contains some of the production related six sigma improvement projects planned for the AMRAAM program.

Name	Description
Deliver 1 Month Ahead	Deliver one month ahead of contract by year end 2000; maintain elevated production rate until goal is met, and align the supply chain to recover deliveries per MRP schedule
12 Month Missile	Develop capability to produce a missile in 12 months.
Deliver Lot 15 Early	Deliver Lot 15 missiles 2 months early to provide additional sales capacity/opportunities
Retest & Rework Reduction	Each Guidance Section fails an average of three times. Error-proof guidance section test process, improve TE variability and capability
Factory Flow, Cycle Time, WIP	Improve Factory Flow & Cycle Time / Reduce WIP for AMRAAM internal critical path
Aft Fuselage	Improve Factory Flow & Reduce Cycle Time / WIP for the AMRAAM AFT Fuselage (longest lead in-house assembly)
Inventory Reduction	Reduce Inventory levels within stores to 1 to 3 months on-hand

Table 4-2 Summary of Planned Six Sigma Projects for AMRAAM Program

Using the model it is possible to calculate the effect of these improvements on financial performance. For example, we can model the overall cycle time reduction to a 12-month missile and determine what the effect would be on cash flow. To better illustrate this example we assume in this scenario that we are suddenly doubling the production rate from 1 to 2 missiles per week and want to see how quickly our cash flow will adjust under the baseline cycle time and the 12 month missile cycle time. In this scenario we assume that the order rate doubling is ordered at time t=0. Also the cash flow shown in Figure 4-23 is lower than other examples because here we have assumed a 1 missile per week order rate. In this example, steady state cash flow is achieved much earlier yielding a higher NPV.

The other six sigma production related programs can be analyzed in a similar way. Also, using the optimization routines it is possible to identify which areas of the program would yield the greatest benefits to a particular measure, such as cash flow, and the required improvements calculated. The model will not indicate how to make these improvements, that is what six sigma tools are for, but it will indicate the magnitude of the required improvement and the area.

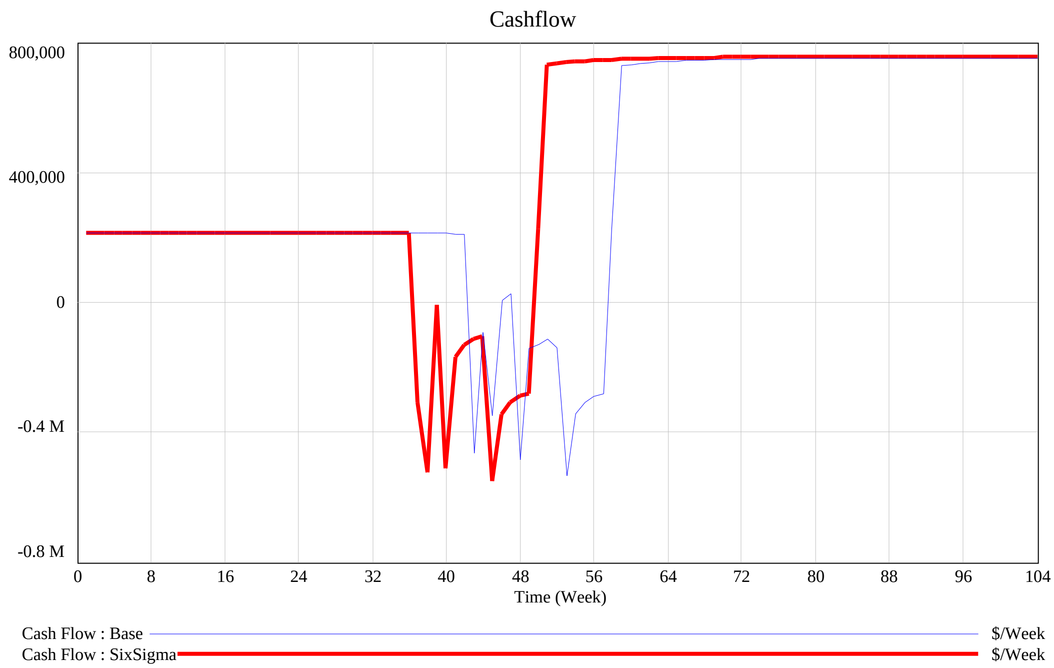

Figure 4-23 Performance Improvement Comparison for 12 Month Missile Six Sigma Project

5 Sensitivity Analysis

Once a model is built, it is possible to apply powerful analysis tools to determine the sensitivity to parameters. Using these tools it is possible to incorporate some of the concepts on uncertainty analysis developed in the background section and complete the tools outlined in Figure 2-15 of the background material.

Error! Reference source not found. showed that eliminating all rework has a positive effect on cash flow as expected, but it was also stated that variability in the rework parameters can have very significant negative impacts on financial performance, especially cash flow. To calculate the effect of variability in system parameters we use the monte carlo simulation capability in Vensim which lets us input statistical distributions for the parameters and determine their effect on key model variables such as cash flow. For example, the data given in Table 4-1 collected from historical data and program personnel interviews, provides the range of variability for the rework fraction parameters. The table gives a minimum value, an average value, and a maximum value. From these 3 numbers it is possible to construct statistical distributions that can then be input to the sensitivity analysis program.

For this example, the Terminal Seeker rework fractions are varied according to the distributions shown in Figure 5-1. Note that the battery/power supply has very little rework while the Terminal Seeker itself and the Seeker Servo have very significant rework fractions. The Vensim software allows for a variety of distributions to be input, and these normal distributions were chosen as the closest approximations to the data in Table 4-1. Many other simulations are possible, but the intent is future use would be guided by structured design of experiments (DOE) methods to determine which parameters most affect each outcome variable.

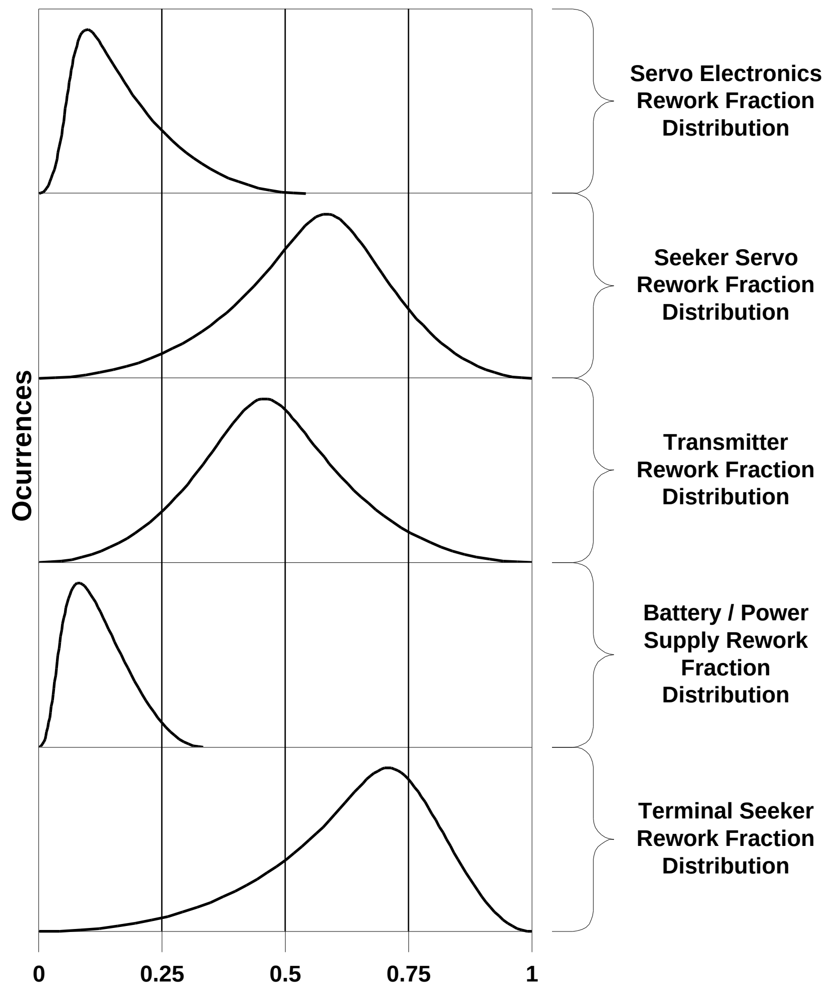

Figure 5-1 Rework Variability Distribution for Terminal Seeker and Components

The resulting sensitivity analysis graph is shown in Figure 5-2. Although our distributions for the uncertainty in Terminal Seeker component rework fractions are standard normal distributions, the end result in Figure 5-2 is not in any way a simple normal distribution due to the complexity of the manufacturing system structure.

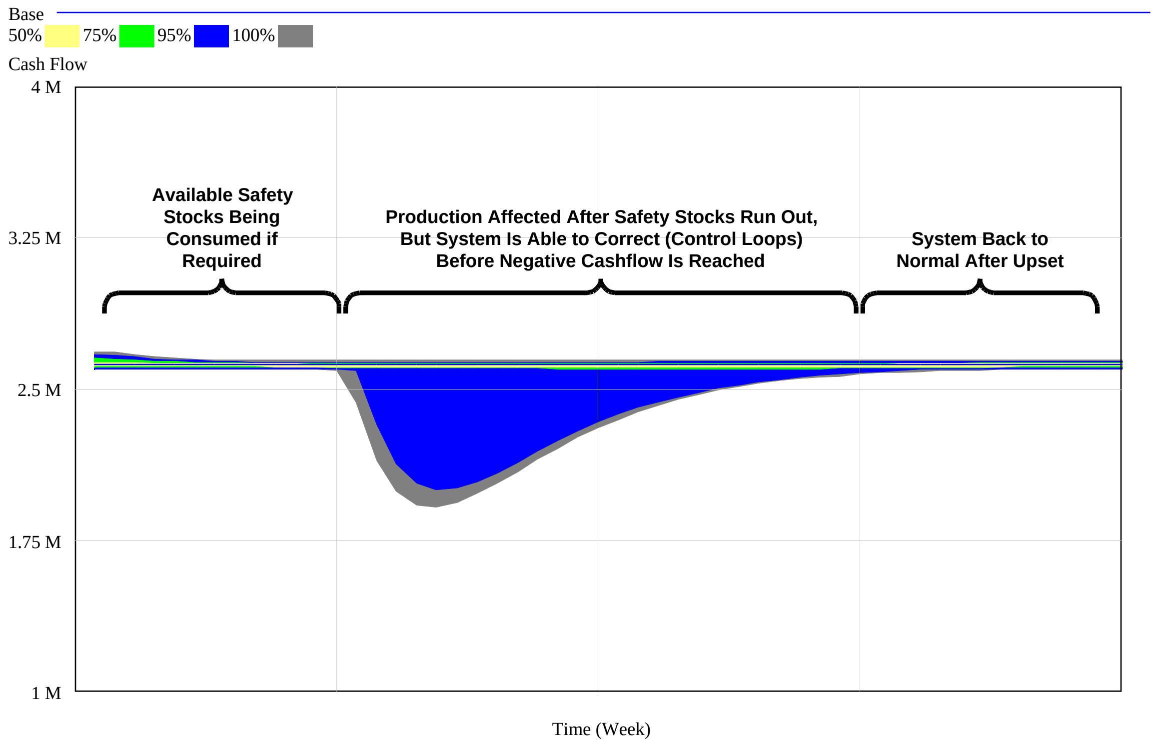

Figure 5-2 Sensitivity Analysis for Variability in Terminal Seeker Rework Fractions

The result shows that variability in Terminal Seeker rework can have a very significant impact on cash flow. The graph has the shape that it does because of the material flow and control structures contained in the model. The first section of time in the graph shows the system apparently operating normally, but it is in fact consuming safety stock to maintain production in the monte carlo runs where the rework fraction is high. Once this safety stock is exhausted, production is affected, but since it is only rework being considered the time to correct the problem is smaller and does not reach a negative cash flow. The system control loops take effect (i.e. management applying overtime, etc.) to correct the problem and the system eventually returns to normal, but not without suffering lower than expected cash flow in certain runs of the monte carlo simulation. In order to correct the situation or at least proactively monitor it, management should deploy six sigma resources to better control the variability in rework fractions (i.e. how much rework) and metrics should also be developed to give management advance notice of higher than expected rework fractions in order to take early corrective action.

It is possible to perform the same analysis using variability in supplier lead times, where the earliest possible delivery, the average delivery, and the latest expected delivery allow us to create statistical distributions to represent this variability. An example of this analysis is not shown here as it would be redundant with the previous example, but this application is a valuable tool to determine what conditions must be placed in contracts with suppliers to minimize the financial impact of late delivery and provide economic incentives for on-time delivery. Many other analyses are possible to investigate the sensitivity of cash flow (or other metrics) to parameters in the model. Thus, as the model becomes more robust and loops for customer satisfaction, employee satisfaction, and other balanced scorecard metrics are added, it is possible to perform the same sensitivity analysis and determine how much cash flow is affected by variation in those parameters.

6 Recommendations

It is not possible to manage a process that is not understood. There is also a corollary to this axiom, which I would postulate as follows: It is not possible to manage a process that is not measured. The tools developed in this thesis are just that. They are powerful, yes, but still only tools. Without a will to use them, to develop a thorough understanding of the enterprise and objectively look at every process to understand how it relates to the other parts of the enterprise, these tools will not be useful. The fundamental recommendation of this thesis is:

Develop a thorough understanding of all processes being managed, codify this knowledge so that it is easily accessible, and use this understanding strategically as a competitive weapon in the marketplace.

There are methods available to develop this understanding with the system dynamics approach presented being one of them. In combination with the balanced scorecard it becomes a unique strategic tool able to provide managers with a method to express the corporate goals to the organization through the balanced scorecard and providing a means to test strategy and better guide the organization into the future through the system dynamics modeling. What follows are specific recommendations related to the work in this thesis.

6.1 Causal Hypotheses

In the present model we have developed the basic framework for material flow, material control, and labor control in the AMRAAM program. However, there are other dimensions of the balanced scorecard that were not specifically addressed that should be developed in a model of the entire program. For example, cash flow in the present model is a function primarily of the material and labor flowing through the system. There are a series of parameters that control this flow, such as the rework fractions, labor productivity, and others, but these are entered into the model as data, and are not expressed as functions of other variables. For example, labor productivity is probably a function of the employee morale, which is partly related to the wages paid, which in turn affects the cash flow of the enterprise. To explain how labor productivity varies according to pay, employee satisfaction, overtime use, amount of rework, and other parameters we can build a set of loops for these causal hypothesis and incorporate them in the model. These hypotheses must be tested however, and this is the crucial point: As managers test these hypotheses they will gain a much deeper understanding for the enterprise and that understanding will be captured in the model for others to use. By doing this, we are in effect building the linkages between metric dimensions called for in the balanced scorecard, but we are doing so in an analytical way with the scientific method to guide us. The following are a set of suggested causal hypotheses that should be investigated as next steps in developing a robust model for missile manufacturing at Raytheon Missile Systems.

<u>Linkage Between Employee Satisfaction and Financial Measures:</u> The satisfaction of employees with their jobs has been shown to correlate with increased productivity in other organizations. Is this really true at Raytheon? What are the key measures of employee satisfaction? For example, is overtime correlated directly with improved throughput, or does it fall off after continued use? In essence we should develop causal loop diagrams for all variables in the employee satisfaction dimension of the balanced scorecard and financial measures. One example is the causal loop diagram shown in Figure 6-1, which is a causal loop hypothesis that greater cash flow can be achieved by raising overtime and therefore raising throughput, but this effect is short-lived since as we raise overtime we also increase fatigue and productivity drops, eventually lowering cash flow. The loop in Figure 6-1 should be read as follows: the greater the production schedule pressure, the greater the overtime use authorized, the

greater the production rate, the greater the cash flow, and the lower the production schedule pressure. But, the greater the overtime use authorized, the greater the fatigue, the lower the productivity, and the lower the production rate. The causal relationship between variables is indicated by the loop polarity (i.e. a + means the greater the input variable, the greater the output variable will be).

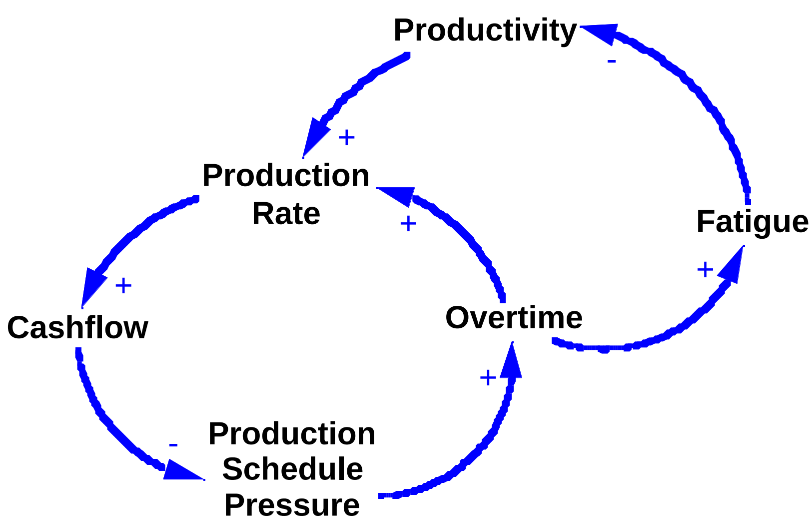

Figure 6-1 Causal Loop Hypothesis for Overtime and Cash flow

Other such loops are possible such as the linkage between employee development programs and productivity increases, etc. The point is that these relationships between employee related metrics and other dimensions in the balanced scorecard should be analytically investigated and similar causal loop hypotheses developed to gain a better understanding of the system.

<u>Linkage Between Customer Satisfaction and Financial Measures:</u> In the same manner, the linkages between customer satisfaction and financial performance should be explored to yield causal loop relationships. For example, does improved schedule delivery performance correlate with reduced schedule pressure, which means less out of sequence work and less rush orders, and

therefore higher cash flow? This is but one example of linkages between the customer satisfaction and financial dimensions and is shown in Figure 6-2.

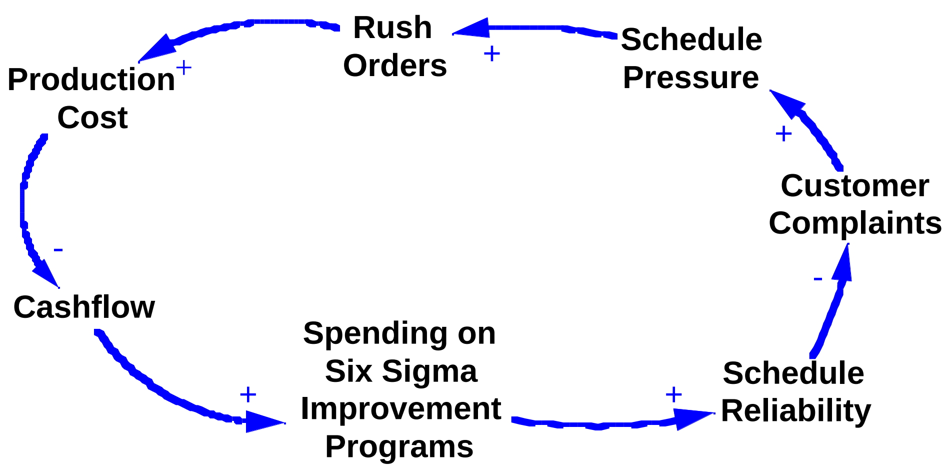

Figure 6-2 Causal Loop Hypothesis for Customer Satisfaction and Cash flow

Again, many other causal loop hypotheses are possible, and it is up to each organization to investigate the ones that make the most sense, but all of these can be "piggybacked" onto the basic material flow framework developed in this thesis.

<u>Linkage Between Innovation and Financial Measures:</u> The linkages between innovation and operational metrics can also be explored and there are many possible hypotheses. Again, it is up to the organization to explore these linkages and develop robust models to understand them and take advantage of this knowledge. These linkages more than any other provide Raytheon with competitive advantage in the market place, and a thorough understanding of the key drivers would be invaluable.

6.2 Additional Control Points

One of the key insights to Raytheon from the work in this thesis, is that many more procedures should be put into place to proactively measure processes rather than rely on "outcome" measures to monitor performance after the fact, and after management is able to make any significant impact. Table 6-1 shows the dimensions currently being measured, examples of current metrics, and the suggested additional control points.

Current Metrics Set	Suggested Additional Metrics
Cash	Cash on hand is an outcome measure. It drives discretionary spending on the part of managers in reaction to cash levels, so if cash is low, spending on improvements or other non-essential items will be curtailed. However, the long-term impact of these decisions can be very detrimental since no significant improvement gets funded. Use of the model suggests that in addition to measuring cash, measuring the key factors that generate cash for the enterprise should be monitored. For example, variability in rework levels was shown to have a significant negative effect on cash flow, so monitoring this and the other metrics suggested below would allow for better pro-active measurement of cash. · **Rework Rates** (Rework Fraction, Rework Cycle Time) · **Critical Path Material Flow** (Establish a true critical path and monitor material flow rates through this path, related to explicit buffers) · **Explicitly State Variability** (Do not hoard safety stocks but explicitly associate them with variability in the process)
Customer Satisfaction	Customer satisfaction is not presently a significant factor in the operations metrics set, with the exception of schedule performance. It is understood that the product delivered will be of high quality and will perform its intended mission, but beyond that other measures important to the customer are not uniquely identified. Other measures are needed to better align the enterprise performance with customer needs. The following pro-active measures are suggested based on the model: · **Supply Chain Flow Milestones** (monitor delivery dates along the supply chain as a predictor of delivery performance) · **Measure Buffers Explicitly** (Instead of hiding buffers in longer than necessary MRP lead times, explicitly measure and mange buffers to meet schedule targets)

Current Metrics Set	Suggested Additional Metrics
Employee Satisfaction	This dimension is the most neglected of the current metrics. There is an annual survey, and a strong emphasis on lost time incidents, but few other metrics. The importance of pro-actively managing this dimension should become apparent, however, once the causal loops linking financial and employee dimensions are completed. Improving baseline productivity, understanding the proper use of overtime, and generating process improvements from employee involvement are crucial to improved financial performance. Some of the suggested metrics are given below: · **Employee Productivity** (not standard values but others such as Overtime vs. Throughput) · **Employee Time on Current Task** (constant rotation of employees can reduce the effective productivity since they must be trained) · **Performance vs. Process Incentives** (Aligning employee rewards with performance metrics, such as units completed is better than rewarding hours spent on the job such as overtime or hours expended) · **Proactive Safety Measures** (Measuring near-misses and correcting those is much better than only measuring lost time accidents)

Table 6-1 Current and Proposed Metrics

Some of the suggested metrics are already being measured, but they are not necessarily being used as a tool to manage the enterprise. First and foremost, the economic incentives of all players (employees, management, suppliers, and customers) need to be reviewed to ensure they are aligned with the enterprise objectives. Once that is accomplished, measuring areas suggested by the model as being critical to achieving the enterprise goals is the next step. Some of the metrics suggested above come from a review of the current model, but as the model is enriched by adding other loops, the metrics should also evolve into a more robust set that truly measures the key performance drivers of the enterprise.

7 Summary and Conclusions

Developing a better understanding of the business by building a model and using the model to determine which areas should be measured to reach enterprise goals is the long-range process suggested in this thesis. Using system dynamics is the suggested tool to build the model, because of the complexity of the value chain in the production of missile products at Raytheon. Combining the system dynamics tools with balanced scorecard methods provides a way to communicate both the strategic goals and the insight generated in the model to the organization as a whole. It is also suggested that one of the key flaws in MRP systems, the explosion of float times due to “hidden” buffers, can also be addressed by developing a model of the enterprise since it is possible to simulate the consequences of variability and therefore better manage the safety buffers or float.

7.1 Methodology

The AMRAAM missile production model developed as a prototype in this thesis can serve as the basis to build similar models for other missile production programs at Raytheon Missile Systems. Using the basic building block presented in Figure 4-11, it is possible to link several blocks together to represent the work breakdown structure for a given program. Once this material flow, material control, and labor control framework is built, it is possible to add further detail to explain the other behavior in the system by adding loops such as the ones shown in Figure 6-1 and Figure 6-2. These models can then serve as “laboratories” to test various management approaches, perform scenario analysis, and more importantly gain a better understanding of the business. The goal would be to create models of each program and link them together into an overall Raytheon Missile Systems model that could predict important performance criteria such as overall cash flow and delivery times. This would allow operations managers to better allocate resources across the programs and prioritize areas to be improved through six sigma programs. The methodology can be summarized by Figure 1-1, but repeated here for clarity as Figure 7-1.

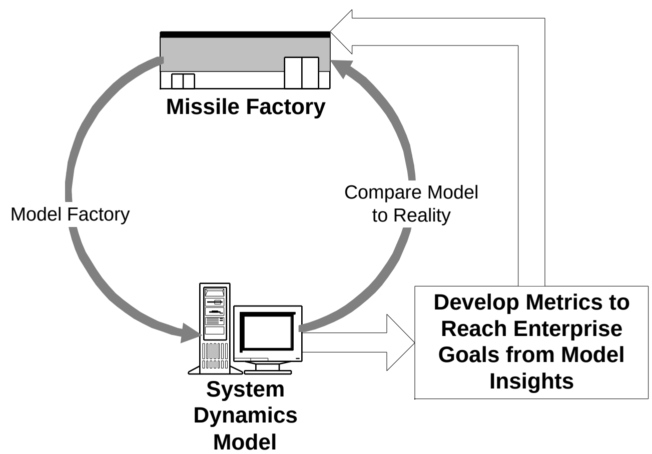

Figure 7-1 Metrics System and System Dynamics Model

7.2 Further Work

The work remaining to produce a robust model of the enterprise is to go through a few iterations of the loop shown in Figure 7-1. The present model is a start, but further comparison to the behavior of the enterprise is required. Also, further model richness must be added to provide dynamic explanations for the behavior of labor productivity, customer satisfaction, rework, and other observations. As the model becomes more robust and is able to better predict reality, managers will start to use it as a strategic planning tool to analytically justify capital expenditures, staffing decisions, and other operations issues. A robust model would also provide much deeper insight to required metrics of key performance drivers. As the enterprise changes, the model will change, but the process should become institutionalized such that the model is used to document management's understanding of the behavior of the organization. New policies and strategies are then much more easily and cheaply tested on the model before trying them on the real organization. Development of a system dynamics capability is therefore crucial to the use of this approach. This does not necessarily mean everyone should be able to develop complex models, but it does require commitment from the top levels in the organization to document their understanding of the dynamics in basic causal loop diagrams. This understanding can then be translated into detailed models.

The individual understanding and models from each program could then be tied to together to form an aggregate enterprise model that would allow Raytheon Missile Systems to maintain tight process control on their financial performance, as well as enabling the success of other dimensions of the enterprise. The vision of the future would be to have new managers enter the company and be trained on a very realistic set of management flight simulators that modeled the parts of the enterprise they would be responsible for. This would significantly improve the performance of the enterprise simply by virtue of having better trained and more proactive personnel, but also from having a deep understanding of the complex dynamics of the enterprise. Raytheon would have a huge market advantage over other companies, and probably also a much better client relationship by pursuing this approach, since a process that is not well understood cannot possibly be well managed.

Bibliography

[1] Kanigel, Robert **The One Best Way: Frederick Winslow Taylor and the Enigma of Efficiency,** Penguin, New York, NY, 1999

[2] Sterman, John D. **Business Dynamics: Systems Thinking and Modeling for a Complex World**, McGraw-Hill, Boston, MA, 2000

[3] Kaplan, Robert S. And Norton, David P. **The Balanced Scorecard**, Harvard Business School Press, Boston, MA, 1996

[4] "Raytheon Missile Systems Vision, Values, and Goals", Raytheon Missile Systems, Raytheon Corporation presentation to outside investors, October 1999

[5] Goldratt, Eliyahu M. **Critical Chain**, North River Press, Great Barrington, MA, 1997

[6] Forrester, J. W. **Industrial Dynamics**, MIT Press, Cambridge, MA, 1961

[7] "STOP for Supervision Supervisor Guide", E.I. du Pont de Nemours and Company, 2000

[8] "Metrics: A Management Guide for the Development and Deployment of Strategic Metrics", Raytheon Company, 1998

[9] R. L. Lynch and K. F. Cross, **Measure Up! Yardsticks for Continuous Improvement**, Blackwell Publishers, Cambridge, MA, 1994

[10] Brown, Graham B. **Keeping Score: Using the Right Metrics to Drive World Class Performance**, Quality Resources, New York, NY, 1996

[11] Vensim DSS, Ventana Systems, Inc., Cambridge, MA, www.vensim.com