Using System Dynamics to Understand Barriers to Cost Reduction

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ABSTRACT

This thesis has two goals:

- To explore how systems thinking and system dynamics can be used to minimize costs throughout the aerospace supply chain, and
- To make the system dynamics process more transparent and useable for newcomers to the field of system dynamics.

To meet both of these goals, a system dynamics model of an aerospace engine manufacturer is created as a part of this thesis. System dynamics simulations are used to gain insight to the first research goal of reducing costs in the aerospace supply chain. However, to make system dynamics more transparent, a description of the entire model evolution process is also included.

This thesis draws upon a case study of an unnamed aerospace engine manufacturer (AEM). Competitive pressures have forced AEM's management to change its product focus from performance to acquisition cost. However, AEM has had difficulty implementing this goal in its product design and development process.

In an effort to translate this goal into a reality, AEM has made a strategic decision to focus on its core competency, engine design. Functions that are not directly related to a core competency or competitive advantage are outsourced. As a result, AEM has been able to eliminate many overhead activities. However, AEM has not been able to make substantial gains in reducing total engine costs. In particular, AEM has had difficulty consistently creating designs that consider the impact of design on manufacturability. Manufacturability problems typically translate into cost increases. Focusing on core competencies has made this problem more difficult, because now 80% of the engine
content is outsourced. As the result, the impact of design on manufacturability is obscured by functional and organizational boundaries. In addition, each of these functional and organizational groups has a different set of goals that are imposed on the designer. In many cases these goals conflict and the designer is forced to make tradeoffs between goals. Designing an engine typically involves tradeoffs between performance, risk, schedule, and cost. Even though the product goals set by management are geared toward costs, performance and schedule still dominate the product design and development process.

Based on system dynamics modeling, this thesis demonstrates that rational but localized decision making causes the designer to create designs that deviate from product goals. The decision making process is a natural response to barriers imposed by the underlying architecture of the product design and development process. Furthermore, due to the priorities inherent to the product design and development process, designers often choose to circumvent processes designed to align goals and reduce costs, such as IPT meetings or design for cost tasks. Moreover, this thesis indicates that time constraints imposed upon the design process force the designer to skip these tasks.

Using simulation as a guide, this thesis identifies characteristics a policy must have to be successfully implemented. The author suggests a number of techniques designed to stimulate cost reduction efforts despite system priorities. In addition, the author suggests a number of techniques to achieve a paradigm shift from product performance to product cost. Furthermore, this thesis recommends a number of process architectural changes that facilitate cost reductions by aligning process and product goals.

The author also makes suggestions to improve the system dynamics process. In particular, the author suggests ways to reduce model complexity through the use of abstraction. Moreover, the author describes steps that can be used to estimate model complexity so that the modeler knows when additional abstraction is necessary. Furthermore, the author describes how the incremental approach to model development can be structured to minimize complexity.
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Jim Hines stimulated my interest in system dynamics. Jim gave me a framework to conduct my research and taught me that I have a lot more to learn about system dynamics.

Finally, my parents provided me with many of the opportunities in my life that led me to MIT.
EXECUTIVE SUMMARY

This thesis has two very different goals:

- To explore how systems thinking and system dynamics can be used to minimize costs throughout the aerospace supply chain, and
- To make the system dynamics process more transparent and useable for newcomers to the field of system dynamics.

Case Study Description

To achieve these goals, a system dynamics model was developed as part of this thesis. Consistent with system dynamics standard practice, the model was developed using a consulting process. The client for this process was chosen based upon two criteria:

- A willingness to devote one hour a week to the project, and
- A strong interest in cost reduction.

The client chosen for the consulting process was Keppel Bharath, Manager of Procurement Engineering and Quality Assurance at an aerospace engine manufacturer, referred to as AEM to protect confidentiality. AEM has over 8,500 employees and
manufactures turboshaft and turboprop engines from 500-5,000 shp and turbofan engines from 2,200-8,000 pounds thrust (AEM Website).

Mr. Bharath agreed to participate in the project because he had recently been assigned the role of supplier development and was actively pursuing cost reduction methods. Mr. Bharath had initiated a number of changes to the procurement process and had plans to make other changes. However, he was not sure about which changes would have the greatest impact on engine cost. Mr. Bharath hoped that the modeling effort would provide a new perspective and help him identify the policies likely to have the greatest impact on reducing costs.

As the project unfolded, information for the modeling process came from three different types of interviews as follows:

**Kickoff Meeting** - A four hour session designed to initiate the project and to outline project goals. After presenting a brief overview of system dynamics, the meeting was conducted similar to a brainstorming session in which participants identified key variables involved in the cost reduction process. Meeting
participants included Mr. Bharath, the Senior Coordinator for Continuous Improvement and Supplier Development, and the author.

**Periodic Meetings** - These meetings were largely phone conversations between Mr. Bharath and the author held on an as needed basis to discuss issues related to modeling such as hypotheses, data collection, and examples. Overall, there were between ten and twenty meetings each lasting an average of two hours.

**Block Interviews** - These interviews were conducted over a one week period. Each interview lasted 1 to 4 hours. These were largely one-on-one interviews with the author. However two design engineers were interviewed simultaneously. The following types of people were interviewed in this process:

- 1 Manager of Procurement Engineering and Quality Assurance
- 3 Design Engineers,
- 1 Project Engineer,
- 1 Experimental/Substantiation Engineering,
- 1 Cost Estimator,
- 1 Configuration Management Engineer,
- 1 Manufacturing Operations Engineer,
- 1 Drafter, and
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- 1 Technical Supervisor Manufacturing.

However, this list of interviewees is not all-inclusive. During the interview process, the interviewee would often ask his coworkers who were within "shouting distance" to provide input. Even though their input was included, no effort was made to capture the titles and positions of these coworkers. In many cases, the coworkers' input just served as a reminder to the interviewee. The interviewee then elaborated upon these outside comments.

These interviews were free form in nature. While the author tried to keep discussions focused on cost related issues, he would let the interviewees discuss issues most relevant to them. In many cases this open approach led to insights not apparent otherwise. For example, the drafters complained that the designers were often behind schedule and the drafters had to compress the drafting process to make up for delays in the design process. At first this does not appear to be a cost related issue; however, further examination indicated that compressing the drafting schedule prevented drafters from fully error checking their drawings. As a result, errors in drafting led to manufacturability problems and increased unit cost.
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Although no rigid set of questions were prepared, the author asked the following questions in one form or another:

- What drives engine costs?
- What are the incentives to reduce engine costs?
- What are the failings of the integrated product development team (IPT) process? and
- What can be done to improve manufacturability?

Thesis Organization

System dynamics model simulations are used to gain insight into the first research goal of reducing costs in the aerospace supply chain. However, to make the system dynamic process more transparent, a description of the entire model evolution process is necessary. Therefore, to meet both research goals, this thesis is arranged chronologically. Consequently, both the successes and failures encountered during the model development process are described in detail. By organizing the thesis in this way the reader can learn by example - what to do and what not to do when performing system dynamics modeling. In fact, knowing what not to do is often more instructive than knowing what to do. While the failures provide insights about system dynamics process, the successes provide insights into the problem of reducing costs throughout the aerospace supply chain.
Following the executive summary, this thesis is divided into nine sections as follows:

- Introduction,
- Literature Review,
- Research Design,
- Problem Definition,
- Dynamic Hypotheses,
- Evolving the Problem Statement and Dynamic Hypotheses,
- Model Development,
- Sensitivity Analysis, and
- Conclusions.

The first two sections provide problem context. The Introduction describes the nature of the research problem, discusses why the problem is important, and provides background information important to understanding the context of the problem. Additional context is provided in the Literature Review by examining other research that is related to this thesis. In particular, the Literature Review describes how past research is applied to this thesis and how this thesis expands upon past research.
Next, the Research Design section describes the system dynamics methodology used as part of this thesis. The methodology used contains the following steps:

1. Define the problem
   - List variables
   - Provide examples
   - Describe reference modes
   - Outline problem statement

2. Describe existing policies

3. Develop dynamic hypotheses
   - Identify dynamic hypotheses
   - Simplify/abstract loops
   - Create hybrid causal model

4. Model single loop

5. Analyze single loop

6. Repeat steps 4 and 5.

(Hines, Class Notes)

This methodology varies from system dynamics standard practice by adding three steps:

- Provide examples,
- Simplify/abstract loops, and
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- Create hybrid causal model.

These steps are an inherent part of system dynamics; however, they are not made explicit in standard practice. The author included these steps after reflecting upon mistakes he made in the model development process. These mistakes are described in Section 5 and 6. By making these steps explicit, the author believes that newcomers to system dynamics can avoid common pitfalls: poor problem definition, and choosing the wrong level of abstraction.

By actively seeking examples, the problem becomes more tangible. Furthermore, the modeler can use these examples as a way of asking questions. By using examples to ask questions, the modeler will elicit better responses because the question involves a real situation rather than a hypothetical one. Overall, examples improve the modeler's understanding of the problem, which usually results in a more focused problem definition.

The simplify/abstract step was added to force the modeler to periodically reflect upon the modeling framework. By including this step, the newcomer to system dynamics will realize that it is common to revise modeling frameworks after starting the modeling process. In addition, this step reinforces the idea that modeling is supposed to be a
simplification of the real world and that a model can become too complex to yield insight. If the modeler actively searches for ways to simplify the model, the modeler can avoid falling into the trap of including too much complexity.

Finally, the hybrid causal model step is included to force the modeler to think about complexity of the chosen modeling framework. In this step, the modeler outlines symbolically a basic architecture for the model. While this architecture should by no means be complete, it should include the major components. If the hybrid causal model is too complex to complete in the time available, then the modeler should reassess the modeling framework. Therefore, the modeler can use this hybrid causal model as an indicator of when to simplify the modeling framework without investing much time.

The Problem Definition section defines the scope of the research problem addressed in this thesis using the system dynamics methodology. In this section it becomes apparent that supply chain costs are largely a function of manufacturability. Table 4-1 provides a list of all the cost drivers, Table 4-2 provides a list of the primary cost drivers, and Table 4-3 provides detailed examples of how these variables drive costs. In addition, a description of AEM's hopes and fears related to these drivers are mapped over time in Figure 4-1 through Figure 4-11. From these tables and figures, the author develops an
initial problem scope that serves as a framework for all the sections that follow. Problem scope is defined in this section by two questions:

- What can AEM do to ensure that manufacturability is considered in the design process? and
- How can AEM reduce the costs associated with outsourcing?

The Dynamic Hypotheses section elaborates upon the framework described in Section 4 by describing how each of the variables interrelates. These interconnections are organized to provide a mental model of the process. Although this section provides a detailed mental model of the design and acquisition process, it is too detailed. This section describes the author's initial attempts to simplify the causal loops and to model these loops. Initially, the author attempted to simplify the causal loops by compressing causal connections and by focusing on a subset of the causal loops. Since many of the loops describe the impact of CAD on manufacturability, the author decided just to focus on these loops. His initial hypothesis was that lack of feedback about CAD errors leads to manufacturability problems and increasing costs.

After translating this initial set of causal loops into a mathematical model, the author realized that the modeling effort was futile because the causal loops were still too detailed. In addition, he learns that his effort to simplify by focusing on a subset of causal
loops led to the development of a model that was trivial and unimportant. While the use of CAD does have an impact on manufacturability, it does not explain AEM's widespread difficulty in implementing design for manufacturability (DFM). Instead, the lack of feedback about CAD errors is an example of AEM's inability to implement DFM. In this section it becomes apparent that the modeling framework needs to be more abstract to yield insight. Even though the model discussed in this section does not effectively characterize the problem of reducing costs in the aerospace supply chain, it yields one major insight that set the tone for the remainder of the thesis: the design process is time constrained. Moreover, this time constraint precludes designers from pursuing cost reductions.

In the section entitled Evolving the Problem Statement and Dynamic Hypotheses, the author describes how the causal loops developed in Section 5 were simplified/abstracted to a useful mental model. Rather than focusing on a subset of the causal loops described in Section 5, the author searched for an underlying theme. This search led to revised framework that enabled insights and captured earlier insights about the time constraints of designers. As part of this simplification process the problem scope was revised to the following questions:

- What skews the product design and development process toward performance?

and
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- How can the product design and development process be changed to focus on costs?

By creating this new problem scope, the author is able to abstract the causal loops into a framework that is more generalizable and useful. Three causal loops are identified and shown in Figure 6-1 through Figure 6-3. These causal loops describe the following hypotheses about why AEM cannot implement cost reductions:

- **Priority Loop** - Designers' priorities are skewed away from cost reduction because they do not receive real-time feedback about costs,
- **Rework Loop** - Designers are so time constrained that they do not perform optional tasks, such as DFM or IPT meetings. As a result, design goals are not met causing rework leading to further time constraints, and
- **Productivity Loop** - Designers are unable to reduce manufacturing costs because they are not knowledgeable about manufacturing costs. As knowledge decreases designers become less productive and are less able to achieve significant cost reductions in the time available.

Although, not explicitly mentioned as a hypothesis, the limited resources of designers is inherent to each of these causal loops.
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The Model Development section describes how the model architecture discussed in Section 6 is translated into a system dynamics model. In addition to describing the model formulation, this section describes how the model development process was ordered to minimize complexity. The model was developed in an incremental fashion such that the feedback of each increment was minimized. Therefore, model complexity increased incrementally rather than exponentially.

In addition, Section 7 includes a detailed description of a new model formulation, referred to as a "dual smooth." This new formulation was used in the model to take account of optimistic behavior observed at AEM. At the beginning of each new design project, project completion estimates are optimistic and this optimism only wanes after project status reports indicate that progress is behind schedule.

In the Sensitivity Analysis section, simulation results are analyzed to test the validity of the hypotheses described in Section 6 as well as test a number of policies. The simulation results show that as designers become time constrained cost reduction tasks are skipped because they have a low priority relative to other design tasks. Next, the sensitivity analysis is used to determine which of the dynamic hypotheses are most plausible. When examining each hypothesis, the productivity loop stands out as the most likely cause of the inability to implement DFM followed by the rework loop. Furthermore, simulation
indicates that priority hypothesis has a negligible impact on the use of DFM. In particular, simulation shows that three factors have the largest impact on implementation of DFM:

- Alleviating Time Pressures,
- Building Knowledge, and
- Communicating Knowledge.

It is not surprising that by alleviating the time constraint on designers, designers will perform more of these cost reduction tasks leading to lower engine costs. However, simulation did indicate something surprising about this constraint. Simulation indicates that even though increasing resources increases labor costs, these increases may be counterbalanced by reduced production costs. In other words, a slight increase in the number of full time equivalent design staff may increase profitability. Furthermore, if the simulation results are considered on a more abstract basis, the simulation suggests that additional effort spent in the early design phase leads to system wide cost reductions.

While this result provides insight, increasing investment in the design process may be off limits in the current corporate environment of cost control. Therefore, a more endogenous approach needs to be applied to the problem of cost reduction. Simulation indicates that practices that improve knowledge are also extremely effective at
encouraging the use of design for manufacturability due to the productivity loop. Increasing knowledge improves productivity, allowing more tasks to be performed in the same amount of time. While reducing rework has a very similar effect, its impact was not as large as increasing knowledge.

Simulation showed that two proposals within AEM had very little effect on implementation of DFM: implementing real-time feedback as discussed in the priority loop and changing designer incentives. The need for real time feedback is the basis for the priority hypothesis. In this hypothesis, designers do not receive feedback about cost. Therefore, the designer assumes that the design is on budget. When the designer finally receives a cost estimate, the design is too far along to be changed. From the simulation process, the author learned that knowledge about cost was important, but that this feedback did not have to occur on a real-time basis to be effective. As long as designers received feedback about cost, they would learn and improve their designs. Real time feedback just started the learning process sooner.

In addition, the modeling process indicated that incentives in the design process are skewed so far away from cost that changing incentives had very little impact on cost. In order for changing incentives to be effective, the entire incentive structure of the design and development process needed to be overhauled.
In the Conclusions section, the author reflects upon the model development process and the model simulations. From this reflection process, the author makes a number of recommendations regarding the system dynamics process and the aerospace supply chain. In terms of system dynamics, the author recommends modifying the standard method to include three steps: provide examples, simplify/abstract loops, and create hybrid causal model. In addition, the author believes that additional time should be spent defining the problem scope, the dynamic characteristics of the model should be chosen up-front, and the model should be developed incrementally in a fashion that minimizes feedback. To aid in the problem definition stage, the author describes the abstraction process and provides a heuristic about the complexity of a causal loop. As a heuristic, causal loops should be simplified/abstracted until there are no more than six variables in each loop and no more than six loops. To eliminate loops and variables, the modeler should search for overarching themes of each of the loops.

The author also makes a number of recommendations aimed at reducing costs in the aerospace supply chain. Many of the recommendations included in this section are pre-existing proposals at AEM. However, companies such as AEM have numerous policies being considered at any given time. Moreover, not all of these policies can be implemented with available time and staff. As a result, the benefit of system dynamics
Using System Dynamics to Understand Barriers to Cost Reduction

simulation is often to identify which policy is most likely to succeed rather than identifying new policies. Therefore, the recommendations are included to provide focus at AEM as well as suggest new policies.

Modeling suggests that time pressures on design resources, knowledge, and communication have the greatest impact on implementing DFM. Furthermore, modeling suggest that in an environment of time constraint, a policy must have the following characteristics to be successfully implemented:

- Product and process goals must be aligned;
- Simplicity relative to the existing process; and
- Easy to learn.

Without these three features, significant management intervention will be required to implement the new policy. Therefore, policies have been chosen to meet these criteria and focus on the factors that have the greatest impact on implementation of DFM. In addition, one recommendation is made to assist in realigning priorities in the design process.

To enhance knowledge, the author recommends expanding benchmarking efforts. These efforts should include benchmarking related industries as well as unrelated industries.
Using System Dynamics to Understand Barriers to Cost Reduction

The author also recommends policies such as rule-based design and creating standard parts lists.

To stimulate communication, the IPT process should become a required step of the design process by implementing a phase gate system. As part of this phase gate system, IPT team members including suppliers should conduct performance evaluations of the design engineers. In addition, the author suggests that communication techniques should take advantage of new technology such as video teleconferencing and conferences rooms equipped with three-dimensional CAD capability.

However, virtual communication and IPTs cannot reach their full potential without supplier involvement. To increase supplier communication, AEM should reduce the time it takes to involve suppliers in the design process. The author suggests that applying lean practices, such as single piece flow, to legal department may speed supplier involvement. In addition, the author recommends empowering designers to talk directly to suppliers and offering supplier collocation incentives.

To alleviate time pressures the author recommends expanding investment in the design phase of the product development life cycle. The goal of this investment is to reduce time
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constraints on designers. The most obvious way to reduce time constraint is through additional design staff, or administrative staff. However, adding staff may not be a possibility due to corporate climate. Therefore, policies more acceptable in the corporate culture such as outsourcing to meet staffing needs or offering incentives for suppliers to work with designers to reduce costs, may achieve the same results because they free designers to perform cost reduction tasks resulting in a system wide cost reductions.

The final recommendation is aimed at changing the underlying priorities in the design process so that they are aligned, even though simulation and experience at AEM indicate that aligning priorities can be extremely difficult because so many different factors influence priorities in the design process. This recommendation was included despite the difficulty associated with aligning goals because it is also designed to increase knowledge and simplify the design process.

The author recommends initiating a limited number of engine design projects, or "pilot projects," without an OEM contract. In addition, the metric used to assess these pilot projects should be knowledge gained. This is a somewhat radical departure from the existing design process. In the current system, engines are designed to meet a contract specification set by the OEM. The OEM contract dictates cost, schedule, weight, and performance. If performance, weight, and schedule goals are not met, harsh penalties are
imposed. In addition, project managers are evaluated based upon meeting schedule, budget, and performance specifications. If schedule and performance goals are not met the project manager is held accountable. However, if AEM assumes the project risk, it is no longer tied to contract terms or process goals. Rather than creating a design to specification, the designer could create a design that served a particular market and could make the optimal tradeoffs rather than those imposed by schedules or contract terms.

Since the projects are pilot projects, schedule is not as rigid and more investment can be made in the design phase. Modeling indicated that without the time constraints imposed by tight schedules, designers could pursue more innovative designs that focus on reducing costs. Success should be based upon knowledge gained rather than profitability of the given engine design project because innovation developed as a result of this process can then be transferred to subsequent engine designs to yield cost reductions across all engine lines. Furthermore, by demonstrating the benefit of additional investment in the design phase, designers and program managers will begin to change their mindset associated with the design process.
SECTION 1 INTRODUCTION

This section describes the nature of the research problem, discusses why the problem is important, and provides background information important to understanding the context of the problem.

Research Goal

This thesis has two very different goals:

- To explore how systems thinking and system dynamics can be used to minimize costs throughout the aerospace supply chain, and
- To make the system dynamics process more transparent and useable for newcomers to the field of system dynamics.

Case Study Description

To achieve these goals, a system dynamics model was developed as part of this thesis. Consistent with system dynamics standard practice, the model was developed using a consulting process. The client for this process was chosen based upon two criteria:

- A willingness to devote one hour a week to the project, and
A strong interest in cost reduction.

The client chosen for the consulting process was Keppel Bharath, Manager of Procurement Engineering and Quality Assurance at an aerospace engine manufacturer, referred to as AEM to protect confidentiality. AEM has over 8,500 employees and manufactures turboshaft and turprop engines from 500-5,000 shp and turbofan engines from 2,200-8,000 pounds thrust (AEM Website).

Mr. Bharath agreed to participate in the project because he had recently been assigned the role of supplier development and was actively pursuing cost reduction methods. Mr. Bharath had initiated a number of changes to the procurement process and had plans to make other changes. However, he was not sure about which changes would have the greatest impact on engine cost. Mr. Bharath hoped that the modeling effort would provide a new perspective and help him identify the policies likely to have the greatest impact on reducing costs.

As the project unfolded, information for the modeling process came from three different types of interviews as follows:
Kickoff Meeting - A four hour session designed to initiate the project and to outline project goals. After presenting a brief overview of system dynamics, the meeting was conducted similar to a brainstorming session in which participants identified key variables involved in the cost reduction process. Meeting participants included Mr. Bharath, the Senior Coordinator for Continuous Improvement and Supplier Development, and the author.

Periodic Meetings - These meetings were largely phone conversations between Mr. Bharath and the author held on an as needed basis to discuss issues related to modeling such as hypotheses, data collection, and examples. Overall, there were between ten and twenty meetings each lasting an average of two hours.

Block Interviews - These interviews were conducted over a one week period. Each interview lasted 1 to 4 hours. These were largely one-on-one interviews with the author. However two design engineers were interviewed simultaneously.

The following types of people were interviewed in this process:

- 1 Manager of Procurement Engineering and Quality Assurance
- 3 Design Engineers,
- 1 Project Engineer,
- 1 Experimental/Substantiation Engineering,
- 1 Cost Estimator,
Using System Dynamics to Understand Barriers to Cost Reduction

- 1 Configuration Management Engineer,
- 1 Manufacturing Operations Engineer,
- 1 Drafter, and
- 1 Technical Supervisor Manufacturing.

However, this list of interviewees is not all-inclusive. During the interview process, the interviewee would often ask his coworkers who were within "shouting distance" to provide input. Even though their input was included, no effort was made to capture the titles and positions of these coworkers. In many cases, the coworkers' input just served as a reminder to the interviewee. The interviewee then elaborated upon these outside comments.

These interviews were free form in nature. While the author tried to keep discussions focused on cost related issues, he would let the interviewees discuss issues most relevant to them. In many cases this open approach led to insights not apparent otherwise. For example, the drafters complained that the designers were often behind schedule and the drafters had to compress the drafting process to make up for delays in the design process. At first this does not appear to be a cost related issue; however, further examination indicated that compressing the drafting schedule prevented drafters from fully error checking their drawings. As
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...result, errors in drafting led to manufacturability problems and increased unit cost.

Although no rigid set of questions were prepared, the author asked the following questions in one form or another:

- What drives engine costs?
- What are the incentives to reduce engine costs?
- What are the failings of the integrated product development team (IPT) process? and
- What can be done to improve manufacturability?

Emphasis on Cost Reductions

The focus on cost reduction in this thesis is due, in large part, to its growing importance in increasing corporate profitability. In the last decade, cost reductions have taken on a negative connotation and become synonymous with layoffs, plant closings, and unemployment. In the late 1980s and early 1990s, newspapers were full of headlines about cost cutting efforts euphemistically referred to as downsizing or right sizing. Despite being vilified in the popular press, cost cutting entails more than reducing staff and is not necessarily negative. Furthermore, cost reduction is one of the main tools available to improve corporate profitability. At a managerial level cost reduction is an
Managers really only have two ways to improve profitability: increasing revenue or decreasing costs. The methods that a manager uses depend in large part on market trends. Prior to the 1980s, most industrial markets were growing and had relatively few new market entrants. Thus, a large component of increasing profitability was through attracting new customers to increase revenue. However, in the 1980s competition became more global. As a result, managers had to take much more aggressive measures to maintain profitability such as cost cutting. Many industries that had not faced much competitive pressure were forced to make rather dramatic cost cuts as evidenced by the large number of downsizing efforts in the 1980s. When confronted with this competition, management was forced to use all tools at its disposal. Cost reduction and revenue generation techniques were used in conjunction no matter how marginal the gain.

In a competitive environment such as in the 1980s, efforts to increase revenue become strongly correlated with cost reduction efforts. To retain existing customers and revenue base in a competitive environment, companies are forced to enhance product value such as reducing delivery delays, increasing quality, and increasing product functionality. In essence, the company is forced to offer more for less. Unless the company is willing to
lower its margins and profitability to offer these value enhancements, efficiency gains or cost reductions need to be made.

**Aerospace Market Trends**

Competitive pressures in the aerospace industry were spurred on by decreases in demand and new market entrants. The defense industry, once considered the "bread-and-butter" of the aerospace industry, suffered large budget cuts due to the end of cold war. Table 1-1 and Figure 1-1 illustrate that the military budget has decreased from a high of $303 billion in 1989 to $270 billion in 1997. As a result, during the same time period, military spending in the aircraft industry remained unchanged. This translates in economic terms to a real decrease in military spending in the aircraft industry from $23 billion to $18 billion using 1987 dollars as a base year. These values are depicted in Table 1-2 and Figure 1-2. To combat these budgetary cuts, the military is exerting tremendous pressure on the aircraft industry to cut costs so that it can maintain its fleet size.
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<th>Fiscal Year</th>
<th>GDP (in Billions)</th>
<th>Net Total Outlay ( ^a )</th>
<th>National Defense Outlay ( ^b )</th>
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\( ^a \) "Net Total" is government-wide total less intragovernmental transactions.

\( ^b \) "National Defense" includes the military budget of DoD and other defense-related activities. Beginning in 1985, the Federal Budget reflects establishment of a military retirement trust fund. Data for prior years adjusted for comparable treatment of military retired pay.

\( ^c \) 1991–1993 reflects transfers from the Defense Cooperation Account funded by foreign government and private cash contributions reducing total U.S.-funded military outlays.

\( ^f \) Revised

Table 1-1 Defense Budget Constant Dollars (Aerospace Industries Association 19)
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Figure 1-1 Defense Budget in Current Dollars (Aerospace Industries Association 19)
### Using System Dynamics to Understand Barriers to Cost Reduction

<table>
<thead>
<tr>
<th>Year</th>
<th>Grand Total</th>
<th>Complete Aircraft &amp; Parts</th>
<th>Aircraft Engines &amp; Parts</th>
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<td>Non Military</td>
<td>Military</td>
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<tr>
<th>Year</th>
<th>Grand Total</th>
<th>Complete Aircraft &amp; Parts</th>
<th>Aircraft Engines &amp; Parts</th>
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<tr>
<td></td>
<td>Military</td>
<td>Non Military</td>
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* Based on AIA's aerospace composite price deflator, 1987=100.

r Revised.

Table 1-2 U.S. Military Sales (Aerospace Industries Association 28)
The situation in the aerospace industry was made worse when considering military spending on research and development (R&D). R&D spending in the aerospace industry declined from a high of 22 billion dollars in 1987 to 16 billion dollars in 1996 largely due to declines in military R&D spending. The decrease in R&D spending not only affects the military aerospace markets but also the commercial aerospace markets. In the past, much of the knowledge gained from military R&D projects was transferred to commercial development projects. In effect, military R&D spending subsidized commercial R&D. However, with the decline of military spending, these companies were forced to compete with less subsidization, as illustrated in Figure 1-3 and Figure 1-4.
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Figure 1-3 U.S. Annual R&D Spending in Current Dollars (Aerospace Industries Association 101)

Figure 1-4 U.S. Annual R&D Spending in Constant Dollars (Aerospace Industries Association 101)
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As military spending decreases, the industry has placed greater emphasis on the commercial sector, which is driven by the airline industry. Yet, demand for air travel does not dictate demand for aircraft. Even though the number of passenger miles, shown in Figure 1-5, has grown steadily over the years, the demand for commercial aircraft, shown in Figure 1-6, has fluctuated wildly. The long product life of aircraft and components allows the commercial airline industry to choose the best time to decommission aircraft based upon the economy. The growth in the commercial sector has balanced some of the decline in military spending. However, European competition for these commercial contracts has increased. As a result, aerospace companies are fighting for fewer contracts and must reduce costs to compensate for decreasing demand.
Figure 1-5 Annual Passenger Miles Traveled Worldwide (Aerospace Industries Association 75)

Figure 1-6 Annual New Aircraft Orders (Aerospace Industries Association 29)
Importance of Aerospace Engine Suppliers

In response to financial pressures caused by decreases in demand and increased competition, the aerospace industry has undergone considerable downsizing. Companies are not just downsizing staff; they are downsizing business units. Vertical integration has become passe. More and more companies have been selling business units that are unrelated to their core competency. They are only keeping the business units for which they have a competitive advantage. As companies eliminate business units, they must find new providers of parts and components. Other companies, called suppliers, must now perform functions that used to be performed internally. As shown in Figure 1-7, the main reasons cited for outsourcing in the aerospace industry is to cut costs and enhance product value.

![Reasons for Outsourcing](image)

*Figure 1-7 Reasons for Outsourcing (Bozdogan and Harris 16, Appendix Figure 2b)*
Description of a Supply Chain

Aerospace companies now rely upon a network of suppliers often referred to as supply chains. In *The Machine that Changed the World*, Womack et al. has described a supply chain as having a tiered structure. The primary company, referred to as the customer, receives components and parts that are essential to their manufacturing process from a number of suppliers, called tier I suppliers. The tier I suppliers also receive parts and components from a number of suppliers, referred to as tier II suppliers. Tier II suppliers have suppliers called tier III suppliers. Tier III suppliers use tier IV suppliers and so forth until the ultimate supplier, usually the raw materials provider, is reached. This group of companies forms a network of cascading suppliers, called the supply chain, and is shown in Figure 1-8 (Womack, et al.).
Need for a Systems Approach to Cost Reductions

The trend to reduce vertical integration and create supply chains is not the cure all. Initially, the trend to reduce vertical integration and rely more on suppliers produced gains because companies could focus on their primary function, their core competency. However, once the "low hanging fruit" was removed from their core functions, companies found cost cutting efforts and value improvement efforts, such as increasing quality,
decreasing delivery delays, and increasing product attributes, difficult. These efforts have proved to be difficult because cost reduction efforts have impacts across functional boundaries and require coordination of efforts between a number of different groups.

**Systems Integration**

Value improvements in a supplier network are even more difficult because coordination efforts must span not only functional boundaries but also corporate boundaries. No single entity controls the entire product. Instead, each supplier controls a small component of the product value. As companies become less vertically integrated and perform fewer functions, they lose knowledge about the system and the components that comprise the system. This loss of product knowledge can lead to localized value improvement efforts that are sub-optimal for the system as a whole.

For example, considerable effort has been made by the aerospace industry to reduce forging costs of turbine disc components. One of the largest costs in a forging is the material cost. While the forging process yields very strong components, a large amount of waste is generated. The forging process cannot be used to produce fine detail. To achieve the detail needed, the part is forged with extra material that is later removed. The ratio of forged material purchased to material actually used or flown in the plane, referred
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to as the "buy-to-fly" ratio, is 12:1. Therefore, creating a forge that has less excess material, or a lower buy-to-fly ratio, could reduce total forging cost. On one occasion, AEM developed a forged shape with less material. Even though the forged shape was closer to the net shape, it was more expensive to manufacture. AEM failed to consider the impact of changing the forged shape on the material removal process. The new shape was more difficult to fixture and required additional setup time. Therefore, the reduction in material cost was counterbalanced by increased machining costs.

To prevent such errors from occurring and to instill a systems view, aerospace companies have implemented a number of procedures. One process, which has gained widespread use throughout the aerospace industry, is the use of integrated product development teams (IPTs). Ideally, IPTs contain representatives from each of the major functional groups in the product value stream. The goal of these teams is to improve the design process by leveraging the collective knowledge of the team to create a systems view.

By having a cross-functional team, each member brings a different type of product knowledge. The team as a whole should understand the product requirements throughout its entire product life cycle, as depicted in Figure 1-9. As a result, the team can shed light on design problems that may not be apparent to the designer. For example, by having a
representative from manufacturing involved in the design process, manufacturability issues can be resolved while the design is still on paper rather than on the production line.

![Figure 1-9 Product Life Cycle (Ulrich and Eppinger 9)](image)

Some manufacturability issues will always occur because designer often has conflicting goals that prevent the consideration of manufacturability. The designer is forced to make tradeoffs between product goals of schedule, performance, risk, and cost. Each of these product goals imposes different pressures on the product form and function, as shown in Figure 1-10. The designer's goal is to balance these pressures to create a product that matches product goals. However, without knowledge of all the system impacts the designer may make tradeoffs that deviate from these goals, as illustrated in Figure 1-11. The IPT process is an effort to equip the designer with the information needed to make the optimal tradeoffs from a system-wide perspective.
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![Diagram](Image)

**Figure 1-10** Product Tensions (Crawley)

![Diagram](Image)

**Figure 1-11** Product Tensions Including Perception versus Fact (Rechtin and Maier 82)

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Systems Architecture

The product design and development process has traditionally been focused on schedule and performance. Over the life of the aerospace industry, procedures have evolved to support these goals, while goals such as cost and risk have taken a back seat. Therefore, process goals often conflict with the new cost focused product goals (Rechtin and Maier 53-85). In effect, the process pulls the product away from its goals as shown graphically in Figure 1-12. To resolve this conflict requires a change in process architecture.
For example, despite a widespread belief that the IPT process adds value to the product, the existing process pressures preclude full implementation. The most noticeable instances of bypassing the IPT process occur with suppliers. Suppliers are often not brought into the IPT process until after the product has been designed and tested. As a
result, manufacturability issues are commonplace. The contracting process often precludes supplier involvement in the design process. In the early phases of the design process suppliers are often still bidding against one another and are reluctant to participate in the IPT process for confidentiality reasons. Furthermore, even though lack of supplier involvement is the most common instance of subverting the IPT process, it is not the only instance.

A number of monetary incentives, such as performance evaluations based upon team performance, were implemented to encourage the use of IPTs. However, the existing process remained mostly intact. Yet, this system was designed to meet different goals: product performance and schedule. Despite management initiatives to make cost the number one priority, all accounts of the product design and development process indicate that schedule and product performance are still the most important process drivers. Furthermore, the product design and development process, which is supposedly responsible for implementing cost goals, has no mechanism to consider cost. Aerospace designers are accountable for product performance, yet they are not accountable in any way, shape, or form, for cost. Therefore, the process architecture causes aerospace products to be skewed heavily toward performance rather than cost.
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New policies cannot be implemented without examining the existing processes and procedures. The underlying architecture of the system must be changed to be consistent with product goals.

AEM Case Study

In an effort to achieve cost reductions, AEM has made a strategic decision to focus on its core competency, engine design. Functions that are not directly related to a core competency or competitive advantage are outsourced. As a result, AEM has been able to eliminate many overhead activities. However, AEM has not been able to make substantial gains in reducing total engine costs.

In particular, AEM has had difficulty consistently creating designs, which consider the impact of design on manufacturability. Designs that fail to consider manufacturability are typically more expensive. Focusing on core competencies has made this problem more difficult, because 80% of the engine content is manufactured by suppliers. As the result, the impact of design on manufacturability is obscured by functional and organizational boundaries. In addition, each of these functional and organizational groups has a different set of goals that are imposed on the designer. In many cases these goals conflict and the designer is forced to make tradeoffs between goals. Designing an engine
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typically involves tradeoffs between performance, risk, schedule, and cost. Even though
the product goals set by management are geared toward costs, performance still
dominates the product design and development process.

Research Questions Addressed

This research uses system dynamics modeling to identify how to change the system
architecture so that cost becomes the priority in the product design and development
process. The thesis attempts to answer the following questions:

- What skews the product design and development process toward performance?

and

- How can the product design and development process be changed to focus on
costs?
SECTION 2 LITERATURE REVIEW

This section describes existing literature related to the thesis. In addition, this section describes how this thesis is different from previous works and how this thesis expands upon previous works.

The literature reviewed in this section forms the building blocks of the thesis. The Literature Review begins by describing works that delineate the importance of cost reductions and supply chains. Then additional literature is reviewed to describe how a supply chain must continuously improve and enhance product value. Next, examples from literature are used to demonstrate the importance of having a holistic view that allows system integration. This section concludes with a description of works that explain the conflict between product and process goals caused by the underlying architecture of the product development process. These are essential components to demonstrate that cost reductions in the aerospace industry are an important area to research.
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Description of Existing Literature

The importance of cost reduction and supply chains is described by Womack et al. in *The Machine that Changed the World*. Womack compares the Japanese automobile industry to that of the U.S. In this work, the concept of a "lean production" process is described. Lean production is a term coined to describe the production practices developed by Toyota and used at a number of Japanese automobile manufacturers. Since the release of the book, the term "lean production" has been used to describe the ideal production process. This process has been idealized because companies that use it have been able to deliver high quality products at low cost (Womack, et al.).

One of the enablers of the lean production process is through supply chain management. At Toyota and other companies that use lean production processes, suppliers are consulted and included in the design process when the product is first conceptualized. The early involvement prevents system level errors. System level errors are commonly referred to as integration errors and include incompatibility errors such as component design and manufacturing process. For example, suppliers have detailed knowledge about component manufacturing. If included in the design process, suppliers can use this knowledge to eliminate designs, which are difficult to manufacture. In a lean production process, suppliers are also encouraged to share production and cost information with its customers. Through information sharing, suppliers can draw upon expertise and
knowledge gained throughout the supply chain. If this information sharing is used appropriately, it can lead to continuous improvement within the supply chain (Womack, et al.).

While The Machine that Changed the World characterizes the concepts and components of a good supply chain, it does not describe how to implement these concepts into an existing organization. Similar to Newton's Law of Inertia - an object at rest remains at rest and an object in motion remains in motion - people and companies resist change. As a result, incentives need to be provided to promote change. While this thesis uses the concept of a supply chain and its tiered structure as described by Womack, this thesis extends the research by investigating incentives that can be used to implement design for manufacturability and other continuous improvement technology.

MacDuffie and Helper in "Creating Lean Suppliers: Diffusing Lean Production through the Supply Chain" elaborate on many of the concepts described in The Machine that Changed the World. MacDuffie and Helper describe some of the key components a supply chain needs to maintain continuous improvement. They also discuss the importance of supplier responsiveness to the customer. For example, in a case study of Honda, they demonstrated that more importance is placed on customer responsiveness than quality. If the supplier is responsive, Honda can teach quality and continuous
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improvement. But, if the supplier is not responsive, it is difficult to accomplish change (MacDuffie and Helper). This thesis investigates the factors, which drive change and cost reduction. However, this thesis looks at what the customer can do to help the supplier rather than vice versa.

Charles Fine elaborates on the importance of supply chain design in his book *Clockspeed*. In particular, Fine discusses the trend among companies to move toward an integrated product design and development process. This process has been referred to as concurrent engineering or design for manufacturability (DFM). This integrated process is in stark contrast to the "throw it over the wall" mentality used by manufacturers in the past. In the past, one group would create a design specification and another group would manufacture the product to the specification. However, from the Toyota experiences, many companies learned that a product that is designed with manufacturing in mind can be produced less expensively and have better quality (Fine 127-154).

Fine elaborates further on the process by outlining the key steps of using concurrent engineering. First, he discusses the idea of product decomposition. Fine states that products should be decomposed into systems and subsystems to identify the interactions. These subsystems are then evaluated to identify the design requirements. Then, he discusses the importance of aligning the process to meet the product design requirements.
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Furthermore, he discusses the importance of aligning the product and process architecture with that of the supply chain. In particular, the supply chain should be structured to fit within the product and process strategy. For example, products with integral architecture should have an integral supply chain. Fine states that an integral supply chain needs proximity. According to Fine, proximity can be defined in terms of geographic, organizational, cultural, and electronic. The level of proximity required among these dimensions depends upon the product, industry, and strategic goals.

The process that Fine describes is more of a framework to use when architecting the product design and development process than a method to implement concurrent engineering. The framework is presented at a fairly high level of abstraction and does not describe in great detail methodologies that can be used to ensure that these architectures are aligned. Overall, Fine's work describes characteristics of the ideal concurrent engineering process. However, this thesis is aimed at identifying the barriers to implementing DFM as well as describing policies that will aid its implementation.

Ulrich and Eppinger provide a more "hands on approach" to the product design and development process in their work Product Design and Development. They describe the DFM process in detail. One of the primary features of a DFM process is the use of cross-functional teams, often referred to as integrated product teams (IPTs). In their
framework, they avoid the "throw it over the wall" mentality by establishing teams containing members from all phases of the product development process. By assembling this team, the designer can draw upon knowledge about the entire product life cycle. Therefore, when the designer is forced to make tradeoffs between conflicting goals it can be an informed tradeoff (Ulrich and Eppinger 137, 179-216). While Ulrich and Eppinger describe in detail how the design process and DFM process should work, they do not describe how to actually implement DFM within an existing organization.

In The Art of Systems Architecting, Rechtin and Maier allude to the fact that concurrent engineering and DFM are difficult to implement due to competing product and process goals. Decisions regarding the product and process are often decoupled. As a result, it often takes more than management directives to implement new processes. A product change can be circumvented if the process operates as usual because processes are typically designed to resist change. As a result, to really change the product may require process changes (Rechtin and Maier 53-73). Consider the example provided by Rechtin & Maier:

A communications spacecraft design was proceeding concurrently in engineering and manufacturing until the question came up of the spacecraft antenna size. The communications engineering department believed that a 14-ft diameter was needed; the manufacturing department insisted that 10 ft was the practical limit. The difference in systems performance was a factor of two in communications capability and revenue. The reason for
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the limit, it turned out, was the manufacturing department had a first-rate subcontractor with all the equipment needed to build an excellent antenna, but no larger than 10 ft. To go larger would cause a measurable manufacturing cost overrun. The manufacturing manager was adamant about staying within his budget, having taken severe criticism for an overrun in the previous project. In any case, the added communications revenue gain was far larger than the cost of reequipping the subcontractor. Lacking a systems architect, the departments had little choice but to escalate the argument to a higher level where the larger antenna was eventually chosen and the manufacturing budget was increased slightly. The design proceeded normally until software engineers wanted to add the original computer hardware design. The argument escalated, valuable time was lost, department prerogatives were again at stake... and so it went.

(Rechtin and Maier 61-62)

Despite acknowledgement by Rechtin and Maier that processes resist change due to misalignment of product and processes, they do not provide much insight as to how to successfully implement change.

Nelson Repenning attacks this issue described by Rechtin and Maier head on in Why Good Processes Sometimes Produce Bad Results: A Formal Model of Self-Reinforcing Dynamics in Product Development. In his work, he demonstrates through system dynamics modeling that companies often operate in a "fire-fighting" mode. In this environment, existing project tasks take precedence over tasks to improve future projects. Scarce resources are allocated to fixing existing problems rather than preventing future
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problems. As a result, new processes and tools widely believed to be better are never implemented because resources are unavailable.

In addition, Repenning demonstrates that the introduction of new processes and tools designed to improve the existing process can often make problems worse. The time it takes to learn a new process or tool places additional burden on already scarce resources. As a result, even less time is available for prevention and more problems occur, which leads to an even greater burden on resources in the form of additional rework.

The model developed by Repenning is somewhat constrained. First, Repenning assumes that only one product is developed at a time. Second, he assumes that the product development cycle is a fixed duration. He also assumes that priorities remain constant during the duration of the project. Finally, his model focuses on two types of tasks: mandatory design tasks, and advanced tasks. Advanced tasks are optional and reduce the probability of rework on future projects (Repenning).

The model developed in this thesis relaxes the constraints in Repenning's model. The model developed as part of this thesis uses a continuous product development cycle rather than a discrete process. In addition, the project priorities change as the project status
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changes. These differences are largely due to a difference in focus. Rather than focus on the impact of optional tasks on future product design and development projects, this thesis focuses on the impact of optional tasks on existing product design and development projects. In particular, this thesis focuses on the impact of non-mandatory design tasks on the cost, performance, and probability of failure of existing product design and development projects. The impact of these tasks is obscured as the design is passed to the supplier. In addition, this thesis focuses on how process priorities given to these non-mandatory design tasks can deviate from the priority indicated by the product goals.
SECTION 3 RESEARCH DESIGN

This section describes in detail the methodology employed to develop the system dynamics model. This thesis relies heavily on a system dynamics modeling methodology commonly referred to as the standard method. According to Hines, the standard method is a consulting process used to define the problem being analyzed, clarify relationships of the system being analyzed, and create a model which emulates the system behavior. In essence the standard method is a structured approach to creating a system dynamics model (Hines, Class Notes).

System dynamics models are often referred to as mental models because these models can be used to create relationships that may exist in perception rather than just physical phenomena. For example, system dynamics can be used to model how morale impacts work productivity. While work productivity is a tangible indicator of performance that can be measured easily, morale is a mental state that is difficult to measure without using some sort of mental intuition. As a result, system dynamics modeling relies heavily on perceptions of the world provided by those actively involved with the system under study, referred to as "system insiders" or "the client."
Overview of the Modified Standard Method

This thesis employs a slightly modified version of the standard method described by Hines. The modified standard method is a six step iterative process as follows:

1. Define the problem
   - List variables
   - Provide examples
   - Describe reference modes
   - Outline problem statement
2. Describe existing policies
3. Develop dynamic hypotheses
   - Identify dynamic hypotheses
   - Simplify/abstract loops
   - Create hybrid causal model
4. Model single loop
5. Analyze single loop
6. Repeat steps 4 and 5.

(Hines, Class Notes)
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This modified standard method is essentially identical to that described by Hines, except three steps have been added to make the process more explicit and to reduce the likelihood of making mistakes in the modeling process. These steps are as follows:

- Outline problem statement
- Simplify/abstract loops
- Create hybrid causal model

The reasons for adding these steps are included below along with the detailed description of the methodology.

Defining the Problem

Defining the problem consists of four tasks designed to bound the scope of the problem. Without boundaries, the model becomes onerous and, rather than becoming a simplification of the real world, becomes a duplication of the world. As Jimmy Stewart's character, George Bailey, found out in the movie "It's a Wonderful Life," even small interactions can influence a system. However, to characterize George Bailey not all of these influences are necessary. The same is true with real world problems - not every influence is needed to characterize the problem. Therefore, in systems dynamics, the modeler's job is not to model every influence. Instead, the modeler's goal is to simplify
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the system to a point that it is easy to understand and gain insight while maintaining as much of the system behavior as possible.

**List Variables**

Even though the goal of the defining the problem is to simplify the problem, the process begins by having system insiders list all of the variables that impact the problem being analyzed. There are two benefits to listing all the variables. First, it is a brainstorming process. It allows the participants involved to think about the problem root causes. It also allows the participants to understand the problem from the perspective of other group members. Second, it gives the modeler a framework to think about the problem, as well as an appreciation for the system complexity. The modeler can then use this framework to ask questions. Many causes and interactions are so obvious to systems insiders that they are taken for granted during the brainstorming process; yet, these causes and interactions are crucial to model development. By going through the brainstorming process, the modeler is able to gain enough understanding of the problem to ask questions that bring these unspoken causes to light.

Once a comprehensive list is created, the simplification process begins in an effort to identify the variables that have the most impact on the problem being analyzed. The
system insiders select the top five variables, which have the greatest impact on the problem under review (Hines, Class Notes).

**Provide Examples**

Examples are not an explicit step in the standard method as presented by Hines. Instead, they typically are stories told when providing reference modes in the next step (Hines, Personal Discussion). However, collecting examples was a distinct step in the modified standard method used as a part of this thesis because examples greatly enhance the understanding of the problem and resolve any differences that may occur due to nomenclature. Different groups of people have different meanings for the same words. As a result, descriptions in the form of a variable list may lead to errors in formulating the mental model. Examples clarify what is really meant from particular terminology. Furthermore, the examples contain background information that explains why certain variables are important. Therefore, the system and its problems become more tangible through examples. Moreover, with concrete examples, the modeler can begin to ask questions about the system more easily. The answers to these questions from system insiders are usually better because they are based on past experiences rather than hypothetical situations.
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Examples developed as part of the standard method process can be used throughout the modeling process to fill in gaps about the mental model. In referring to examples, the modeler answers questions of "Why?" Not only do these examples help the modeler, but also the system insiders. As they reflect upon these experiences, the system insiders begin to understand the root causes of the problem. Understanding these root causes will lead to a better problem statement and a better hypothesis for the dynamic behavior of the system. Examples can also be used as sources of information for model inputs during the modeling process. Finally, the modeler can use the common nomenclature developed from the examples in the model structure to make it more realistic, believable, and understandable for the system insiders.

Describe Reference Modes

Next, the major parameters of the system are mapped over time. The time frame used for this mapping is left to the discretion of the system insider. The maps should extend far enough in the past and future to understand current trends. The system insider should provide both a pessimistic and an optimistic prediction of the future (Hines, Class Notes).

These maps are referred to as reference modes because the modeler refers to them when developing the dynamic hypotheses and the model. The output from the model should
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approximate the historical process maps. As a result, the dynamic hypothesis should generate behavior shown in the reference modes. If the hypothesis does not generate this behavior then it is not the cause of the system problems. As a result, the modeler can use these maps as a reference to judge model performance. Model performance is discussed in more detail in Section 8.

The reference modes are also used to evaluate policy recommendations developed as a result of using the model. The goal of any policy recommendation is to change the system in such a way that output closely emulates the optimistic estimates and deviates from the pessimistic output. The difference between optimistic and pessimistic estimates gives the modeler insight into the variability associated with the system. In systems with little variability, model inputs must be carefully scrutinized because small errors in calibration could change the system behavior. As a result, policy recommendations could vary greatly. In instances where past information is available and is considered to be representative of the future, historical information can be used to assist with model calibration.
**Outline Problem Statement**

Drawing upon the list of variables, examples, and reference modes, the modeler can begin to outline the problem scope in the form of a problem statement. The statement simply defines the symptoms of the problem and which symptoms need to be changed.

**Describe Existing Policies**

This step simply documents the policies that participants would use to solve the problem prior to embarking upon the standard method. This step is done to demonstrate the benefit of the modeling process, particularly in the early phases. One of the benefits of the standard method is that it clarifies what is already known. In addition, the standard method is participatory process, in which everyone makes contributions as the process continues. As a result, many of the benefits of the standard method appear obvious in hindsight. However, the methods of attacking the problem often change dramatically due to participating in the process. As a result, participants may not realize the benefit of the exercise until they see how much their mental model has changed from the start of the process (Hines, Class Notes).
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Develop Dynamic Hypotheses

Once the problem has been defined the modeler begins exploring why the problem persists. System dynamics is based on the premise that system behavior is due to endogenous variables. Thus, the system dynamic model is a closed feedback loop system. These feedback loops are presumed to cause system behavior, until proven otherwise. While system dynamics models do have exogenous inputs that influence the system, these inputs should not drive system behavior. Furthermore, if exogenous variables are the system drivers then the problem statement has been formulated incorrectly and needs to be revised to focus on the causes of changes in these exogenous variables (Hines, Class Notes) (Richardson and Pugh 63-66).

The presumption of an endogenous closed feedback system is in part due to the types of problems for which system dynamics is applied. The system dynamics framework is typically applied to recurring problems. These problems have often been examined closely and countermeasures have also been implemented. Yet, the problem persists and often gets worse, suggesting that measures designed to correct a problem make the problem worse. In order for corrective measures to worsen the problem, these measures must be part of a loop (Richardson and Pugh 63-66).
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Furthermore, this focus on endogeneity is due to the proactive approach taken in the field of system dynamics. The goal of system dynamics is to control or change a particular circumstance rather than identify blame or respond to a circumstance. If the cause of a problem is endogenous, it can be controlled. If the cause of a problem is exogenous, it cannot be controlled and a more reactive position must be taken. The only recourse with a reactive approach is to minimize the impact of exogenous factors (Richardson and Pugh 63-66).

Identify Dynamic Hypotheses

Since system dynamics is a closed feedback system problem causes are defined in terms of loops, referred to as hypotheses of causal loops. To identify these causal loops, the modeler uses a process similar to Toyota's root cause analysis referred to as "Five Why's." When Toyota identifies a problem, a team is sent to find the root cause. The team assumes that the problem identified is a symptom of an underlying problem. To identify the underlying problem, the team asks, "Why did the symptom occur?" Answering the initial question usually leads to another symptom, so the question is asked again about this symptom. Toyota believes that asking "Why...?" five times will lead to the underlying cause (Mishina).
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Although the standard method uses this process of asking "Why...?", the focus is slightly different. Because system dynamics inherently assumes a closed loop framework, the question of "Why...?" is asked until a closed loop formed. Consider the example in Table 1-1 of a gear manufacturing line that is experiencing declining yield. The Toyota process stops once it has identified tool wear and inspection frequency as the problem. In system dynamics the process does not end until the initial problem identified leads back to itself.
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<table>
<thead>
<tr>
<th>Problem: Gear yield is decreasing</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Toyota Process of Five Why's</strong></td>
</tr>
<tr>
<td>Why?</td>
</tr>
<tr>
<td>Gears do not couple.</td>
</tr>
<tr>
<td>Why?</td>
</tr>
<tr>
<td>Grinding equipment does not hold dimensional accuracy.</td>
</tr>
<tr>
<td>Why?</td>
</tr>
<tr>
<td>Chatter on grinding equipment.</td>
</tr>
<tr>
<td>Why?</td>
</tr>
<tr>
<td>Excess wear on grinding tool.</td>
</tr>
<tr>
<td>Why?</td>
</tr>
<tr>
<td>Grinding tools not inspected frequently enough and need to be replaced more frequently.</td>
</tr>
</tbody>
</table>

| **System Dynamics Standard Method** |
| Why?                             |
| Gears cannot be assembled.       |
| Why?                             |
| Manufacturing equipment performance is decreasing. |
| Why?                             |
| Manufacturing equipment is wearing out. |
| Why?                             |
| Preventive maintenance is not performed. |
| Why?                             |
| Maintenance staff time spent adjusting grinding equipment control parameters. |
| Why?                             |
| Yield is decreasing.             |

Table 3-1 Comparison of "Five Why" process to causal loop identification

In addition, system dynamics is performed at a higher level of abstraction. Notice, in the example given in Table 3-1, the causal connection does not state that grinding tools need to be replaced more frequently as in the Toyota process. Instead, the causal connection is that preventive maintenance is not performed. As described in the modified standard
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method, the abstraction process is sometimes an additional step. By using two steps the connection between the examples and causal loops becomes clearer. Whether these causal connections are initially described in abstract terms or in the detailed terms depends upon the problem and the modeler's skill level. However, even skilled modelers should make efforts to abstract loops identified to a higher level. This abstraction process is described in more detail below.

These causal loops are represented graphically in causal loop diagrams and portray the interaction of variables. The diagram for decreasing gear yield is shown in Figure 3-1. In the diagram, arrows are used to connect cause and effect. Arrow direction is drawn from cause to effect. The relationship between cause and effect, called the polarity, is indicated on the arrow with a positive or negative sign. A positive sign (+) indicates that the cause is directly related to the effect, or as the cause increases so does the effect. A negative sign (-) indicates that cause is inversely related to the effect, or as the cause increases the effect decreases (Richardson and Pugh 25-30). For example, in Figure 3-1 the arrow from Manufacturing Equipment Performance to Ability to Assemble Gears has a positive sign to indicate that as performance of manufacturing equipment increases the ability to assemble gears increases.
The causal loop itself also has a polarity. A positive loop, also called a reinforcing loop, indicates that an increase to the loop or system leads further increases. Reinforcing loops are associated with exponential growth or decay. A negative loop, also called a balancing loop, indicates that an increase in the system leads self-correcting pressures that counterbalance the increases. Balancing loops stabilize a system and are associated with oscillation. The polarity of the causal loop is the product of the individual polarities. The product of a positive polarity and a negative polarity is a negative polarity. The product of two positive or two negative polarities is a positive polarity. Therefore, a loop with an even number of negative polarities is a positive loop, and a loop with an odd number of negative polarities is a negative loop (Richardson and Pugh 25-30).
Polarity can also be determined by tracing the impact from variable to variable. For example, in Figure 3-1 assume that more time is allocated for preventive maintenance. Based on the polarities in Figure 3-1 and the description provided in Table 3-1, an increase in the time allocated to maintenance will increase the frequency with which grinding tools are replaced resulting in a decrease in equipment wear. Decreasing equipment wear results in increased equipment performance because fewer tool discontinuities result in more accurate grinding and cutting. Increasing the accuracy of grinding and cutting, increases the ability to assemble gears because the gears are easier to couple. If the gears couple more easily fewer have to be scrapped, thus, increasing yield. As yield increases, maintenance staff has fewer crises to solve and has more time available. As their available time increases, the maintenance staff is more able to conduct preventive maintenance activities. This tracing demonstrates that the loop is positive because an increase in time allocated to preventive maintenance leads to even more time allocated to preventive maintenance.

**Simplify/Abstract Loops**

Defining all the causal loops results in a maze of causal connections. This maze is an indicator of model complexity. Although not explicitly part of the standard method as espoused by Hines, simplification/abstraction of causal loops is an inherent part of the
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system dynamics modeling process. Therefore, this simplification process was made an explicit step of the modified standard method used as part of this thesis.

The causal loop representation developed in coordination with system insiders usually results in a very detailed description of the system. This description effectively decomposes the system into subsystems and subsystems of the subsystems. Modeling this level of granularity can lead to models, which are too complex to gain insight. Therefore, choosing the appropriate level of problem decomposition becomes an important part of system dynamics. The process used to choose the appropriate level is iterative and may have to be revisited as the model evolves. To avoid falling into an abyss of complexity, the subsystems should be simplified and abstracted.

Even though abstraction and simplification are synonymous, these terms are used to represent two separate processes. Simplification refers to the process of eliminating unnecessary causal connections, whereas abstraction refers to the process of making the causal loops more generalizable. The difference between these processes is very subtle. The simplification process reduces the complexity of a given level of decomposition. The abstraction process reduces complexity by choosing the appropriate level of decomposition. Furthermore, this simplification and abstraction process will allow the modeler to estimate which causal connections are the most important. Once the causal
loops are aggregated and simplified, the modeler may need a finer level of granularity. The modeler can then decompose the system again. Even though this step will return the causal diagram to the original level of decomposition, it should be much less complex because many of the causal connections were removed at the system level.

To illustrate the simplification process, consider the gear yield problem discussed earlier in Figure 3-1. This causal loop diagram is missing an obvious connection between Time for Maintenance Activities and Manufacturing Equipment Performance. The connection can be made clearer by adding the variable Equipment Repairs. As more maintenance is performed, more equipment is repaired and manufacturing equipment performance improves. The new causal loop diagram is improved by further delineation of the variables and is shown in Figure 3-2 below.
This diagram represents the way in which maintenance staff is allocated between preventive maintenance work and repair work. If the problem statement is to determine the appropriate allocation between repair and maintenance activities to reduce total downtime, it becomes apparent that our causal loop representation may be too detailed. For example, the Ability to Assemble Gears does not provide insight into the problem of total downtime. Yet, if we include it in our model, it will add additional structure and complexity. As a result, the causal loop diagram should be simplified. The revised causal loop diagram contains all the major features as before, except the diagram is more...
targeted toward the problem at hand. In addition, by reducing extraneous variables the model development will be much less complex.

![Diagram of Manufacturing Equipment Performance](image)

**Figure 3-3 Revised Diagram Preventive Maintenance Versus Equipment Repair on a Gear Production Line**

The abstraction process is more difficult than the simplification process. It involves identifying an underlying theme. As mentioned previously, the abstraction process is illustrated in Table 3-1 by comparing the Toyota method of "Five Why's" to the standard method. In this example, the Toyota method is a detailed description of the gear yield problem while the standard method is a more abstract description. In the Toyota process
a symptom of the gear yield problem is grinding tool chatter. While in the standard method, the same symptom is identified as reduced equipment performance.

**Create Hybrid Causal Model**

Once deciding upon a level of abstraction, the modeling process can begin. However, in practice an intermediate step is often used. While this step is not an explicit part of the standard method, it can play a crucial role in outlining the architecture of the system dynamics model. This thesis relies heavily on this hybrid methodology. The advantage of performing this step is that it provides the modeler with a holistic view of the process. If the modeler jumps immediately from causal loop diagrams to modeling single loops, the modeler is likely to create model structures which make sense for the individual loop but do not fit the framework of the model as a whole.

System dynamics modeling requires a paradigm shift for those familiar with other types of programming and modeling techniques. For example, in the software programming, the main structure, or the backbone, is set at the beginning of the process. Placeholders are designated within this system for each of the subsystems to ensure that each subsystem interface is consistent. The subsystems are then developed and tested offline. Only later are these subsystems attached to the system. Unlike the software architect, the system dynamicist does not have the luxury of being able to design a central backbone
that supports the underlying subsystems, or individual loops. System dynamics is a reverse engineered process. The architecture is imposed by the architecture of the system being modeled. The system dynamicist must build the system from the individual subsystems represented by causal loops. This reverse engineering process is made more difficult by the uncertainty associated with choosing the appropriate level of decomposition. In some sense, the starting level of decomposition is merely a guess, which begins an iterative design process. As such the modeler has to be willing to accept the idea that the model structure may have to be revised or even discarded at some point. If the architecture is not revisited periodically, the modeler will become awash in a sea of complexity.

For the new modeler, the iterative nature of system dynamics can be particularly frustrating. According to Jorgen Randers in "Guidelines for Model Conceptualization," modelers have difficulty changing frameworks. Once deciding upon a framework for an individual loop, the modeler often becomes focused on that framework and finds it difficult to transition to a new framework. The ability to transition from one framework to another is particularly difficult for newcomers to the field of system dynamics (Randers 137).
In many instances, the newcomer may realize that the architecture is flawed but continue because so much time is already invested in one particular framework (Randers 137). The modeler may not realize that moving backwards may make moving forwards so much easier that it is well worth the investment in additional time. Furthermore, the newcomer may also attribute model difficulties to a lack of understanding rather than poor architecture.

Creating the initial architectural vision with this hybrid structure allows the modeler to resolve many of the architectural issues visually and avoid much iteration without much time investment. First, the modeler will gain a feel for how a simple causal loop will increase in complexity as it is translated into a mathematical model. As a result, the modeler will choose a level of abstraction that is more appropriate from the start. Second, the modeler gains a view of how each loop impacts another. For example, a modeler may choose to model one project rather than a continuous stream of projects. However, the structure of the model will often vary greatly depending upon whether it is a continuous or discrete process. The modeler must make sure that the structures are consistent across loops. Examples of this reexamination process encountered during the development of this thesis are discussed in more detail in Section 5, Section 6, and Section 7.
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Model Single Loop

After developing the causal loops, the modeling process begins. In many cases the causal loop process is sufficient to yield insight into the problem statement; however, the modeling process is used to make causal connections more explicit. This added detail often leads to further insight. A series of mathematical equations is used to define the relationships between variables. A model consists of four different types of variables: stocks, flows, auxiliaries, and constants. Each type of variable is described below, and their graphical representations are shown in Figure 3-4.

Stocks

Stocks are variables that accumulate over time. System dynamics has often been compared to a water reservoir system. A stock is a reservoir in which material accumulates. There are two types of representations for stocks. The rectangle is used to illustrate a stock that has been fully specified. A cloud is used to represent a stock that has not been fully specified. An unspecified stock with an outflow is a source, while an unspecified stock with an inflow is a sink. Mathematically, the value of a stock is the integral of its inflows and outflows (Richardson and Pugh 30-32).
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Flows

Flows are inputs to stocks and are represented by pipe and valve structure. The arrow represents the direction of the flow. In the reservoir analogy, flows are the pipes that feed or empty the reservoir. Flows are essentially the rates at which that material enters or leaves a stock (Richardson and Pugh 30-32).

Auxiliaries

Auxiliaries are represented by variable name. These variables are intermediate values used to calculate flows and the initial values of stocks.

Constants

Constants are also represented by variable name. As their name implies, constants are variables that have a constant value. These constants are inputs to auxiliary equations, flows, and initial values of stocks.
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Auxiliaries and constants do not have any graphical representation because they are not fundamental structures of system dynamics. Constants and auxiliaries can be substituted into the equations for stocks and flows. As a result, system dynamics is said to consist entirely of stocks and flows. The reason for adding auxiliaries and constants is to make the model more transparent.

Using the hybrid approach discussed above, the first phase of the modeling process is to create the system architecture. Using the dynamic hypotheses in Figure 3-3, the model architecture might be defined as shown in Figure 3-5. The hybrid architecture shown is relatively complete. However, as the models become more complex the hybrid architecture is often incomplete and needs to be augmented in the modeling process.
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**Figure 3-5 System Architecture for Preventive Maintenance Dilemma**

The primary structure for this model consists of a chain of two stocks connected by flows. These stocks represent the two states of equipment: utilized capacity and degraded capacity. As equipment deteriorates, a fraction of the utilized capacity is transformed into non-functioning equipment or degraded capacity. The rate of this decay is a function of time to failure. Time to failure is a function of staff allocated to preventive maintenance.
The more staff allocated to preventive maintenance the longer the time between failures. Essentially the representation of the utilized capacity and the deterioration rate is a delay.

The model also includes a stock for perceived deterioration rate. The representation of perceived deterioration rate is designed to emulate the information delay between actual and perceived equipment deterioration. The perceived deterioration rate uses the standard formulation used by system dynamicists for perception delays, a smooth. A smooth is a stock with an inflow. The inflow rate can be positive or negative and is influenced by new information and the stock itself. This formulation implies that both the past and present influence perceptions. Or, in other words, the formulation represents an information delay. For example, even though changes in the deterioration rate occur instantaneously, they are not perceived instantaneously. This information delay can occur for a number of reasons: equipment may not be checked frequently enough to notice changes, or it may take time before the deterioration is observable due to the sensitivity of detection equipment. Based on the perceived deterioration, staff is allocated to either repair or preventive maintenance.

Part of the model development process includes data collection. Models should use real data for inputs whenever possible. However, models often include variables to describe perceptions and feelings for which hard data does not exists. To include these variables,
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"fuzzy" data based on the insights and knowledge of system insiders should be used. If the analysis process shows that the model is highly sensitive to these inputs, the estimates for these variables should be refined.

**Analyze Single Loop**

After a loop is modeled, the impact of changing each variable should be reviewed. The level of analysis really depends upon goals of the modeling process. If the goal of the model is to demonstrate that past actions caused certain behavior then the model output needs to be highly correlated with past data. However, if the goal of modeling is to learn about the system, then the output does not need to be strongly correlated with past data but should instead follow the same general trends.

When looking at the past, events that are one time in nature and exogenous in nature can be included in the model. These events are often unpredictable except when looking retrospectively. While these events help explain the past, they often do not help improve understanding of the future. For example, a model that includes the impact of a hurricane or the great depression assists in correlating the model to these events; however, they do not improve learning about the future unless the model is designed to answer questions about catastrophic events. If the problem statement revolves around improving gear
yield, including the exogenous effects of hurricanes and depressions is unnecessary. Furthermore, the model should represent a response rather than a correlation. A model based upon correlation will show a strong fit with past data but may not be robust enough to provide insight about the impact of changing the system.

When the goal of analysis is to learn, it is often beneficial to start the modeling process in a steady state condition. By starting in the steady state, the model is easier to analyze because there is not as much "noise." It becomes easier to separate the dynamics of the model from the impact of the individual variables. In addition, steady state is often the desired state of the system being evaluated. Two different methods can be used to start the model in steady state. The first method is to run the model for a long enough time period that the model reaches an equilibrium state. Then, set the initial conditions for each of the stocks and flows equal to the steady state values. The other method is more difficult but more robust. This alternate method requires solving the simultaneous model equations by assuming that actual values are equal to the desired values. Then use the values obtained as the initial conditions (Hines Class Notes).

In steady state the dynamic behavior of the model is eliminated. In order to test the model, it has to be disturbed from the steady state. At first, it may seem counterintuitive to bring the model into equilibrium and then disturb it from equilibrium. However, by
starting in equilibrium and then disturbing the equilibrium state, the disturbance is more controlled and easier to distinguish the underlying causes of the dynamic behavior.

Introducing a pulse to one of the constant variables is often sufficient to disturb the equilibrium. The modeler should then go through and increase and decrease each of the model inputs to identify their impact. Prior to simulating, the modeler should estimate the impact of increasing and decreasing each of the model inputs independently. This estimation process prior to simulation tests the modeler's understanding of the system. If the model output differs from the modeler's expectations, the modeler should identify why the behavior deviated from expectations. In general, there are three different causes for these deviations from expectations:

- Model formulation errors;
- Missing causal loops; or
- Flawed mental model.

To determine the cause of the unusual behavior, the modeler should examine the impact of changes to each variable. A commonly employed technique in system dynamics is causal tracing. The modeler begins by evaluating the variable that exhibits unusual behavior. The evaluation process includes the examining the effect of that variable on other variables or the causes of that variable until an entire loop is traced. The tracing
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process continues from variable to variable and loop to loop until the modeler can explain the unusual behavior. In addition to improving the modeler's understanding of the system, this causal tracing process allows the modeler to debug the model.

Causal tracing is applied to the example provided above to illustrate that staffing level and the method of allocating staff is paramount to the gear yield problem. In particular, causal tracing shows that the allocation method used in the gear yield example places greater emphasis on repair rather than preventive maintenance. Consequently, a sudden decrease in the time to failure leads to neglect of preventive maintenance on the remaining equipment. As a result, the system is pushed to a new equilibrium with yield below desired yield.

An example of the causal tracing process is shown for the variable maximum desired downtime because it best illustrates the emphasis on repair. This variable represents the maximum time to correct the disparity between desired and actual yield. In effect the shorter the maximum desired downtime, the greater the desired rate to improve yield, referred to in the model as the desired gap close rate. This loosely corresponds to the amount of emphasis given to repair. As a result, trying to shorten the downtime of degraded capacity can actually lead to additional capacity degradation because preventive
maintenance is sacrificed in favor of repair. Therefore, the failure rate of the equipment increases leading to further degradation.

The causal tracing process for maximum desired downtime has four steps: disturb the model from equilibrium, analyze the disturbed state, analyze the disturbed state with maximum desired downtime halved, and analyze the disturbed state with maximum desired downtime doubled. To disturb the model from equilibrium, the author multiplied normal time to failure by 0.8 at time equal to two months for a period of three months. Then the impact of changing the maximum desired downtime was tested by first halving and then doubling its value. As shown in Figure 3-6, and Figure 3-7, when halving maximum desired downtime, degraded capacity rises and actual yield declines. Both stabilize over time at a new equilibrium. In this new equilibrium, actual yield is well below desired yield of 0.6. However, when doubling maximum desired downtime, degraded capacity rises and actual yield falls temporarily then return to the pre-disturbance equilibrium values.
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Graph for Degraded Capacity

Degraded Capacity: Equilibrium 1 1 1 1 gears/Month
Degraded Capacity: Time to Failure Disturbance 2 2 gears/Month
Degraded Capacity: Disturbed Half Max Downtime 3 3 gears/Month
Degraded Capacity: Disturbed Double Max Downtime 4 4 gears/Month

Figure 3-6 Gear Yield Simulation Output: Graph for Degraded Capacity
To understand the differences in output, first the effect of the disturbance on the simulation output was traced. By multiplying the normal time to failure by 0.8, the amount of degraded capacity increases above the initial equilibrium value, as depicted in Figure 3-6. As more equipment degrades, yield falls as Figure 3-7 illustrates. Accordingly, more staff is allocated to repair this growing quantity of degraded equipment as shown in Figure 3-8. Correspondingly, staff allocated to preventive maintenance falls, demonstrated in Figure 3-9. The decline in preventive maintenance
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shortens time to failure even more, leading to further degradation of capacity and lower yield.

![Graph for Maintenance Staff Allocated To Repairs](image)

**Figure 3-8 Gear Yield Simulation Output: Graph for Maintenance Staff Allocated to Repairs**
Next, the impact of changing the maximum desired downtime was traced. When halving the maximum desired downtime, the desired rate to close the gap becomes rather large, as illustrated in Figure 3-10. Hence, a large portion of the total maintenance staff is allocated to repairs rather than preventive maintenance. Decreasing preventive maintenance shortens the time to failure as shown in Figure 3-11 and accelerates the failure rate degrading equipment capacity and decreasing yield.
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Graph for Desired Gap Close Rate

Desired Gap Close Rate: Equilibrium 1 1 1 1 1 1/\text{Month}
Desired Gap Close Rate: Time to Failure Disturbance 2 2 2 1/\text{Month}
Desired Gap Close Rate: Disturbed Half Max Downtime 3 3 3 1/\text{Month}
Desired Gap Close Rate: Disturbed Double Max Downtime 4 4 4 1/\text{Month}

Figure 3-10 Gear Yield Simulation Output: Graph for Desired Gap Close Rate
On the other hand, when doubling the maximum desired downtime, the desired rate to close the gap is much smaller, as illustrated in Figure 3-10. Therefore, not as much of the maintenance staff is allocated to repair and fewer staff are pulled away from preventive maintenance as depicted in Figure 3-8 and Figure 3-9 respectively. Thus, equipment capacity is not degraded as quickly and yield remains higher, in accordance with Figure 3-6 and Figure 3-7.

The equations for this example model are included in detail in Appendix A.
**Model and Analyze Next Loop**

If the modeler cannot find any modeling errors or flaws in the mental model and the model still does not generate the reference mode, then the model has not captured the dynamic nature of the problem and a new dynamic hypothesis needs to be developed. The unusual behavior is likely to result from loops that have not been specified in the model to date. In this case the model and analyze process is then repeated. In some instances, the causal loop development and problem definition processes will need to be repeated as well.

What to include in the modeling process is discretionary. For example, the modeling process does not have to include all of the causal loops developed throughout the modeling process. The number of loops to model and analyze depends upon the benefit that can be gained from including them. The modeler must decide if the insights or benefits gained from additional modeling will outweigh the cost or time of additional modeling. If the benefits do not outweigh the costs, the modeler should stop the modeling exercise.
SECTION 4 PROBLEM DEFINITION

This section describes how the problem definition was developed for this thesis. Since the goal of this thesis was to identify cost reductions within the aerospace supply chain, this modeling effort relies upon a case study of AEM. The framework or mental model for this system is based upon interviews with AEM's Manager of Procurement Engineering/Supplier Quality Assurance and other AEM personnel. Based upon these discussions, it became apparent that supply chain costs at AEM are largely a function of manufacturability. Consequently, the problem was defined in this section by two questions:

- What can AEM do to ensure that manufacturability is considered in the design process? and
- How can AEM reduce the costs associated with outsourcing?

In later sections this problem definition is revisited and refined.
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Defining the Problem

The problem definition phase is designed to narrow the scope of the problem into something that can be solved in the time period available. Without this focus, the system dynamics process can become overly complex.

Variables

The problem definition phase begins by outlining the key problem variables. To understand what these variables are, the modeler draws upon the experience of the system insiders, which in this case is AEM, to create a list of variables important to the system under review. Table 4-1 contains a list of variables, which AEM identified as having an impact on supply chain costs. Two things become immediately apparent from this list. First, these variables have little relationship to contract negotiation and market prices, the two areas which procurement is typically involved. This implies that to achieve cost reductions, procurement will need to step outside its historical boundaries. Second, suppliers have very little control over many of these variables. In fact, AEM has control over many of the factors listed, such as manufacturability and trust. Therefore, the biggest determinant of AEM's supply chain costs may be its supply chain management.
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**LIST OF VARIABLES**

<table>
<thead>
<tr>
<th><strong>Manufacturability</strong></th>
<th><strong>Supplier Process Fit</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard parts</td>
<td>Match batch size to takt time</td>
</tr>
<tr>
<td>Commonality</td>
<td>Match batch size to demand schedule</td>
</tr>
<tr>
<td>One part fits all</td>
<td>Match batch size to carrying cost</td>
</tr>
<tr>
<td>Commonality of specifications</td>
<td>Product mix</td>
</tr>
<tr>
<td>Design for manufacturability and assembly (DFM/DFA)</td>
<td>Economies of scale</td>
</tr>
<tr>
<td>Integrated product/process team (IPT)</td>
<td></td>
</tr>
<tr>
<td>Develop conjoint design standard</td>
<td></td>
</tr>
<tr>
<td>Standard drawing definition</td>
<td></td>
</tr>
<tr>
<td>IPT effect on other part</td>
<td></td>
</tr>
<tr>
<td>Level of part dependence</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Level of Trust in Customer</strong></th>
<th><strong>Ability to Innovate</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Trust</td>
<td>Technical capability</td>
</tr>
<tr>
<td>Level of prime investments</td>
<td>Continuous improvement mindset</td>
</tr>
<tr>
<td>Sole supplier status/dual supplier partnering</td>
<td>Opportunistic</td>
</tr>
<tr>
<td>Don't want 100% dependency on one supplier</td>
<td>Adaptability</td>
</tr>
<tr>
<td>Risk of switching</td>
<td>Technical competency</td>
</tr>
<tr>
<td>Dependability on supplier</td>
<td>Process maturity</td>
</tr>
<tr>
<td>Responsiveness of customer</td>
<td>Exposure to innovation of clients</td>
</tr>
<tr>
<td></td>
<td>Asset specificity</td>
</tr>
<tr>
<td></td>
<td>Ability to disclose of innovation or application to other customers</td>
</tr>
<tr>
<td></td>
<td>Ability to imitate and simplify innovation of others</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Level of Trust in Supplier</strong></th>
<th><strong>Financial Position</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Trust</td>
<td>Initial cash outlay</td>
</tr>
<tr>
<td>Level of supplier investments</td>
<td>Financial stability prior to commitment</td>
</tr>
<tr>
<td>Freedom from engineering source approval</td>
<td>Return on sales</td>
</tr>
<tr>
<td>Freedom to use own tools machines inspection techniques</td>
<td>Return on investment</td>
</tr>
<tr>
<td>Process ownership</td>
<td>Return on capital outlay</td>
</tr>
<tr>
<td>Responsiveness of supplier</td>
<td></td>
</tr>
</tbody>
</table>
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<table>
<thead>
<tr>
<th>Supplier Direct Costs</th>
<th>Quality Controls</th>
</tr>
</thead>
<tbody>
<tr>
<td>Labor rates</td>
<td>Operation sheets with inspections built in</td>
</tr>
<tr>
<td>Line rate</td>
<td>First article inspections</td>
</tr>
<tr>
<td>Tax burden, local, state, federal</td>
<td>Post substantiation design changes</td>
</tr>
<tr>
<td>Tooling</td>
<td>Availability raw materials</td>
</tr>
<tr>
<td>Setup times</td>
<td>Choice of raw materials</td>
</tr>
<tr>
<td>Scrap</td>
<td>Sub-tier suppliers</td>
</tr>
<tr>
<td>Rework</td>
<td>Proximity</td>
</tr>
<tr>
<td>Quality dispositioning</td>
<td>Geographic location</td>
</tr>
<tr>
<td>Spare part sales</td>
<td>Inventory</td>
</tr>
<tr>
<td>Component repair</td>
<td>Delivery to point of use</td>
</tr>
<tr>
<td></td>
<td>Payment on time</td>
</tr>
<tr>
<td></td>
<td>Reduction of testing</td>
</tr>
<tr>
<td></td>
<td>Incoming inspection</td>
</tr>
<tr>
<td></td>
<td>Drawing validation after first article inspection</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Supplier Uncertainty</th>
<th>Level of Quality</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volatility of customer market</td>
<td>Quality</td>
</tr>
<tr>
<td>Awareness of customer's demand forecasts</td>
<td></td>
</tr>
<tr>
<td>Risk</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Level of Bureaucracy</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level bureaucracy suppliers and prime</td>
<td>Regulations</td>
</tr>
<tr>
<td>Single point contact with authority</td>
<td></td>
</tr>
</tbody>
</table>

Table 4-1 List of Variables (Bharath, and AEM supplier development staff member)

To simplify the process further, AEM participants were asked to choose the variables that had the most impact on the process. These variables are listed in Table 4-2. Note that there is some correlation between the variables. Manufacturability, product fit with supplier product mix, and IPT technical capability all hint at AEM's ability to design for
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manufacture. Further still, each of these variables point toward AEM's inability to integrate design requirements across functional and corporate boundaries.

---

**LIST OF MOST IMPORTANT VARIABLES**

<table>
<thead>
<tr>
<th>Manufacturability</th>
<th>Level of Quality</th>
</tr>
</thead>
<tbody>
<tr>
<td>Product Fit with Supplier Product Mix</td>
<td>Trust</td>
</tr>
<tr>
<td>IPT Technical Capability</td>
<td></td>
</tr>
</tbody>
</table>

**Table 4-2 List of Most Important Variables (Bharath, and AEM supplier development staff member)**

---

**Examples**

The interdependence between these variables becomes even more apparent from examples provided by AEM. A number of examples are provided for each variable.

<table>
<thead>
<tr>
<th>Manufacturability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressor Blades</td>
</tr>
</tbody>
</table>
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discovered prior to manufacturing. This error is also a symptom of a fundamental problem with CAD. In the past, engineering drawings were done in actual size. However, with CAD, designers and drafters can draw with the part magnified by a factor of 10 or more. As a result, the drafters often lose their intuitive feel for the part size. In this enlarged scale, the part looks large enough to accommodate the serial number identification.

**CAD Errors**

Other examples of the CAD leading to manufacturability issues include compressor blade design. These parts are relatively small. As a result, the draftsman performs much of the design work magnified by a factor of 10. CAD allows the drawing of continuous curved surfaces, yet many of the manufacturing processes are not capable of producing these continuous curved surfaces. The designer has to design the part with a stepped surface that approximates the desired shape. In this magnified view, the steps visually appear very large. Therefore, the draftsman often uses a step size, which is smaller than the manufacturing equipment is really capable of producing. When the supplier receives the specification, they are often pressured to push forward and manufacture the part despite the process capability. During inspection, these parts are then identified as defects because they do not conform to specification. When in fact, the part has very little variation and the specification is wrong. The error is then attributed to manufacturing rather than design.

A similar error can occur when designing large parts. Designers will draw specifications in a view that has been reduced by a factor of 10 or 1/10\(^{th}\) actual size. In this scale small variations are minimized. As a result, the designer may not notice these variations. If left unchecked, these variations may cause dynamic problems and fail testing.

These errors are often perpetuated because drafting does not receive feedback about these errors.

**Casting Supplier Involvement**

AEM embarked upon a new engine development program with a focus on reducing engine production costs. As a
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means of reducing costs, many external components were incorporated into the internal structure of the engine. As a result, the diameter of the engine began to grow beyond the size originally discussed with suppliers. It was not until the design was completed, that the design team realized that the supplier could not manufacture the engine because it was too large. As a result, the supplier was forced to modify its production equipment to meet the requirements of the new design. These modifications increased the cost of the design. In this case the supplier was able to modify its process. However, such an error could have brought the engine development process to a halt and could have required a complete engine redesign.

<table>
<thead>
<tr>
<th>Quality</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-standard Tolerances</td>
</tr>
<tr>
<td>Parts are designed using a standard set of tolerances. However, sometimes on small parts these tolerances cannot be met. Drafting needs to exercise discretion. However, when using CAD in the magnified 10x view, the drafter loses the intuitive feel for the part and does not realize the non-standard tolerances should be used. When production begins, AEM's internal manufacturing group or its suppliers cannot meet the specified tolerances at normal yield rates. As a result, the low yield triggers rework and non-conformance tracking.</td>
</tr>
<tr>
<td>Squirrel Cage Design - Lessons Learned Not Captured</td>
</tr>
<tr>
<td>One particular squirrel cage design was the source of many manufacturability problems. As a result, the squirrel cage was later redesigned. However, on subsequent engine designs this same problematic design was used and implemented. Designers had to revise these subsequent squirrel cage designs after the production process began.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>IPT Technical Capability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drafting Not Involved</td>
</tr>
<tr>
<td>Drafting is often overlooked in the IPT process until a concept has been finalized. Once the concept is finalized, drafting is asked to participate in the process mostly to provide input about lead-time required for drafting. However, drafting has the best understanding of how parts translate from two dimensions to three dimensions. As a result, drafting can often identify concepts that will not work</td>
</tr>
</tbody>
</table>

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<table>
<thead>
<tr>
<th>Section</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manufacturing Department and Suppliers Not Directly Involved in IPT Process</td>
<td>Prior to being fully designed. Furthermore, drafting is exposed to the widest variety of projects. Each drafter works on 5-10 projects at a time whereas a designer might only work on 2-3. This knowledge is not being utilized in the IPT process. Advanced manufacturing is often used as a surrogate for manufacturing and suppliers in the IPT process. Although advanced manufacturing creates the initial design and has a broad understanding of the manufacturing process capabilities, it is not aware of the detailed process capabilities needed for detailed design. AEM's internal manufacturing group does not have time to participate in the IPT process. The group currently operates 24 hours a day, 5 days a week. The production process is operating near full capacity. As a result, manufacturing cannot leave the production floor to participate in the IPT process.</td>
</tr>
<tr>
<td>Suppliers</td>
<td>Suppliers are not involved in the production process for a number of reasons, such as inability to complete contractual confidentiality agreements in the design phase. As a result, advanced manufacturing is required to serve as a surrogate for AEM's internal manufacturing and suppliers in the IPT process.</td>
</tr>
<tr>
<td>Cost Engineering Unable to Participate in IPT Process due to Time Pressures</td>
<td>While this group used to be heavily involved in the manufacturing process, it is now mostly involved in concept development. Because manufacturing processes have changed over the years, this group does not represent manufacturing very well in the IPT process. Cost engineering consists of no more than ten people. This staff is responsible for preparing cost estimates on all of the components designed at AEM. They are invited to attend a number of IPTs. However, there are so many IPTs that cost engineering cannot attend them all. Even if they could attend, they would not have time to prepare. As a result, much of the IPT process is conducted without involvement of cost engineering. Consequently, designs are developed without feedback about costs.</td>
</tr>
</tbody>
</table>

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<table>
<thead>
<tr>
<th>Product Fit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Customized Tab Washers</td>
</tr>
</tbody>
</table>

| Trust |
| Suppliers are not Willing to Provide Information due to Confidentiality Issues | Suppliers do not want to participate in the IPT process for confidentiality reasons. Suppliers are often still bidding against competitors in the concept development phase and even in the detailed design phase. As a result, many suppliers fear that participating in the IPT process will reveal competitive information. Moreover, many suppliers fear that AEM will take cost reduction ideas and use another supplier with a lower labor rate. Due to these issues, many suppliers do not want to participate in the IPT process until an agreement is signed. Yet, AEM does not want to sign an agreement for fear of supplier gouging. |

Table 4-3 Examples of Cost Drivers (Bharath) (Bharath, et. al)

These examples show that AEM is creating product/component designs, which are difficult to manufacture. As a result, these designs cost more to manufacture. Even though AEM does not incur these costs directly, these costs are passed on from the suppliers in the form of increased prices. Furthermore, the price increases do not reflect the full cost of designs, which are difficult to manufacture. These problems are often
initially identified as nonconformance issues rather than manufacturability issues. As a result, the cost of nonconformance tracking increases. AEM implemented the IPT process to force designers to consider manufacturability in the design process. However, these examples demonstrate that the IPT process is often bypassed. In addition, AEM has implemented a number of tools to increase productivity. Yet, these tools have shortcomings, which cause manufacturability problems that the IPT process has been unable to correct.

Reference Modes

Based on discussions with AEM, reference modes are shown for each of the important variables in Figure 4-1 through Figure 4-11. The reference modes do not have any units specified because they are just shown to indicate trends of overall behavior. These reference modes are based entirely on the perceptions of AEM personnel rather than hard data. However, hard data ultimately influences these perceptions.
The first two reference modes are related to manufacturability. The first reference mode, Figure 4-1, is a graph of manufacturability that shows it has been increasing slightly over time. However, AEM hopes to increase manufacturability significantly over time and fears that it will decrease significantly.

Figure 4-1 Reference Mode: Manufacturability Versus Time (Bharath, and AEM supplier development staff member)

Figure 4-2 shows the hopes and fears regarding the use of standardized parts. The level of standardized parts is a metric of manufacturability, so it is not surprising that this reference mode has the same overall shape as manufacturability.
Figure 4-2 Reference Mode: Parts Standardization Versus Time (Bharath, and AEM supplier development staff member)

Figure 4-3 and Figure 4-4 describe the reference modes for enterprise level costs. The first reference mode is the cost associated with outsourcing and the second is the supplier price charged. These curves are similar because supplier price dominates the cost associated with outsourcing. Both of these graphs show that AEM's costs have been rising over time. In addition, these graphs show AEM's hope that their costs/supplier prices will fall over time and fear that their costs/supplier prices will rise over time. It is interesting to note the inverse correlation with manufacturability. AEM hopes that manufacturability increases while costs/supplier prices fall. This lends circumstantial evidence to support the idea that manufacturability drives costs.
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Figure 4-3 Reference Mode: Costs Associated with Suppliers Versus Time (Bharath, and AEM supplier development staff member)

Figure 4-4 Reference Mode: Supplier Prices Charged Versus Time (Bharath, and AEM supplier development staff member)

The next set of graphs, Figure 4-5, Figure 4-6, and Figure 4-7, represent AEM's hopes and fears regarding several specific process improvements: Quality, IPT Technical
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Capability, and Supplier Technical Capability. These improvements are somewhat correlated; thus, the reference modes for each are similar. Quality, IPT Technical Capability, and Supplier Technical Capability have all been rising and are expected to increase in the future. The hope is that they will increase significantly and the fear is that they will increase only slightly.

Figure 4-5 Reference Mode: Quality Versus Time (Bharath, and AEM supplier development staff member)
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Figure 4-6 Reference Mode: IPT Technical Capability Versus Time (Bharath, and AEM supplier development staff member)

Figure 4-7 Reference Mode: Supplier Technical Capability Versus Time (Bharath, and AEM supplier development staff member)
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However, on a more general level the hopes and fears for process improvements are more pessimistic. The reference mode shows that processes have improved very little over time. AEM hopes that significant improvements will be made over time but fears that the level of improvements will decline over time.

![Continuous Improvement Versus Time](image)

**Figure 4-8 Reference Mode: Continuous Improvement Versus Time (Bharath, and AEM supplier development staff member)**

Figure 4-9 and Figure 4-10 describe AEM's hopes and fears about their suppliers. Figure 4-9 shows AEM's suppliers becoming more diversified over time. AEM fears that this will reduce its leverage over the suppliers because the suppliers will be less dependent on AEM and the aerospace market in general. The decreasing demand of the market, industry downsizing, and erosion of profit margins only stimulate fears that supplier
product mix will increase over time. AEM still remains hopeful that product mix will decrease. This graph is somewhat contradictory with Figure 4-7, which shows supplier technical capability increasing over time. Although it may just indicate that specialization on a particular product within an industry may not be as important to improving technical capability as specializing in a particular product across industries.

![Supplier Product Mix Versus Time](image)

**Figure 4-9 Reference Mode: Supplier Product Mix Versus Time (Bharath, and AEM supplier development staff member)**

Figure 4-10 describes AEM's relationship with suppliers. In the past, AEM's supplier relationship has been very adversarial. Suppliers have historically not been very trustful of AEM due to past experience. However, AEM hopes to build trust with its suppliers over time in order to increase supplier involvement and improve manufacturability.
However, AEM fears that its past supplier interactions will bias the suppliers' perceptions and AEM will not be able to gain their trust.

![Trust Versus Time](image)

**Figure 4-10 Reference Mode: Trust Versus Time (Bharath, and AEM supplier development staff member)**

The final reference mode, Figure 4-11, shows the hopes and fears for cost on a project level rather than an enterprise level. This graph is largely based on historical project data. The hope is represented by the target cost. Estimated cost and the supplier quote represent AEM's fears. This reference mode is an attempt to describe the phases of a design. At the start of the project the cost goal is always less than the initial cost estimate to manufacture the engine. As the project continues, the estimated engine costs rise. Upon the completion of the design process, suppliers begin to provide quotes for the manufacturing cost. These costs are inevitably higher than the estimated engine cost. As
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the manufacturing process matures, suppliers begin to achieve economies of scale and the product cost falls to the target level.

![Cost Over Product Life](image)

Figure 4-11 Reference Mode: Cost Over Product Life (Bharath, et al.)

**Problem Statement**

Based on the list of variables, examples and reference modes, the initial problem statement was as follows:

- What can AEM do to ensure that manufacturability is considered in the design process? and
- How can AEM reduce the costs associated with outsourcing?
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However, the problem statement is not a static in system dynamics, it evolves as the modeling process evolves. During the course of the modeling process, these questions lead to new questions and a new problem statement. The problem statement evolved to the following:

- What skews the product design and development process toward performance?
  and

- How can the product design and development process be changed to focus on costs?

The evolution of this problem statement is described in the sections that follow.
SECTION 5 DYNAMIC HYPOTHESES

This section elaborates upon the framework described in Section 4 by describing how each of the variables interrelates. These interconnections are organized to provide a mental model of the process or an initial set of causal loops. Although this section provides a detailed mental model of the design and acquisition process, it is too detailed. This section describes the author's initial attempts to simplify the causal loops and to model these loops. Initially, the author attempted to simplify the causal loops by compressing causal connections and by focusing on a subset of the causal loops. Since many of the loops describe the impact of CAD on manufacturability, the author decided just to focus on these loops. His initial hypothesis was that lack of feedback about CAD errors leads to manufacturability problems and increasing costs.

After translating this initial set of causal loops into a mathematical model, the author realized that the modeling effort was futile because the causal loops were still too detailed. In addition, he learns that his effort to simplify by focusing on a subset of causal loops led to the development of a model that was trivial and unimportant. While the use of CAD does have an impact on manufacturability, it does not explain AEM's widespread difficulty in implementing design for manufacturability (DFM). Instead, the lack of feedback about CAD errors is an example of AEM's inability to implement DFM. In this
section it becomes apparent that the modeling framework needs to be more abstract to yield insight. Even though the model discussed in this section does not effectively characterize the problem of reducing costs in the aerospace supply chain, it yields one major insight that set the tone for the remainder of the thesis: the design process is time constrained. Moreover, this time constraint precludes designers from pursuing cost reductions.

While many of the loops discussed in this section are ultimately revised, the entire development process is included in this thesis to demonstrate how the modeling process evolved from a very detailed form to a more abstract form. Furthermore, this iterative process was included to illustrate the problems that a newcomer to the field of system dynamics often faces. To be proficient at system dynamics involves striking a balance between model simplicity and model realism/complexity. If this balance is not carefully thought through, the modeler can head down a path that will not provide any useful insights. For the newcomer to system dynamics, failure to gain insight can lead to disillusionment and abandonment of system dynamics as a tool. By examining the mistakes made in this section, others can avoid making the same mistakes themselves.
Initial Causal Loops

The initial causal loops were developed in a "stream of consciousness manner." System insiders at AEM would elaborate upon a causal loop as it became apparent to them. These loops were developed largely through interviews with Keppel Bharath. However, the impetus for identifying these loops was due to interviews with other AEM personnel. The initial causal loops are presented in the order in which they were identified.

Concurrent Engineering Loops

The first set of loops identified is the concurrent engineering loops. These loops represent how industry pressures to reduce cycle time have lead to the use of concurrent engineering. Concurrent engineering means structuring the product design and development process so that design, testing, and manufacturing ramp-up tasks are performed concurrently rather than sequentially.
There are two different concurrent engineering loops. The first loop, shown in Figure 5-1, is negative. This loop illustrates that pressure to reduce cycle time increases the use of concurrent engineering. Increasing concurrent engineering reduces cycle time which indirectly reduces holding costs and total acquisition costs. As acquisition costs fall less pressure is exerted to reduce costs and cycle time because goals have effectively been met.

Figure 5-1 Concurrent Engineering Loop - Impact on AEM Holding Cost
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The complimentary form of this causal loop demonstrates the impact of concurrent engineering on suppliers. As depicted in Figure 5-2, the pressure to reduce cycle time, increases the use of concurrent engineering, and decreases manufacturing cycle time. Consequently, supplier holding costs and total supplier costs decrease leading to increased supplier margins. As supplier margins increase, the customer exerts additional pressure to lower supplier prices. Lower prices decrease acquisition costs and reduce cycle time pressure.

Figure 5-2 Concurrent Engineering Loop - Impact on Supplier Price
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**CAD Impact on Tolerance Loop**

The use of concurrent engineering has stimulated the use of computer-aided design (CAD) and computer aided manufacturing (CAM) to improve design productivity. However, CAD has a few pitfalls that are not fully realized. The CAD Impact on Tolerance Loop describes the design errors that can result from using CAD. Specific examples of these errors are described in Table 4-3. CAD has gained widespread use as a means to improve productivity and aid in the use of concurrent engineering. These tools allow designers to share drawings electronically. In addition, three-dimensional representations of the designs can be made. However, these tools are not mature and have a few undiscovered error modes.

One of the error modes results from creating designs in a scale other than one to one. Traditionally, engine designs were drafted using a one to one scale. CAD allows the draftsperson to create the design in whatever scale is convenient. The draftsperson will draw large parts in a reduced view and small parts in an enlarged view. By moving away from this one to one scale, the draftsperson loses the intuitive feel, or dimensional perspective, for part size. This loss of dimensional perspective can lead to tolerances, which are difficult to manufacture, as described in Table 4-3.
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By not having enough tolerance, the manufacturing cycle time increases due to the additional controls needed to manufacture the parts and the rework needed to meet these tolerances. This creates additional pressure to compress the design process and further reliance on CAD. This phenomenon is represented by a positive causal loop shown in Figure 5-3.

Figure 5-3 CAD Impact on Tolerance - Dimensional Perspective
CAD Impact on Use of Standard Parts Loops

Another unanticipated side effect of increased CAD use is the impact on standard parts usage. CAD offers the designer/draftsperson much greater precision than in the past. In the past, the designer was forced to use another design as a starting point because of the time-savings associated with using a standard design. By using standard parts, a smaller portion of the design needed to be reinvented. However, with CAD using standard designs does not greatly simplify the design process. As a result, designs are completed from scratch rather than using a standard design. In addition, with CAD a draftsperson can create a design to any dimension desired.

By using nonstandard parts, suppliers must retool the manufacturing process to make the design, which increases the manufacturing cycle time, increases supplier costs, and increases total acquisition costs, as shown in Figure 5-4.
Furthermore, as parts become more specialized fewer suppliers are willing to custom manufacture the part. As a result, cycle time is then dictated by the supplier's availability, which slows the manufacturing cycle time increasing supplier costs and total acquisition cost.
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costs. Rising costs create more pressure to reduce the total design cycle time causing further reliance on CAD as depicted by the positive loop in Figure 5-5.

Figure 5-5 CAD Impact on the Use of Standard Parts - Supplier Capability
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**Design Cost Loop**

With all of the undesired effects of CAD/CAM shown in the loops so far, it is not apparent why CAD/CAM was implemented. The negative loop shown in Figure 5-6 indicates that CAD/CAM has been implemented because it tremendously reduces the design cycle time and design costs. As cycle time and design costs are reduced, pressure to compress the design process decreases.

![Figure 5-6 Design Cost Loop](image_url)
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**Standard Parts Cost Loop**

In addition to CAD use, design costs are driven by the use of standard parts. As illustrated in Figure 5-7, the use of standard parts reduces the design cycle time because not as much new design work is involved. Moreover, having less design work translates into fewer labor hours spent designing. As a result, design costs are reduced which in turn reduces pressure to compress the design cycle.

![Diagram of Standard Parts Cost Loop]

Figure 5-7 Standard Parts Cost Loop

**DFM/DFA Policy Impact Loops**

All of the loops presented to this point allude to the importance of design for manufacturability (DFM) and design for assembly (DFA). Five negative loops are used to document the importance of DFM/DFA in counterbalancing the increasing acquisition
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costs experienced in the aerospace industry. In other words, these loops describe AEM's reasons for trying to implement DFM/DFA.

AEM believes that implementing DFM/DFA will increase the pressure to create conservative designs. These conservative designs have wider tolerance bands, greater use of standard parts, and more standard material properties, making them easier to manufacture. As manufacturability increases, manufacturing cycle time decreases and so does acquisition cost. In addition, the use of standard parts and materials increases the number of suppliers capable of manufacturing the components, decreases manufacturing cycle time, and decreases acquisition cost. As cost decreases, the pressure for using DFM/DFA decreases. The impact of DFM on tolerance is shown in Figure 5-8, while the impact of DFM on standard parts usage is shown in Figure 5-9 and Figure 5-10, and the impact of DFM on material properties is shown in Figure 5-11 and Figure 5-12.
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Figure 5-8 DFM/DFA Policy Impact - Tolerance
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Figure 5-9 DFM/DFA Policy Impact - Standard Parts Use on Cycle Time
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Figure 5-10 DFM/DFA Policy Impact - Standard Parts on Supplier Capability
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Figure 5-11 DFM/DFA Policy Impact - Material Properties on Cycle Time
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Figure 5-12 DFM/DFA Policy Impact - Material Properties on Supplier Capability

**Cost Tool Loop**

Although not included in the DFM/DFA Policy Impact Loops, the cost tool loop is closely related. The cost tool loop is a specific measure or solution proposed by AEM to increase the use of DFM. As such, this loop is designed to counterbalance the increasing acquisition costs just like the DFM/DFA policy is as a whole. The only difference being that as the pressure for DFM/DFA increases, so does the need for cost tools. Cost tools
are tools, which provide feedback to the designer about the cost of a particular design. As feedback increases designers' knowledge about cost, pressure for a conservative design increases. The remainder of the loop, shown in Figure 5-13, is identical to that shown for the DFM/DFA policy impact loop.

Figure 5-13 Cost Tool Loop
Product Fit Loops

The product fit loops were developed to explain the benefit of creating designs that closely match the supplier's capabilities. Like the cost tools loop, the product fit loops are essentially specific implementations of DFM/DFA. Figure 5-14 illustrates the impact of product fit on implementation of DFM/DFA. In this loop, as products more closely match the supplier's capabilities, or product fit increases, prices decrease due to economies of scale. These economies of scale lead to lower acquisition costs and less pressure to implement DFM/DFA. Therefore, fewer standard parts are used and product fit declines. In other words, this negative loop characterizes why companies try to increase product fit when faced with rising acquisition costs.
Figure 5-14 Product Fit - Impact on DFM/DFA
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The remaining product fit loop outlines the effect of product fit on pricing. As acquisition costs rise, so does customer pricing. Due to the competitive pressure in the industry, AEM tries to counter price increases by increasing product fit. As with the other product fit loop, Figure 5-15 illustrates that increasing product fit decreases acquisition cost.

![Diagram of Supplier Margins, Supplier's Price Charged, Total Acquisition Cost, Product Fit, Customer Price, and Variable Costs vs Fixed Costs]

Figure 5-15 Product Fit - Impact on Price

Tolerance Cost Loops

Loops shown previously document the indirect impact of tolerance on cost due to its impact on cycle time, but tolerance has a more direct effect on cost, which is portrayed by
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the Tolerance Cost Loops. In these loops large tolerances represent material that is wasted. As waste increases so does the total cost of waste. These costs have both reinforcing and balancing effects.

In the first loop, the additional cost of waste leads to an overall increase in the acquisition cost and additional pressure for DFM and DFA. The pressure for DFM/DFA leads to more conservative designs, wider tolerance bands, more waste, and additional cost. Figure 5-16 illustrates this reinforcing effect.

Figure 5-16 Tolerance Cost - Influence on DFM/DFA
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This reinforcing loop is balanced by the loop shown in Figure 5-17. As with the other tolerance cost loop, this balancing loop indicates that as tolerance increases, waste increases, and the cost associated with waste increases. However, this new tolerance cost loop indicates that rising waste costs lead to pressure for a less conservative design with tighter tolerances.

Figure 5-17 Tolerance Cost - Influence on Design Conservatism

In actuality, these loops probably have a negligible impact because the cost of waste is small compared to other costs within the system. As a result, little effort is made to reduce this cost.
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**Performance Pressure Loops**

The performance pressure loops are designed to show the interplay between a number of manufacturability metrics and engine performance. In particular, these loops explain that as tolerance decreases, material properties increase, and integrality of design increases, engine performance increases. These increases lead to increases in customer/user satisfaction resulting in less pressure to improve performance and more pressure to create a conservative design. As designs become more conservative, tolerance increases, material properties decrease, and integrality of design decreases, as shown in Figure 5-18, Figure 5-19, and Figure 5-20, respectively.

![Diagram of Performance Pressure Loops](image)

*Figure 5-18 Tolerance Impact on Performance*
These loops balance the pressure toward ever increasing engine performance caused by competitive pressures. For example, as engine performance increases, so does market
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share. Competitors then respond by improving their performance, creating additional pressure to improve engine performance. While Figure 5-21 only shows the impact of this competitive pressure with respect to tolerance, similar loops could be shown for material properties and integrality of design.

![Figure 5-21 Competitive Pressure Impact on Tolerance](image)

The integrality of design has yet another balancing effect on the system and, in particular, on the use of DFM/DFA. As the design becomes more integral rather than modular, the use of standard parts decreases. As a result, manufacturing cycle time and total acquisition cost increase causing additional pressure to use DFM/DFA. In general, this
pressure to use DFM/DFA leads to a more conservative modular design, or in other words, a design that is less integral. Figure 5-22 details the negative nature of this loop.

![Figure 5-22 Integrality of Design - Impact on Standard Parts](image)
**Quality Loops**

Six causal loops were developed to represent the impact of quality. The first loop is a more detailed specification of the CAD Impact on Tolerance Loop. The difference between the two loops is that the relationship between tolerance and cycle time is explained in greater detail. In this new loop, Figure 5-23, tighter tolerances result in parts which are more difficult to manufacture. Consequently, the number of off-spec parts increases and measured quality decreases. As quality decreases, cycle time increases and acquisition costs increase leading to more pressure to cut design costs and design cycle time. Pressure to speed design leads to further reliance on CAD and tighter tolerances.
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Figure 5-23 Impact of CAD on Quality
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The next two quality loops outline the reinforcing aspect of quality improvement. As quality improves, staff availability increases allowing quality staff to exert pressure on the designers to create conservative design specifications in terms of manufacturability. This pressure leads to wider tolerances and improved quality, as illustrated in Figure 5-24.

![Figure 5-24 Quality Staff Influence on Design - Level of Involvement](image-url)
A similar reinforcing effect, Figure 5-25, is also caused by this increased availability of quality staff. Increasing availability allows the quality staff to get involved in the design process sooner. As a result, the quality staff is more able to influence the design.
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Still another effect is caused by the increased availability of the quality staff, Figure 5-26. With the additional time available, the quality staff can exert more pressure within the company to improve yield as evidenced by programs in the aerospace industry such as ACE or Six Sigma. These quality improvement programs lead to implementation of further quality control and better quality.

Figure 5-26 Quality Staff Influence on Quality Control Implementation

The reinforcing effect of quality is also caused by the presumed cost benefit of improving quality. As companies such as AEM embark on quality improvement programs, they track the cost of nonconformance, scrap, and rework, but fail to differentiate between the
cost of control and scrap/rework. As pressure to improve quality increases, additional controls are implemented. However, additional controls increase the cost of nonconformance tracking. Without differentiation between controls costs and scrap/rework costs, this cost increase serves as a signal to improve yield leading to implementation of further controls. The reinforcing nature of this loop is depicted in Figure 5-27.

![Figure 5-27 Quality Improvement Influence on Cost](image)

The final quality effect occurs as a result of meeting quality goals and is illustrated in Figure 5-28. As quality increases, nonconformance costs decrease resulting in decreased pressure to improve quality. The need for improving quality decreases because cost goals
have been met. As a result, fewer quality controls are implemented, more off-spec parts are produced, and quality decreases.

![Figure 5-28 Quality Goal Satisfying Behavior](image)

**IPT Capability Loops**

The IPT Capability Loops outline the effect of involving the suppliers in the design process. The first three IPT capability loops describe the impact of DFM/DFA on supplier involvement and design changes. As the pressure for DFM/DFA increases, suppliers will become more involved in the design process. Since the suppliers possess better knowledge of the manufacturing process, this involvement should lead to fewer manufacturability problems and fewer design changes. By reducing the number of design
changes, acquisition costs decrease. As acquisition costs approach desired acquisition costs, the pressure to implement DFM/DFA decreases. This behavior is represented in Figure 5-29.

The next loop is virtually identical to Figure 5-29 except that supplier involvement is divided into two components: time to involve suppliers in the design process and ability to influence design. In other words, as pressure for DFM/DFA increases, suppliers are brought into the design process earlier. In these early stages, the design has not been
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finalized and is easier to modify giving the supplier greater influence over the design. The complete specification of this loop is included in Figure 5-30.

![Figure 5-30 IPT Capability - Time to Involve Supplier](image)

Next, supplier involvement is related back to the issue of design conservatism and standard parts. As indicated in the previous discussion, suppliers are more keenly aware of their manufacturing capability and are more likely to recognize the need for a conservative design than the customer. Therefore, as their involvement increases so does pressure for conservative designs. These conservative designs lead to greater use of
standard parts, decreased cycle time, decreased acquisition cost, decreased pressure for DFM/DFA, and ultimately, decreased need for supplier involvement as depicted in Figure 5-31.

Next, the supplier involvement is traced to design costs. Increasing involvement of suppliers requires additional design time for coordination and meetings. Additional
design time translates into additional design costs. To combat rising design costs, suppliers are excluded from the design process, as portrayed in Figure 5-32.

Figure 5-32 IPT Capability - Supplier Involvement on Design Cost
Even though increasing supplier involvement increases design costs by increasing administrative functions, actual design time may be reduced due to this involvement. In this scenario, depicted in Figure 5-33, the supplier involvement loop becomes reinforcing. Increasing supplier involvement reduces the number of manufacturability problems and the number of design changes that result from these problems. Reducing design changes effectively reduces total workload and design costs.

![Figure 5-33 IPT Capability - Design Changes on Design Cost](image)

**Trust Loops**

The trust loops depict the reinforcing nature of trust and its impact on supplier involvement. The first loop, Figure 5-34, describes how to build trust by example. As the customer behaves in a more trustful manner, the supplier's trust of the customer
increases. The supplier reciprocates to demonstrate goodwill and encourage the customer's behavior. As the supplier demonstrates its trustworthiness, the customer responds again in a trustful manner and the trust building process continues.

In addition, as trust increases so does supplier involvement. The IPT Capability Loops discussed previously indicate that this supplier involvement will lead to increased manufacturability and lower costs. One mechanism to stimulate this involvement is trust. Increasing supplier involvement increases supplier influence resulting in fewer design changes. Traditionally, suppliers have used design changes as leverage to change price. Suppliers often bid low to win a contract. However, suppliers know that these contracts need to be revised as designs change and that these changes are frequent. To recoup some of their losses in the initial bid, suppliers will raise prices as design changes are
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issued. Therefore, by reducing the number of design changes, suppliers are less able to raise prices and unable to exhibit opportunistic behavior of the past. Eliminating this opportunistic behavior results in lower prices and builds trust with suppliers' customers. Increasing trust only leads to further efforts to involve suppliers as shown in Figure 5-35.
The final trust loop depicted by Figure 5-36 is virtually identical to that illustrated in Figure 5-35, except that this new trust loop also includes the effect of supplier trust on supplier involvement. In order for supplier involvement to increase, both the customer and supplier must demonstrate a level of trust.

![Figure 5-36 Trust - Supplier Trust on Supplier Involvement](image)

Customer opportunism can best be illustrated in the bidding process. The bidding process was designed to create low cost bids. It is not clear whether supplier opportunism led to the bidding process and customer opportunism or vice versa. It is a "chicken or the
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egg" situation. However, in the bidding process suppliers compete on price and capability. Suppliers are asked to submit a proposal to explain how they will manufacture a given part and to provide a cost estimate. If the contract is awarded to that supplier, the proposal is used as a scope of work. However, the bidding process is full of stories of engine manufacturers such as AEM taking an innovative proposal from one supplier and sharing it with another lower cost supplier. The engine manufacturer then awards the project to the low labor cost supplier. The engine manufacturer is able to capture both the benefit of innovation and low wage rate. However, this behavior leads to an environment of mistrust.
Customer Volume Loops

The customer volume loops describe the market pressures faced by the customer, in this case AEM. The first loop depicts pricing pressures. As prices increase so do margins. However, as margins increase, the airframer exerts pressure on AEM to reduce price. This phenomenon is represented by the negative loop Figure 5-37.

![Figure 5-37 Price versus Margin](image)

Another competitive loop is derived from the basic theories of economics. This loop, Figure 5-38, portrays the relationship between demand and price. In the aerospace market, demand has been declining. Sales volumes or customer volume has declined proportionately. Falling volumes decrease the economies of scale and profit margins. Declining margins lead to pressure to raise prices, and increasing prices lead to decreasing demand.
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Figure 5-38 Demand Impact on Price
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This interplay between price and demand can also be observed on an individual company basis. Figure 5-39 shows that demand for an individual company's product is dependent upon its price relative to its competitors. As AEM's price increases demand decreases, effectively decreasing demand for the AEM's product or market share. Declining market share translates into lower production volumes. As volume decreases, so do economies of scale and margin. As margin falls, the prices are increased to meet profitability goals.

Figure 5-39 Customer Price Impact on Market Share

The final Customer Volume Loop, Figure 5-40, reflects the idea that the level of competition is dynamic. This loop demonstrates that as margins decline, companies exit the market. As competitors exit the market, AEM's market share and/or sales volume
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Increases. Increasing volumes lead to increased economies of scale and higher margins. As these margins become more lucrative, competitors are attracted to the market.

Figure 5-40 Economies of Scale on Competitive Market Entrants
Supplier Volume Loops

Many of the same volume pressures generated at the customer level are transferred to the suppliers. For example, the first supplier volume loop demonstrates the relationship between price and margins. As supplier prices increase, so do margins. However, as margins increase, pressure is exerted upon the supplier to reduce price, resulting in the negative loop shown in Figure 5-41.

![Supplier Margins versus Price](image)

Figure 5-41 Supplier Margins versus Price

Similar to Figure 5-38, the loop shown in Figure 5-42 portrays the relationship between demand and price. Declining demand leads to lower market volume. As a result, supplier sales volumes decline proportionately. Falling volumes decrease the economies of scale and profit margins for the supplier. Declining margins lead to supplier pressure to raise prices. Supplier price increases translate into higher acquisition costs at the
customers, such as AEM. These acquisition costs cut into customer margins forcing prices to rise. As prices rise, demand falls even further.

Figure 5-42 Demand Impact on Supplier Price
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The final Supplier Volume Loop, represented by Figure 5-43, illustrates that as supplier margins decline, supplier companies exit the market. As a result, the volume of the remaining suppliers increases. Increasing volumes lead to increased economies of scale and higher margins.

Figure 5-43 Economies of Scale on Supplier Market Entrants
Process Maturity and Investment Loops

The process maturity and investment loops describe the investment behavior of suppliers, which is driven by expected return and drives productivity improvement. The main loop in this process, portrayed by Figure 5-44, details the diminishing returns associated with productivity improvement. As a process matures, improving productivity becomes increasingly difficult. Therefore, the expected return from productivity improvement decreases, which decreases the likelihood of suppliers investing in productivity improvements.

![Figure 5-44 Process Maturity](image-url)
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However, process maturity is not the only factor that influences expected return. Trust plays a large role in investment decisions. As shown in the Trust Loops, trust generates reinforcing behavior. This same reinforcing behavior is apparent with investment due to the influence of trust on investment decisions. As trust increases between suppliers and customers, supplier investment increases. The trust building process is depicted in Figure 5-45. Note that as supplier investment increases, customer opportunism decreases. As opportunism decreases, suppliers become more willing to accept risk and increase their investment in process improvement.

![Figure 5-45 Stimulation of Investment through Trust](image-url)
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The outcome of additional supplier investment is productivity improvements, which reduce acquisition costs. These cost reduction efforts reduce customer opportunism and supplier trust of the customer. Consequently, suppliers are more willing to accept the risk associated with process investment and productivity improvement efforts. Therefore, stimulating trust should lead to more and more productivity improvements as long as the process maturity loop related to ROI does not cause investment to stagnate due to diminishing returns.

Figure 5-46 Stimulation of Productivity through Trust
System of Loops

The loops outlined in this section can be combined to form a system of loops. These loops interact with one another to generate the total system behavior. This system of loops is shown in Figure 5-47.
Initial Causal Loop Simplification

Based on a cursory review of the loops, the Customer Volume Loops, Supplier Volume Loops, and Process Maturity and Investment Loops were eliminated from consideration. While these loops have an impact on cost, they are exogenous inputs and AEM has very little ability to control these loops. Therefore, these loops had little chance of providing insight into methods of reducing costs associated with outsourcing. Since many of the remaining loops revolved around manufacturability issues caused by CAD, these CAD and manufacturability related loops were chosen as the starting points for model development. Loops unrelated to CAD or manufacturability were omitted from the mental model. In particular, the simplification process focused on the following loops:

- Design Cost Loop,
- DFM/DFA Policy Impact Loop,
- Cost Tool Loop,
- Tolerance Cost Loops, and
- IPT Capability Loops.

In this initial phase, loop simplification consisted of compressing the causal connections. For example, the causal connections between manufacturing cycle time, supplier holding costs, total supplier costs, supplier margins, and supplier price charged could be simplified to manufacturing cycle time and supplier price charged, as illustrated in Figure
5-48. Although the abstraction process discussed in section 3 was used in this initial phase, it was only used minimally.

Figure 5-48 Compressing Causal Loops
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Using this simplification process, the CAD and manufacturability loops were simplified to the system of loops shown in Figure 5-49.

![Figure 5-49 CAD Loops](image)

Once simplifying the causal loops, the model development process began. The modeling effort focused on the hypothesis that lack of feedback about CAD errors led to continued manufacturability problems. However, as the modeling process began a new hypothesis began to take form. The variable excess time was introduced during the modeling
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process to explain how drafters learned about CAD and the errors associated with using CAD. This variable represented the idea that drafters must learn tools such as CAD in their "spare time." The addition of this variable led to the hypothesis that drafters have too much work and never fully learn to use tools such as CAD because they have no spare time. The mental model was then updated to include this hypothesis as shown in Figure 5-50.

Figure 5-50 CAD Loops with Time Constraint Hypothesis
Despite this insight about the time constraints of drafters, the modeling process was stopped after translating a few loops into the dynamic model shown in Figure 5-51.

While model structure was created to represent the loops shown in Figure 5-52, a number of loops remained to be modeled, such as the Cost Tool Loop and the IPT Capability Loops. Yet, the model was growing in complexity and was not providing any real
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insight. Furthermore, the model was only demonstrating the adoption of CAD, which took place a number of years ago, and was not addressing the errors associated with CAD or the impact on manufacturability. Moreover, it seemed obvious that CAD was not responsible for AEM's inability to fully implement DFM. Instead, CAD errors are just one example of AEM's inability to implement DFM. Therefore, it was becoming clear that the modeling effort under way was futile.

Figure 5-52 Loops Captured by the Initial Model
However, the hypothesis that draftsmen have too much work led to an insight about the design process. Many examples described in Section 4 have a common theme: the design process and designers are time constrained. While this idea of time constraint was not included in any of the original causal loop development process, it became central as the modeling process evolved and is discussed in the next section. This time constraint issue was so inherent to the design process that system insiders did not mention it. Instead, it was not introduced until the modeling process required additional detail about how drafters learn new tools such as CAD. However, once the idea of time constraint was made explicit through asking questions of Why...?, time constraint can be seen as an underlying cause in most of the examples given in Table 4-3.
SECTION 6 EVOLVING THE PROBLEM STATEMENT
AND DYNAMIC HYPOTHESES

After beginning the modeling process described in Section 5, it became apparent that only a small fraction of the supplier costs were being captured in the system dynamics model. To capture a larger portion of the problem using the existing causal loops would require a tremendous modeling effort because the causal loops were too detailed to gain much intuitive insight. Consequently, this section describes how the causal loops developed in Section 5 were simplified/abstracted to a useful mental model.

Rather than focusing on a subset of the causal loops as described in Section 5, the author searched for an underlying theme. This search led to a revised framework that enabled insights and captured earlier insights about the time constraints of designers. As part of this simplification process, the problem scope was revised to the following questions:

- What skews the product design and development process toward performance?
  and

- How can the product design and development process be changed to focus on costs?
By creating this new problem scope, the author is able to abstract the causal loops into a framework that is more generalizable and useful. Three new causal loops are identified in this section as hypotheses about why AEM cannot implement cost reductions:

- **Priority Loop** - Designers' priorities are skewed away from cost reduction because they do not receive real-time feedback about costs,
- **Rework Loop** - Designers are so time constrained that they do not perform optional tasks, such as DFM or IPT meetings. As a result, design goals are not met causing rework leading to further time constraints, and
- **Productivity Loop** - Designers are unable to reduce manufacturing costs because they are not knowledgeable about manufacturing costs. As knowledge decreases, designers become less productive and are less able to achieve significant cost reductions in the time available.

Although, not explicitly mentioned as a hypothesis, the limited resources of designers is inherent to each of these causal loops.

**Simplification/Abstraction Process**

While these loops were ultimately refined, they demonstrate the importance of the simplification and abstraction process to system dynamics modeling. In system dynamics
it is easy to begin with too much complexity. Therefore, it is important that the modeler realize a particular modeling approach is futile and to identify a new approach. Without making this realization of futility, the modeler may continue the modeling process without ever achieving useful insights. The newcomer to system dynamics may even become disillusioned with the field of system dynamics.

To assist the modeler in recognizing the futility of a modeling approach, the modeler should constantly reassess the modeling framework and look for means of simplification or abstraction. When engrossed in the modeling process, the newcomer to system dynamics may be hesitant to change their framework because they have spent so much time pursuing a particular path. In addition, the newcomer may fear that changing paths will only put them behind schedule. However, the simplification and abstraction process usually reduces the total effort. Typically, the simplification and abstraction process requires some initial time investment, but it makes the modeling process so much easier going forward that it is well worth the effort.

Although discussed in much greater detail in Section 3, simplification and abstraction are really two separate processes. Decomposition is an important part of each process. The abstraction process is essentially a search for an overarching theme, while the
simplification process is the process of respecifying the causal loops based upon the overarching themes.

**Abstraction Process**

When viewing the initial causal loops at a higher level of abstraction, one aspect is very striking. A large portion of the loops focused on design for manufacturability. Consider the following loops:

- **Design Cost Loop** - clarifies the impact of using standard parts and CAD on design costs,
- **The Standard Parts Cost Loop** - describes the impact of standardized parts on reducing the manufacturing cycle time and total acquisition costs,
- **DFM/DFA Policy Impact Loop** - illustrates how design for manufacturability and assembly leads to lower acquisition costs,
- **Cost Tool Loop** - outlines a specific measure to increase DFM/DFA,
- **Product Fit Loops** - specifies how creating designs consistent with supplier capability can be used to reduce manufacturing costs,
- **Tolerance Cost Loops** - outlines the effect of tolerance on manufacturing costs,
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- Quality Loops - indicates that design influences quality and that quality influences the acquisition costs,
- IPT Capability Loops - characterizes the influence of supplier involvement on manufacturing costs, and
- Trust Loops - elaborates why suppliers act opportunistically and how this behavior influences the acquisition costs.

Not only do these loops describe the impact of manufacturability on costs but also they inherently include solutions about how to increase manufacturability, such as using standardized parts, using standardized materials, using cost tools, and expanding the IPT process. Based upon this cursory review of the causal loops and reflection upon the list of important variables, it became clear that AEM knew that it must focus on design for manufacturability to reduce costs. However, AEM had not been able to effectively implement many of these design for manufacturability techniques. This paradox suggested that the initial problem statement of how to reduce costs associated with outsourcing had been too superficial. Moreover, it implies that there is an underlying problem prohibiting the implementation of cost reduction methods, such as design for manufacturability.
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To gain additional insight into the problem, it became necessary to reevaluate the problem statement. In attempt to provide clearer focus, an intermediate problem statement was formulated as follows:

- How to implement design for manufacturability so that cost reductions could be achieved?

In an effort to further refine the problem statement, the process of abstraction was applied to the list of variables, the reference modes, the problem statement, the causal loops, and the initial modeling effort. Two themes emerged from the abstraction process: designers have many tasks to perform and time available to perform these tasks is constrained.

Consider the examples in Table 4-3 regarding IPT Technical Capability, each of these examples discussed how the IPT process was bypassed due to time constraints. This also implies that many tasks, which are not immediately critical, are skipped. In the cost estimator example, the IPT process was skipped due to their lack of time. This triggers a number of other questions, such as how do designers and other staff decide what tasks to work on and what tasks to skip?
Next, consider the remaining causal loops. Many focus on exogenous issues that were deemed irrelevant at the outset of the initial modeling process, such as Customer Volume Loops, Supplier Volume Loops, Process Maturity and Investment Loops. These loops focus on the competitive pressure of the aerospace engine market as a whole. The competitive pressures described in these loops accurately reflect industry pressures but are better suited to a problem statement that focuses on whether the market is viable in the future rather than on how to reduce costs given that AEM plans to continue in the aerospace engine market.

The Concurrent Engineering Loops reinforce the time pressure theme discussed above. At their highest level of abstraction, these loops depict how pressures to reduce costs and manufacturing cycle time have led to widespread use of concurrent engineering. As a result, designers have much less time to design parts.

The Performance Pressure Loops indicate that designers are driven to improve product performance. This pressure to improve performance drives tighter tolerances and lower manufacturability.
The final two loops were discussed in the initial modeling effort. At their highest level of abstraction, the CAD Impact on Tolerance Loop and the CAD Impact on Use of Standard Parts Loops, demonstrate that tools or processes designed to improve productivity and indirectly reduce costs may not be beneficial. In particular, these tools may have hidden failure modes or may not be fully utilized because designers do not have time to learn how to use these tools or processes.

Finally, interviews with AEM personnel indicated that designers have an inherent prioritization scheme based on the goals of the design process. These goals are as follows from most to least important:

- Schedule,
- Performance,
- Weight, and
- Cost.

Yet, at a corporate level, the goals for the products are as follows from most to least important:

- Cost,
- Performance,
- Schedule, and
- Weight.
Notice the striking difference in product and process priorities. In terms of product priorities cost is the most important; yet, cost is the least important process priority. The underlying problem is the conflict between process and product goals at an enterprise level. As a result, the final problem statement evolved to the following:

- What skews the product design and development process toward performance?

and

- How can the product design and development process be changed to focus on costs?

**Causal Loop Simplification Process**

Now that a clearer problem statement had been identified, the causal loop process became much simpler. For example, tolerance, standard parts, modularity, and materials requirements are all metrics of design for manufacturability. In addition, manufacturability can be represented in terms of unit cost and can be thought of as a task. The more design for manufacturability tasks that are performed, the lower the unit cost.
Respecification of Causal Loops

The essence of the problem can be described by three causal loops: the priority loop, the productivity loop, and the rework loop. Each of these loops is described in detail below.

Priority Loop

The priority loop, shown in Figure 6-1, represents the hypothesis that manufacturing costs have risen because designers do not receive feedback about cost. In this hypothesis designers have a variety of tasks that need to be performed for each design. Some of these tasks are optional and some are mandatory. Designers allocate their time based upon the estimated completion rate. However, the feedback about completion rate is delayed. At project initiation, designers are optimistic about achieving project goals and do not adjust this optimism until they receive feedback about the actual completion rate. Furthermore, the feedback delay is longer for cost than for other design characteristics. As a result, the estimated cost is always lower than the actual cost. Since the estimated cost is optimistic, designers do not assign a high enough priority to reducing cost and do not allocate enough time to performing cost reduction or design for manufacturability. Even though this is a balancing loop, costs spiral out of control because the feedback is so long that priority does not change to be consistent with the desired priority given the actual completion rate.
Task priority is set by a number of factors: personal priority, process priority, product priority, and contract priority. Personal priority is based upon the individual preferences of the designer. Two factors influence these preferences: probability of accountability and task familiarity. As the probability of accountability and task familiarity increase so does priority.

Process priorities describe the priorities imposed on the designer by individual project managers in the design process. These priorities are based upon the incentives of project managers. Project managers are responsible for schedule and budget. However, budgetary goals have a lot of slack. Furthermore, budgetary pressures place greater
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emphasis on immediate costs such as capital outlays rather than life cycle costs such as unit cost of production. As a result, schedule is the dominant factor. Performance is a factor largely due its impact on schedule and product perceptions. Designs that fail certification can set the project back months due to the rework. Consequently, process priority is based upon marginal benefit of completing the task and the impact of performing the task on probability of failing certification. As a result, the more performance related tasks performed the lower probability of failure. Therefore, as the estimated status increases, the process priority decreases.

Product priorities are set at a corporate level by AEM. These priorities represent AEM's corporate vision. These goals are ultimately driven by AEM's beliefs about the future. In particular, these goals are driven by AEM's expectations about demand and competition.

Finally, contract priorities are based on the contract terms with the original equipment manufacturer (OEM). The further a product is from the contract goals the stiffer the penalty. Therefore, as more tasks are estimated complete the lower the estimated contract penalties, thus the lower the priority.
These priorities then drive the allocation of design time and indirectly determine which tasks are completed and which tasks are not. As the relative priority for one type of task compared to other types of tasks increases, the amount of time allocated to that task increases. Increasing the time allocated leads to an increase in the number of these tasks completed.

**Rework Loop**

The rework loop, Figure 6-2, is a positive loop to portray the hypothesis that manufacturing costs have risen because rework has risen. The main premise of this hypothesis is that as the number of design tasks performed increases, the probability of a design failing certification or failing to meet supplier process capability requirements decreases. In other words, the more tasks performed in the design phase, such as supplier meetings and structural analysis, the lower the probability of problems in later stages such as test manufacturing or certification testing. As the number of problems decreases, the amount of rework decreases. Furthermore, reducing rework enables the designer to perform more design work.
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Figure 6-2 Rework Loop

**Productivity Loop**

The productivity loop, Figure 6-3, is a positive loop that represents the hypothesis that manufacturing costs have risen because designers are not knowledgeable about cost reductions. As more tasks of a particular type are performed, knowledge about performing that task increases, resulting in increased productivity and leading to an increase in the number of tasks performed.

Figure 6-3 Productivity Loop
System of Loops

As alluded to in the priorities loop description, these loops have some additional interaction that was not entirely specified in the priority loop. The priority loop clearly spelled out that product priorities and contract priorities are determined by estimated status.

However, personal priorities and process priorities have other drivers. For example, the personal priority is driven by expected probability of accountability and task familiarity. Although expected probability of accountability is driven by estimated status, task familiarity is not. Instead, task familiarity increases as task knowledge increases. Moreover, process priority increases with expected probability of failure and marginal benefit. Marginal benefit is quantified in terms of expected productivity. As expected productivity increases, so does marginal benefit. Furthermore, expected productivity increases as actual productivity increases. Similarly, expected probability of failure increases as actual probability of failure increases. These loops are combined to form the system of causal loops, as represented by Figure 6-4.
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Figure 6-4 Causal Loop Representation of System
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This complete set of loops influences which tasks are performed. Each task has its own set of loops. In essence the causal loop structure shown is repeated for each type of task the designer must perform. Although not explicitly shown in the system of loops, the causal loops for each type of task is related to the loops for every other type of task by the total time available to designers. Increasing the time allocated to one task decrease the time available for other tasks. Rework also has an impact on the amount of time that needs to be allocated to each type of task. Furthermore, priorities are relative; thus, increasing the priority of one task decreases the priority of another. These additional causal connections were omitted to simplify the description of the causal loops. However, each of these causal connections is included in the model outlined in Section 7.

Architectural Framework

Based upon these causal loops, an architectural framework was created for the model. The model architecture consisted of the three primary loops delineated above, plus a structure for the product design and development process. While this model was created to represent how work performed in the design phase influence product characteristics such as performance and cost, these characteristics remain with the product throughout its entire product life. As a result, the product design and development process structure was added as a means of tracking the impact of performing these tasks on cost throughout the entire product life cycle.
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The initial architectural view of the model is shown in Figure 6-5. However, this vision only illustrates the structure needed for one type of task. To represent each of the different tasks performed in the design phase, a layered structure was chosen. Each task type has an identical structure to that shown in Figure 6-5. The initial vision did not specify which design tasks to model, but did propose a number to be considered. Based on the examples, reference modes, and causal loops, a number of tasks to model were proposed:

- Backlog Completion,
- Design for Cost,
- IPT Meetings,
- Design for Thrust,
- Design for Weight,
- Tool Learning,
- Failure Mode Correction, and
- Design for Maintainability.
The initial vision for the model shows a priority loop that contains a smooth to estimate task completion rate, referred to as the estimated burn rate. A smooth is a specific stock and flow structure, in which flow is influenced by the stock itself. This inherently means the value of the stock is based on both the new value, as well as the past value. This structure is often used to represent perceptions. The smooth structure was chosen to account for the information delay that occurs between completing tasks and estimating the project status.
To trace the impact of rework during the design and development process, a stock and flow structure was created to represent the process. In the initial architectural vision the product development process was divided into four distinct phases: design, testing, manufacturing ramp-up, and product release. As a product is designed, it progresses through each of these phases. A number of tasks must be performed as the design enters these phases.

The following stocks are used to represent the pool of work to do in each phase of the product design and development process: Backlog, Work to Be Tested, Work To Do Manufacturing Ramp-Up, and Completed Designs. Two additional stocks are used to represent the rework tasks that need to be performed: Design Rework and Manufacturing Rework. The remainder of the rework loop was represented through auxiliaries. In this formulation as tasks are completed, they flow from the backlog phase to the testing phase. As the ratio of non-mandatory to mandatory tasks increases, probability of failure in the testing and manufacturing phases decreases due to the over-design that comes from performing these non-mandatory design tasks.

Similar to the computation of probability of failure, this initial architecture uses auxiliaries to compute productivity in the productivity loop. As more tasks are completed on a design, the designers become more familiar with the task and their productivity...
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improves. In the initial vision the ratio of non-mandatory to mandatory tasks is an indicator of the task familiarity. As the ratio increases so does productivity. This productivity improvement then increases the design completion rate, which influences the flow between the backlog and testing phases.

The three loops are related by their impact on priorities. These priorities are driven by perceptions about productivity and probability of failure. To capture this relationship, additional structure was included in the initial architectural vision. Smooths were also used to represent expected task productivity and expected probability of task failure in the testing and manufacturing ramp-up phases.

To demonstrate the impact of performing the individual design tasks discussed above on cost, a chain of stocks and a series of interconnected smooths were used. The chain of stocks represents the evolution of a product as production processes age. The smooths track the impact of the evolution from immature to mature products on cost and production. Early in a product life, manufacturing processes are immature and costs are high. As the product matures, the manufacturing process is refined and becomes less expensive. Production rate is a smooth of demand and changes as products are introduced and as they mature. Since cost and production rates change with introduction
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and maturing of products, the immature dilution time and the mature dilution time drive these rates of change.

This architectural vision changed as the model was constructed, but remnants of the initial architecture remain in the final model. The final model is described in the section that follows.
SECTION 7 MODEL DEVELOPMENT

This section describes how the model architecture discussed in Section 6 is translated into a system dynamics model. In addition to describing the model formulation, this section describes how the model development process was ordered to minimize complexity. The model was developed in an incremental fashion such that the feedback of each increment was minimized. Therefore, model complexity increased incrementally rather than exponentially.

In addition, this section includes a detailed description of a new model formulation, referred to as a "dual smooth." This new formulation was used in the model to take account of optimistic behavior observed at AEM. At the beginning of each new design project, project completion estimates are optimistic and this optimism only wanes after project status reports indicate that progress is behind schedule.

Model Development Approach

In addition, to deciding upon an architectural framework for model structure, another architectural decision was made up-front to create an enterprise level model rather than a project level model. The decision was made based upon the dynamic characteristics of
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the problem. Designers typically work on multiple projects simultaneously. As a result, they must allocate their time across these projects. A continuous or an enterprise model best represents this type of framework. However, a continuous model is often more difficult to develop. For example, in a project model scheduled completion time is a fixed variable; yet, in a continuous stream of projects scheduled completion time is not constant. The scheduled completion time changes as new work is introduced. The structure that the modeler would use for a continuous versus a discrete model is often different so it was important to make this decision early in the model development process.

After developing a hybrid architecture and choosing the appropriate dynamic properties to model, discrete versus continuous, the modeling process began. Rather than building the model in its entirety, the model was developed incrementally. By constructing the model in this fashion, the dynamics of the model were much easier to discern. Using the incremental approach reduces the modeler's perceived complexity of analyzing the output. The dynamic behavior starts out relatively simple and becomes more complex as model structure is added. The causes of unusual behavior are more apparent with an incremental approach because the causes of this new behavior are limited to the component most recently added. Whereas, a model created in its entirety has no limits to causes of dynamic behavior.
This incremental approach to model building was achieved by dividing the model into "chunks" or components. In the hybrid architecture proposed in Section 6, there were five major components. As shown in Figure 7-1, these components are as follows:

- Priority Loop,
- Design and Development Process,
- Cost and Production Tracking,
- Productivity Improvement, and
- Probability of Failure.

Figure 7-1 Hybrid Architecture Chunks
The order in which chunks are added to the model depends upon two factors: importance of the chunk to answering the problem statement, and complexity of the chunk. In general, the modeling process should start with the chunks that are the most important to the problem statement. However, chunks should also be added in a manner that minimizes complexity. If the chunk is too complex, the modeler will have difficulty understanding the dynamics of the system being analyzed.

To minimize complexity, this thesis uses insights from the field of system architecture. In *Principles of Design*, Nam Suh outlines principles of good architecture. One of the primary axioms is to minimize the coupling of the design. Furthermore, he states that coupled designs increase design complexity (Suh 25-54). Even though system dynamics is not a design field in the traditional sense of the word, the model development process is. In system dynamics minimizing couplings is equivalent to minimizing feedback. By eliminating the feedback between components, the cause of dynamic behavior can be more clearly defined. Once model behavior is understood for this minimum level of feedback, more detailed feedback structure can be added.

Transforming these architectural chunks into a dynamic model consisted of a seven step process as follows:
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- Create Scaled-Down Priority Loop for Two Tasks,
- Model the Phases of the Product Design and Development Process,
- Develop Cost, Production, and Revenue Tracking,
- Include Productivity Improvement Loop,
- Detail the Dynamic Nature of Priorities,
- Add IPT Tasks and Performance Tasks, and
- Develop Probability of Failure Calculation.

From this process, the model evolved to the system shown in Figure 7-2. This evolution is described below.
It is important to note that specific numbers are provided in sections 7 and 8 regarding AEM's operations. However, many of these numbers have been disguised to protect confidentiality.

**Create Scaled-Down Priority Loop for Two Tasks**

Specification of the dynamic model began with the priority chunk because it is essential to the problem statement. This loop is the embodiment of how designers allocate their time and is essential to determining what skews the product design and development process toward schedule and performance rather than cost.

Although not immediately apparent from the hybrid architecture chunks in Figure 7-1, this loop is very complex. As indicated in the causal loop development process, each designer has at least eight different design tasks to perform in the design process. Furthermore, each of these tasks is coupled because spending time on one task reduces the time available to perform other tasks.

Therefore, the initial development of this chunk was scaled-down to include only two tasks: backlog and design for cost. Backlog tasks represent the minimum number of tasks...
that must be performed to create an engine design, or in other words the required or mandatory tasks. Design for cost tasks represent the number of tasks that must be performed to reach cost targets. These design for cost tasks are optional and do not need to be performed to create an engine. By only starting with two tasks, the complexity of the model is greatly reduced because the coupling between variables is minimized.

Another simplification was made in the initial design of the priority chunk. Rather than develop an elaborate specification of priorities, the priorities were assumed to be equal for each type of task. This simplification was necessary because priority is influenced by a number of different variables. To include the effect of each of these variables would require specification of the model in its entirety greatly increasing complexity. Out of sheer convenience, only a fixed contract penalty was specified. In addition, the penalty was equivalent for each task. As the model evolved this fixed contract penalty was replaced with a variable penalty.

In the early phases of model evolution, the scaled-down priority loop consisted of two stocks: work to do and estimated status, as shown in Figure 7-3. Work to do consists of two inflows and two outflows and represents the quantity of work that needs to be performed to complete design jobs or engineering change requests (ECRs). Work to do
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Increases as design jobs are won and as engineering changes are requested. Work to do decreases as design jobs or engineering changes are completed or become obsolete.
Three separate formulations were considered for work to do: level of effort, tasks, and goal-gap. Formulating work to do in terms of level of effort means that a certain number of labor hours are required for each design job or ECR. Work to do in terms of tasks implies that a certain number of tasks need to be performed for each design job or ECR. The goal-gap formulation represents work to do as the difference between the design goal and the design at initiation of the design job. For example, AEM has a number of pre-existing engine designs that could be manufactured for $675,000 per engine. However, to meet the terms of the design contract and the company profit goals, an engine must be designed for a unit manufacturing cost of $450,000 per engine. Therefore, work to do in a goal-gap formulation is defined as the difference between the baseline value of $675,000 per engine and the target of $450,000 per engine, or a cost reduction of $225,000 per engine. Any of these formulations could be utilized for the priority allocation chunk; however, when considering the system as a whole, one formulation is better than the others are.

The level of effort formulation for work to do was discarded immediately, because of the productivity loop. In this loop, increasing knowledge leads to productivity improvements, which decreases work to do. As a result, the stock of work to do would change as productivity changed as well as with work completion. To account for this
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change would require a fundamental change to the system architecture proposed in Figure 7-1.

Next, the task formulation was considered. Since design projects are typically divided into a clear set of tasks as part of the bidding process, this approach seemed promising. However, tasks in a design project are only specified for backlog completion not for cost reduction. To use this task formulation would require an arbitrary formulation for cost tasks and an arbitrary formulation for productivity in terms of these tasks.

Finally, the goal-gap formulation was considered. Designing for cost is typically thought of as a goal. When a design job is initiated, a designer often knows how to create the design for a given level of performance. However, this baseline design may be much more expensive than the target cost specified in the design contract. The difference between the baseline and the target represents the amount of cost reduction that needs to be performed. When specifying work to do in this manner, real measures can be used. Consider the impact on productivity improvement in this formulation, productivity can be represented in terms of dollars cost reduction per worker-month. As a result, the goal-gap formulation is the best representation of work to do because this framework fits within the architectural framework shown in Figure 6-5 and uses the same methodology as encountered in the real world.
The actual quantity of work flowing into work to do is based upon the project win rate and rate of engineering change requests multiplied by the goal-gap formulation. The backlog goal-gap is defined in terms of tasks. The goal with backlog tasks is to maximize the number of tasks completed; thus, the goal-gap formulation for backlog win rate is the difference between the target and the baseline. Whereas, the goal of design for cost tasks is to minimize cost, so the goal-gap formulation of design for cost is the difference between the baseline and the target costs.

As the backlog, or mandatory tasks are performed, the designer has discretion to release the design to testing as represented by the design completion rate or continue working on the design. For each backlog task there are a specified number of optional design for cost tasks. The number of design for cost tasks per backlog task is based upon the goal-gap. If backlog is completed at a rate faster than these optional tasks, these optional tasks become obsolete because the design has already been released to a subsequent stage of the design process.

The completion rate is based upon how designers allocate their time and their productivity. Allocation is estimated by using a pre-defined algorithm, referred to as the Wood Algorithm (Ventana Systems, Inc.). In this algorithm, the designer allocates
available time to each task type based upon its priority and the effort required to complete
the tasks. The algorithm separates the assigned priority into two variables: width and
height. By splitting priority into two variables, priority essentially has a range. Width
defines the range and height represents the importance weighting in the
middle of the range. In the model, width was set to 75% of the total priority range.
Height is computed within the algorithm as the quotient of priority and width. In this
priority formulation, tasks with the greatest priority are completed first. However, since
each is defined as a priority range, different tasks may effectively have overlapping
priorities and must compete for resources.

In the scaled-down priority loop, priority is an input to the Wood Algorithm and is based
upon a fixed contract priority. As a result, effort is allocated in a manner that both tasks
are completed equally on a percentage basis. The amount of effort required to complete
each task is based upon the expected productivity and the desired completion rate.

In this phase of model development, expected productivity was held constant. As other
chunks were added to the model, expected productivity became a dynamic variable. On
the other hand, desired completion rate was a dynamic variable from start of the modeling
process. Desired completion rate represents the rate required to complete a project within
the scheduled design cycle, referred to as the desired cycle time. Since desired cycle time
represents the average time to complete a design job, the desired completion rate is equivalent to the stock of work to do divided by cycle time.

If the project is on schedule, the desired completion rate formulation is sufficient. However, if a project falls behind schedule, the completion rate will need to be accelerated so that the designer can bring the project back on schedule. The additional effort required to bring the project back on schedule depends upon the time available to bring the project back on schedule and how far behind schedule the project is. The deviation from schedule is estimated by comparing the projected or estimated status at the end of design cycle to the desired status. If estimated status is less than desired status then additional effort is allocated.

The projected or estimated status is based upon historical completion rates as well as perceptions about the future. At project initiation, the designer and project manager typically believe that the project will be completed on budget and within the scheduled or the desired cycle time. The designer only alters this perception when information shows otherwise. For example, a designer typically considers the project on schedule until a status report is issued that compares actual to scheduled progress to date. To represent the estimated completion rate, or estimated burn rate, a unique smooth formulation is
used. This formulation is referred to as a dual smooth and is discussed in more detail in the dual smooth example below.

To incorporate the belief that design projects will be completed on schedule, the estimated burn rate is a function of the actual burn rate and the estimated initial burn. Estimated initial burn represents the expectations about completion rate at project initiation. Ideally, the initial burn rate is equivalent to the desired burn rate because this is the rate required to complete the project on schedule. However, after a certain point designers will realize that they are overloaded and cannot complete the design jobs within the desired cycle time. To portray this limit to the estimated initial burn rate, a ceiling formulation is used.

The formulation for the ceiling is based upon a structure described by Hines in *Molecules of Structure Version 1.4 Building Blocks for System Dynamics Models*. In this formulation, the estimated initial burn rate is a fraction of the maximum burn rate. This fraction is a function of the ratio of desired initial burn rate to maximum burn rate. If the ratio is less than one, the fraction approximates the ratio. If the ratio exceeds one, the fraction is equivalent to one (Hines *Molecules*, 50-51).
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Dual Smooth Example

The estimated burn rate formulation uses a rather unique formulation referred to as a dual smooth. This formulation was developed as part of this thesis to represent the optimism that occurs at project initiation. To ensure that this formulation accurately reflected the behavior observed at AEM, a small model was created to test the dynamic behavior.

The test model consists of two stocks and is shown in Figure 7-4. The first stock represents work to do and the second stock depicts estimated burn rate using the dual smooth formulation. Work to do had one inflow and one outflow. The inflow for work to do represents the initiation of project work. The outflow represents the actual task completion rate and depletes the stock.
In the dual smooth structure, initial burn represents the optimistic belief that tasks will be completed at the rate required to complete the project within the desired cycle time. Each time a new project is introduced, the estimated burn is reset to account for optimism at project initiation. As project status is updated through status reports about the actual burn rate, the estimated burn rate is changed to account for the new information.

Two test inputs were used to test the behavior of the dual smooth structure: one discrete and one continuous. In the discrete example, flow into work to do is represented by a
two-project pulse. The first pulse is introduced at time zero and the second pulse is introduced at desired cycle time of 10 months. In addition, initial values are set equal to zero and actual cycle time is twice desired. Moreover, the completion rate is set to a constant value equal to the number of tasks in each pulse divided by the actual cycle time.

A simulation was then used to illustrate model behavior. As anticipated, the output in Figure 7-5 shows that after ten months the first project is only half completed. Also after ten months the work to do surges by 100 additional tasks, which represents the inflow of the second pulse.
Moreover, estimated burn rate surges as work is introduced to represent the optimism at project initiation as shown in Figure 7-6.
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Graph for Est Burn

Est Burn: Two Project Pulse

Figure 7-6 Estimated Burn in Discrete Case

In the continuous case, the win rate and the actual burn rate are both set equal to the number of tasks per project divided by the actual cycle time. These rates are then used as inputs to the estimated burn rate. Then, the initial values for each of the stocks are computed so that the model starts in equilibrium, which in this case means that all model outputs are constant.

As shown in Figure 7-7, work to do remains at a constant value of 100 tasks.
Figure 7-7 Work to Do in Continuous Case

In addition, Figure 7-8 shows that the actual burn rate is a constant value of 5 tasks/month.
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**Figure 7-8 Actual Burn Rate in Continuous Case**

In this case the initial burn is equivalent to work to do divided by desired cycle time or the desired completion rate. As with the discrete case, the actual cycle time is twice the desired cycle time. As a result, the completion rate is less than the desired completion rate. The disparity between the two values represents the optimism that occurs at project initiation. In this scenario, the optimism should skew estimated burn rate so that it is higher than the actual burn rate. As hoped, the test module emulates this behavior. Even though the completion rate has a constant value of 5 tasks/month, the estimated burn rate
shown in Figure 7-9 is 5.457 tasks/month. These simulations were then deemed sufficient to demonstrate that the dual smooth structure adequately represents the behavior observed at AEM and should be included in the model as a whole.

*Figure 7-9 Estimated Burn in Continuous Case*

The equations for the test model are include in Appendix B.
Model the Phases of the Product Design and Development Process

Next, the modeling process focused on depicting the rework loop. However, this chunk is only a partial specification of the rework loop. In the rework loop, as the number of tasks performed increases the probability of failure or rework decreases. However, this cause and effect relationship does not really hold for backlog and design for cost tasks. To include this causal relationship would require the specification of additional tasks. Due to the interrelationship between tasks, adding more tasks unnecessarily increases the complexity at this point in the modeling process. Therefore, probability of failure was held constant in this phase of the modeling process. Instead, development of this chunk focused solely on the progression of the design through the product design and development process.

For purposes of modeling, the design and development process was divided into three phases: design, test manufacturing, and certification testing. In the design phase engineers and draftsmen create drawings to represent components of an engine design. Concurrently, suppliers work on creating the manufacturing plan for these designs. Test parts are created using these manufacturing processes. These parts are then tested to ensure that they meet performance requirements set by the OEM and safety requirements of the Federal Aviation Administration (FAA). Designs that pass certification are deemed complete.
AEM uses a concurrent design and development process rather than a sequential process. As a result, the test manufacturing process begins before the design process is complete. Moreover, the testing process begins before the test manufacturing process is complete. The design process could be represented by the timeline shown in Figure 7-10.

![Figure 7-10 Timeline of the Product Design and Development Process](image)

A chain of four stocks represents the progression of the design throughout the various stages of the product design and development process. As shown in Figure 7-11, each stock represents a separate phase in the product design and development process. The progression of work from the design phase to the test-manufacturing phase was described in the previous chunk. However, this progression only represents the inflow of work into the test-manufacturing phase not the outflows.
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Figure 7-11 Phases of the Product Design and Development Process

The total outflow from the testing manufacturing phase is based on the time to complete a testing manufacturing task. This formulation inherently assumes that test-manufacturing resources are unconstrained. Therefore, no matter how much the test manufacturing work increases the completion rate increases proportionally. Since manufacturing is largely outsourced, resources are somewhat unconstrained. However, this assumption is not entirely accurate because not all manufacturing is outsourced and AEM has a limited supplier base. This assumption remained throughout the entire evolution of the model because constraints imposed by test manufacturing were not expected to yield any further insights. Furthermore, if test manufacturing constraints were important to the problem statement, many of the insights about constraints on designers would most likely apply to test manufacturing as well.
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The outflow from test manufacturing is split into two flows to represent that not all designs pass test manufacturing. Designs passing test-manufacturing progress to the testing phase, represented by the stock testing work to do. Designs that fail test manufacturing are added to a pool of failed designs. The split between passing and failing test manufacturing is dictated by the average percent failing test manufacturing. Designs that fail test manufacturing must be redesigned. Before modifying the design an engineering change request must be issued. The time to initiate an ECR drives the depletion of the stock of failed test manufacturing designs as well as the inflow of ECRs into the stock of design work to do. The formulation for rework entering work to do assumes that the design rework must be started over from scratch. In actuality, parts of the failed design are still useable and designers are able to perform rework faster than other design work because they have some experience with the design.

The formulation for the testing phase is very similar to that of the test-manufacturing phase and assumes that testing resources are unconstrained. While testing resources are typically available, this assumption is unrealistic. However, this assumption remained throughout the entire evolution of the model because constraints imposed by testing were not expected to yield any further insights. Furthermore, if test manufacturing constraints
were important to the problem statement, many of the insights about constraints on
designers would most likely apply to testing as well.

The total outflow from the testing phase is driven by the time it takes to perform the
testing process. However, this outflow is split into two flows based upon the probability
of a design failing testing. Designs that pass testing are deemed complete and released to
the production process. Designs that fail testing are flawed and flow into a pool of failed
designs. As engineering requests are initiated, these designs re-enter the design work to
do stock as rework. As with test manufacturing rework, the formulation for rework
assumes that the design must be completed from scratch.

**Develop Cost, Production, and Revenue Tracking**

The cost, production, and revenue tracking chunk, shown in Figure 7-12, was developed
to quantify the benefit of performing various types of design for cost tasks. This chunk is
not intended to depict any dynamic behavior. Yet, without this chunk the modeling
process may not be fully appreciated. By quantifying the cost benefit of performing
design for cost tasks, the value of the modeling process becomes more apparent. This
chunk quantifies the benefit in terms of metrics that managers use, such as average unit
cost and percent margin.
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Figure 7-12 Cost and Production Tracking

The cost, production, and revenue tracking chunk quantifies the benefit by tracking the progression of the design to production. As designs are completed it is released for production as a new product. Each product has production process associated with it. There are three stages in the life of a product and its production process: immaturity, maturity, and obsolescence. A stock and flow structure is used to represent this evolution. In the early stages of production, the process is immature and unrefined. As more products are produced, the production process matures and process improvements are made. In effect, the production rate drives the maturing rate. Ultimately, the
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product reaches the end of its useful life and the production process is dismantled. The rate of obsolescence is driven by the average life of a product.

Since production rate drives the rate of maturing and is an essential component of AEM's revenue, production rate is included in the model. Separate formulations for production rate were given for mature and immature products. The production rates of immature and mature engines are smooths of the demand for each engine product. The demand for immature engines is less than for mature because the market for immature products is still being developed. As the product matures the demand grows. Since changes in demand are not central to the problem statement, demand for both mature and immature products was assumed to be constant.

A stock and flow structure is used to represent the evolution of a product and its production process. Each stock represents a phase of the product life: immaturity, maturity, and obsolescence. The inflow to the chain of stocks is the rate that new products are released from the design process. The production rate drives flow from immature to mature products. In the early phases of a production process many refinements are made. This refinement process usually continues until the mature volume is exceeded. The production process continues for the life of the product. At the end of the product life, the products and production processes become obsolete.
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The benefit of performing design for cost is also traced to replacement or spare parts. After a period of time, AEM’s products need replacement either due to regular maintenance or regulations of the aircraft industry. This time period, referred to as the mean time between replacement (MTBR), drives need for replacements. The demand for replacements is equivalent to the number of units that need to be replaced divided by the desired time to fill replacement orders. The production rate is a smooth of this demand. This formulation inherently assumes that MTBR is equivalent for all engine components. In addition production rate is specified in terms of number of engines. This essentially means that in the MTBR the entire engine is replaced component by component.

Next the cost is estimated for each engine product. As backlog tasks are completed or finalized, the design is released for production. In the early stages of production the process is immature so the unit cost is equivalent to the cost reduction achieved by performing design for cost tasks subtracted from the baseline cost. This cost is then averaged as each new product is introduced. The average cost is a smooth of unit cost with an averaging period equivalent to the time to replace the entire contents of the stock of immature products or the dilution time of immature products. By making process improvements in the immature phase, the mature unit cost drops by one third. The average cost of mature products is a smooth of immature unit cost multiplied by the cost.
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reduction factor. The averaging period for mature products is equal to the time required to replace the entire contents of the stock of mature products or the dilution time for mature products. The cost of replacements is the average cost of mature and immature products smoothed over the dilution time of replacements.

The total costs incurred at AEM include production costs, labor costs, and capital costs. Production costs are estimated by multiplying the average unit cost by the production rate. These production costs accumulate in the stock total manufacturing costs. Labor costs are a function of the number of designers and their labor rate. The labor cost for testing, test manufacturing, and miscellaneous staff is endogenous and based upon the current costs at AEM. Capital costs are based upon the number of tasks performed including rework. The total outflows from testing and test manufacturing are multiplied by the capital cost associated with each task and accumulate in the stock of capital costs.

Include Productivity Improvement Loop

This chunk, shown in Figure 7-13, outlines the productivity improvement loop. In this loop, productivity is a function of task knowledge and the ambitiousness of the goals. Overall, as task knowledge increases so does productivity. The rate of change in task knowledge is driven by the time it takes for a designer to absorb available task
knowledge. In this phase of model evolution, knowledge available is a function of the
difficulty of project goals and the relative tasks complete per person. The ambitiousness
of goals is represented as the ratio of the target gap to the target. This ratio is then
compared to the ambitiousness typically encountered.
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Figure 7-13 Productivity Improvement Loop
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The relative fraction complete per person is the ratio of the actual completion rate per person to the normal completion rate per person. As the effective completion rate per person increases so does available task knowledge. As the model evolves, other factors are included which influence the knowledge available to the designer.

**Detail the Dynamic Nature of Priorities**

At this point in the model development process, the priority, productivity, and rework loops have all been at least partially specified. Therefore, the interrelationship between these loops can be developed. As shown in Figure 7-14, these loops are all interrelated by their impact on priorities.
In conducting interviews with AEM Personnel four types of priorities were identified, personal, process, product, and contract priorities. Designers then use their discretion to weight importance between process, product, and contract priorities. Personal priorities weigh the importance between different tasks. Task familiarity and probability of accountability skew this weighting. As task familiarity and probability of accountability increase, so does the weighting for that task. Task familiarity is just a surrogate for task
knowledge. Probability of accountability is influenced by the estimated fraction of tasks complete. As the fraction complete increases, the probability of accountability decreases. This fraction is the ratio of estimated status desired status.

Process priorities represent the weighting given by designers to a particular task in the product design and development process. Designers are risk averse and try to avoid creating designs that fail in later stages. In addition, designers are time constrained so they focus on the tasks that give them the "biggest bang for their buck." As a result, priority increases as the expected probability of failure and expected productivity increase.

Product priorities represent the priority given by the company for each task. These priorities are influenced by the goals of the company and represent the tradeoffs that the company wants its designers to make. Often at the beginning of the design process, trade studies are performed to estimate these tradeoffs, referred to as trade factors. These vary from project to project; thus, a surrogate measure was used to estimate these trade factors. Trade factors were calculated by estimating the priority to complete each type of task on the project. The priority for each task was divided by the target gap for each task to yield surrogate trade factors.
The terms and conditions in the design contracts also influence priorities. Design contracts have fixed penalties and variable penalties. Fixed penalties represent the penalty charged if goals are not met. Contracts also have variable penalties based upon a sliding scale, the further the project is from meeting targets the greater the penalties. AEM's contracts typically mandate schedules and levels of performance. If a project does not meet schedule, a penalty is assessed based upon the number of days behind schedule. The penalty is equivalent to 3% of the contract value for each day behind schedule.

Performance has a little more flexibility than schedule. Some performance measures are flexible others are mandatory. Rather than create a complex formulation for performance to capture all of these nuances a more generalized formulation was used. In many cases if the performance is not met, the engine cannot be delivered. As a result, the performance penalty is essentially a schedule delay. These contract terms essentially provide equal weighting to meeting performance and schedule. Then as the project falls behind schedule, the weighting changes based upon which tasks are behind schedule.

To represent this monthly delay penalty in the model, the indicated demand is multiplied by three percent. The delay is then estimated by dividing the status gap by the estimated burn rate. A base value is assigned to the delay equal to one month because it represents the marginal delay associated with falling further behind. The delay is then added to
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marginal delay to yield total delay. This delay is multiplied by the monthly penalty to estimate the total contract penalty, which is used as a surrogate for contract priority.

Add IPT Tasks and Performance Tasks

The only loop remaining to specify at this point is the remainder of the rework loop. To complete the rework loop requires the specification of probability of failure. However, backlog or design for cost tasks do not influence probability of failure. Instead, the IPT tasks and performance tasks influence probability of failure. As a result, these two tasks had to be added before including the impact of task completion on probability of failure. Incorporating these tasks does not change the dynamic structure but adds two layers to the model.
However, performing IPT tasks not only decreases the probability of failure, but also increases team knowledge and indirectly increases task knowledge. To adequately capture the impact of IPT tasks on task knowledge, some structure was added to the model, Figure 7-15. The IPT process effectively increases the designer's knowledge base by increasing the information available to the designer. Increasing IPT team size, diversity, team communication, supplier willingness to communicate, supplier proximity, or supplier knowledge increases task knowledge available to the designer. Over time designers learn this additional knowledge. As their knowledge increases so does productivity.
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Figure 7-15 Impact of IPT Tasks
IPT team size, diversity, team communication, supplier proximity are all exogenous variables. Effective supplier knowledge is a smooth of the knowledge base of the supplier and the supplier's communication of this knowledge. While supplier knowledge is exogenous, supplier willingness to communicate is not. Supplier willingness to communicate is a function of the number of confidentiality agreements signed during the design phase. As the fraction of confidentiality agreements signed in the design phase increases so does the supplier's willingness to communicate.

As a new design job is initiated, contracts must be initiated at AEM's suppliers. Suppliers often require AEM to sign confidentiality agreements. Confidentiality agreements are represented by a stock, which is depleted as the confidentiality agreements are signed and as designs are released to the testing phase. Signed confidentiality agreements are also represented by a stock, which is depleted as designs are released to testing.

**Develop Probability of Failure Calculation**

The final phase of model development completes the rework loop by incorporating the probability of failure chunk, Figure 7-16. The testing failure fraction and manufacturing failure fraction are based upon the number of tasks performed in the design phase. In particular, as the number of IPT meetings and performance tasks performed increases for
every backlog tasks the probability of failing manufacturing and testing decreases, respectively.

![Diagram of Probability of Failure Chunk]

**Figure 7-16 Probability of Failure Chunk**

As the knowledge of design IPT related tasks increases and the number of IPT related tasks completed for an individual design job increases, the probability of that design job failing test manufacturing decreases. The number of IPT related tasks completed is an indicator of probability failing test manufacturing and the impact of completing these tasks are not felt until the design reaches the test manufacturing phase. To capture this
delay and represent the probability of failing test manufacturing, a special smooth structure, referred to as a coflow (Hines, *Molecules* 36-38), is used. This formulation is referred to as a coflow, because the rate of change is driven by the flow rate of another stock. The difference between the indicated probability of failure and the existing probability of failure, represents the amount the stock should be changed based upon the most recent information. The rate of change is equal to the indicated change divided by the time for the entire contents of the testing stock to be replaced. This time period is referred to as the test manufacturing dilution time.

Testing failure fraction is also represented by a coflow. However, it uses a chain of coflows, or a cascaded coflow (Hines, *Molecules* 41-43). This chain is created to represent the delayed impact of design on testing failure fraction. An intermediate stock is created to represent the average testing failure fraction of tasks in test manufacturing. The formulation used for this is similar to that used for the test manufacturing failure fraction except that the indicated testing failure fraction is a function of the number of performance related tasks performed. The rate of change is equivalent to change in testing failure fraction divided by the dilution time. The relative number of performance related tasks is estimated by comparing the actual number of performance tasks per design to the desired performance tasks per design.
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The average testing failure fraction of tasks in the test manufacturing stock is an indicator of the testing failure fraction in the testing phase. The stock is driven by flow of designs between test manufacturing and testing. This flow is indirectly driven by the flow between design and test manufacturing.

In addition, structure was included to formulate perceived fraction failure. This perceived fraction influence process priorities. The perceived fraction failure is based upon the estimated fraction of goal met and the actual failure fraction. The time over which these perceptions change is equivalent to the time for the design to cycle through to that phase. The estimated fraction of goal met is the actual ratio non-mandatory tasks performed per mandatory tasks to the estimated ratio.
SECTION 8 SENSITIVITY ANALYSIS

In the Sensitivity Analysis section simulation results are analyzed to test the validity of the hypotheses described in Section 6 as well as test a number of policies. In actual practice, simulation is performed with the addition of each model increment to confirm that the model has been specified correctly and to minimize the complexity of the analysis. However, only the final model simulations are shown in this section to reduce the number simulations runs included in the thesis. The methodology used to analyze each phase of model development is the same as the analysis performed in this section. Therefore, showing the intermediate simulation runs would not add value to this section.

The simulation results show that as designers become time constrained cost reduction tasks are skipped because they have a low priority relative to other design tasks. Next, the sensitivity analysis is used to determine which of the dynamic hypotheses are most plausible. When examining each hypothesis, the productivity loop stands out as the most likely cause of the inability to implement DFM followed by the rework loop. Furthermore, simulation indicates that the priority hypothesis has a negligible impact on the use of DFM. In particular, simulation shows that three factors have the largest impact on implementation of DFM:

- Design resources available,
Knowledge of design resources, and
Communication of knowledge to the design staff.

It is not surprising that by alleviating the time constraint on designers, designers will perform more of these cost reduction tasks leading to lower engine costs. However, simulation did indicate something surprising about this constraint. Simulation indicates that even though increasing resources increases labor costs, these increases may be counterbalanced by reduced production costs. In other words, a slight increase in the number of full time equivalent design staff may increase profitability. Furthermore, if the simulation results are considered on a more abstract basis, the simulation suggests that additional effort spent in the early design phase leads to system cost reductions.

While this result provides insight, increasing investment in the design process may be off limits in the current corporate environment of cost control. Therefore, a more endogenous approach needs to be applied to the problem of cost reduction. Simulation indicates that practices that improve knowledge are also extremely effective at encouraging the use of design for manufacturability due to the productivity loop. Increasing knowledge improves productivity, allowing more tasks to be performed in the same amount of time. While reducing rework has a very similar effect, its impact was not as large as increasing knowledge.
Simulation showed that two proposals within AEM had very little effect on implementation of DFM: implementing real-time feedback as discussed in the priority loop and changing designer incentives. The need for real time feedback is the basis for the priority hypothesis. In this hypothesis, designers do not receive feedback about cost. Therefore, the designer assumes that the design is on budget. When the designer finally receives a cost estimate, the design is too far along to be changed. From the simulation process, the author learned that knowledge about cost was important, but that this feedback did not have to occur on a real-time basis to be effective. As long as designers received feedback about cost, they would learn and improve their designs. Real time feedback just started the learning process sooner.

In addition, the modeling process indicated that incentives in the design process are skewed so far away from cost that changing incentives had very little impact on cost. In order for changing incentives to be effective, the entire incentive structure of the design and development process needed to be overhauled.
Sensitivity Analysis Methodology

The sensitivity analysis begins with the inputs. To ensure the validity of the model, system insiders specify inputs. AEM's procurement manager estimated inputs for this model. The simulation process begins with the model in equilibrium. To achieve the equilibrium state actual values are set equal to the desired values including initial conditions. Equilibrium provides a baseline, which is easily quantifiable. Although the equilibrium state is easy to comprehend, it does not yield much insight into the dynamic nature of the problem. To understand the dynamic nature of the problem, the model is disturbed from equilibrium. This disturbed equilibrium state is then used as a base case for comparison in the sensitivity analysis.

Understanding the Impact of Disturbing the Equilibrium

To disturb the model from equilibrium, a pulse was added, which temporarily increased the design job win rate. The effects of this disturbance were then analyzed. From the simulation, it is apparent that as workload increases, the design staff becomes overwhelmed. Tasks that are not essential to getting the job "out the door" are omitted. So tasks such as design for cost and IPT meetings are skipped.
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To understand how design for cost tasks are skipped, the impact of the disturbance is traced for both backlog and design for cost tasks. Figure 8-1 and Figure 8-2 depict the surge in incoming work from the disturbance. This surge leads to an increase in the work to do for each type of task as shown in Figure 8-3 and Figure 8-4.

Graph for Backlog Inflow

Backlog Inflow[BLOG]: Equilibrium - - - - - - Tasks/Month
Backlog Inflow[BLOG]: Base Disturbance -- -- -- -- Tasks/Month

Figure 8-1 Impact of Disturbance on Inflow for Backlog Tasks
Graph for Backlog Inflow

Backlog Inflow[DFCOST] : Equilibrium \(1 \rightarrow 1 \rightarrow 1 \rightarrow \) Tasks/Month
Backlog Inflow[DFCOST] : Base Disturbance \(-2 \rightarrow -2 \rightarrow -2 \rightarrow\) Tasks/Month

Figure 8-2 Impact of Disturbance on Inflow for Design for Cost Tasks
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Graph for Design Work To Do

Design Work To Do[BLOG] : Equilibrium 1 1 1 1 1 Tasks
Design Work To Do[BLOG] : Base Disturbance --2--2--2--2--2 Tasks

Figure 8-3 Impact of Disturbance on Work to Do for Backlog Tasks
As the work to do increases so does the effort required to complete work to do within the desired cycle time. However, when comparing perceived effort required and design effort allocated something striking appears. Perceived effort required increases for both backlog tasks and design for cost tasks, Figure 8-5 and Figure 8-6 respectively.
Graph for Perceived Effort Required

Figure 8-5 Impact of Disturbance on Perceived Effort Required for Backlog Tasks
Yet, design effort allocated only increases for backlog tasks not design for cost tasks as shown in Figure 8-7 and Figure 8-8, respectively. The effort allocated to design for cost tasks falls sharply. This drop coincides with a period in which designers are fully allocated, Figure 8-9. This full utilization implies that designers may be over committed. By summing the perceived effort required for each task shown in Figure 8-10, it is clear that designers cannot perform all the tasks required in the desired cycle time.
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Graph for Design Allocation

Design Allocation[BLOG]: Equilibrium 1 1 1 1 1 1 Worker
Design Allocation[BLOG]: Base Disturbance -2 -2 -2 -2 -2 Worker

Figure 8-7 Impact of Disturbance on Design Allocation for Backlog Tasks
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Graph for Design Allocation

Design Allocation[DFCOST] : Equilibrium  \[1 1 1 1\] Worker
Design Allocation[DFCOST] : Base Disturbance  \[-2 -2 -2 -2\] Worker

Figure 8-8 Impact of Disturbance on Design Allocation for Design for Cost Tasks
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Graph for Total Allocation

![Graph for Total Allocation](image)

Time (Month)

Total Allocation: Equilibrium
Total Allocation: Base Disturbance

Figure 8-9 Impact of Disturbance on Total Allocation
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Graph for Perceived Effort Required

![Graph for Perceived Effort Required](image)

Perceived Effort Required[BLOG] : Base Disturbance  ———  Worker
Perceived Effort Required[DFCOST] : Base Disturbance  ———  Worker
Perceived Effort Required[IPT] : Base Disturbance  ———  Worker
Perceived Effort Required[PERF] : Base Disturbance  ———  Worker

Figure 8-10 Impact of Disturbance on Perceived Effort for Each Task Type

Since backlog and performance have the highest priority as indicated by Figure 8-11, these tasks are completed first. Moreover, as backlog tasks are completed, designs are released to testing preventing any further design effort to expend on optional tasks such as design for cost. Considering that the testing or certification process requires the design to be frozen, any optional tasks not performed in the design phase will never be performed unless an engineering change request is initiated in the form of rework. As a result, these
optional tasks such as design for cost tasks become obsolete as backlog is released to testing, Figure 8-12.

**Graph for Relative Priority**

![Graph](image)

- Relative Priority[BLOG] : Base Disturbance
- Relative Priority[DFCOST] : Base Disturbance
- Relative Priority[IPT] : Base Disturbance
- Relative Priority[PERF] : Base Disturbance

**Figure 8-11 Relative Priority of Each Task Type**
Sensitivity Analysis

After explaining the impact of the disturbance, a sensitivity analysis was conducted to determine which variables had the greatest impact on cost. To test the sensitivity of the inputs, each variable was increased and decreased by a factor of two. The simulation output is then compared to the baseline disturbance. In this evaluation process, staffing
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and productivity have the greatest impact on cost followed by policies that increase designer effective knowledge.

Causal Tracing for Staff Size

The initial disturbance shows that as designers become time constrained, cost reduction tasks are skipped. As a result, it became immediately apparent that staffing levels and productivity have a tremendous impact on cost. In the last few years AEM has undergone significant staff reductions, including design staff reductions. Simulation shows that if staff reductions are not balanced by productivity improvements, designers will become overbooked and design for cost tasks will be bypassed, as illustrated in Figure 8-13 by the decrease in the completion rate and in Figure 8-14 by the increase in the obsolescence rate. Or in other words, the savings from staff reductions may be counterbalanced by increases in manufacturing costs, as illustrated by comparing Figure 8-15 and Figure 8-16. Figure 8-17 illustrates more clearly that reducing staff may actually decrease margins.
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Graph for Estimated Burn Rate

Estimated Burn Rate[DFCOST]: Half Staff 1 1 1 1 Tasks/Month
Estimated Burn Rate[DFCOST]: Base Disturbance -2 -2 - Tasks/Month
Estimated Burn Rate[DFCOST]: Double Staff 3 3 3 Tasks/Month

Figure 8-13 Sensitivity Analysis of Staffing on Estimated Burn Rate
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Graph for Obsolete Rate

Obsolete Rate[DFCOST] : Half Staff
Obsolete Rate[DFCOST] : Base Disturbance
Obsolete Rate[DFCOST] : Double Staff

Figure 8-14 Sensitivity Analysis of Staffing on Obsolescence Rate
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Graph for Monthly Labor Cost

Monthly Labor Cost: Half Staff

Monthly Labor Cost: Base Disturbance

Monthly Labor Cost: Double Staff

Figure 8-15 Sensitivity Analysis of Staffing on Monthly Design Labor Cost
Using System Dynamics to Understand Barriers to Cost Reduction

Graph for Production Spending

<table>
<thead>
<tr>
<th>Time (Month)</th>
<th>Production Spending: Half Staff</th>
<th>Production Spending: Base Disturbance</th>
<th>Production Spending: Double Staff</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
<td>-2</td>
<td>-3</td>
</tr>
<tr>
<td>60</td>
<td>1</td>
<td>-2</td>
<td>-3</td>
</tr>
<tr>
<td>120</td>
<td>1</td>
<td>-2</td>
<td>-3</td>
</tr>
<tr>
<td>180</td>
<td>1</td>
<td>-2</td>
<td>-3</td>
</tr>
<tr>
<td>240</td>
<td>1</td>
<td>-2</td>
<td>-3</td>
</tr>
<tr>
<td>300</td>
<td>1</td>
<td>-2</td>
<td>-3</td>
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<tr>
<td>360</td>
<td>1</td>
<td>-2</td>
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<tr>
<td>420</td>
<td>1</td>
<td>-2</td>
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<td>480</td>
<td>1</td>
<td>-2</td>
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<tr>
<td>540</td>
<td>1</td>
<td>-2</td>
<td>-3</td>
</tr>
<tr>
<td>600</td>
<td>1</td>
<td>-2</td>
<td>-3</td>
</tr>
</tbody>
</table>

$/Month

Figure 8-16 Sensitivity Analysis of Staffing on Monthly Manufacturing Costs
The simulation indicates that the benefit of reducing staff is small when compared to the savings that could result from reducing manufacturing costs. Staffing costs are short-term costs. However, cost reductions in the design phase have an impact on cost over the product's entire lifetime. A poor design remains expensive to manufacture well after the product design phase, whereas excess staffing only has an impact on the costs in the design phase. Therefore, simulation suggests that erring on the side of excess staff reduces the lifecycle cost of the system.
In a more abstract sense, the benefit of additional effort in the design phase may outweigh the cost. Even though policies such as adding staff to assist designers with overhead activities, outsourcing to meet staffing needs, or offering incentives for suppliers to work with designers, may cost more, they free designers to perform cost reduction tasks resulting in a system wide cost reductions.

**Causal Tracing for Knowledge**

Even though simulation indicates that extra effort in the design phase leads to lower system costs, many of these options are off-limits due to policies designed to reduce costs such as hiring freezes. However, sensitivity analysis shows that significant gains can be achieved by focusing on policies that increase designer knowledge.

In the model development process, several methods were identified to increase knowledge: Team Communication, Diversity, IPT Teams, Proximity, Supplier Willingness to Communicate, and Supplier Knowledge. The methods identified in the modeling process and the examples provided in Table 4-3 suggest that a paradigm shift is needed to improve knowledge. Using IPTs and increasing diversity are all aimed at gaining a broader perspective. Figure 8-18 and Figure 8-19 show the impact of increasing
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communication on percent margin and unit cost, respectively. Similar results could be shown for the other methods of improving knowledge. Causal tracing is used to explain the impact of communication.

Graph for Percent Margin

![Graph for Percent Margin](image)

Percent Margin: Half Cost Comm  
Percent Margin: Base Disturbance  
Percent Margin: Double Cost Comm

Figure 8-18 Sensitivity Analysis of Communication on Percent Margin
Using System Dynamics to Understand Barriers to Cost Reduction

Graph for Average Cost Immature

![Graph for Average Cost Immature](image)

Average Cost Immature: Half Cost Comm $1.1.1.1.1$ /unit
Average Cost Immature: Base Disturbance $22222$ /unit
Average Cost Immature: Double Cost Comm $33333$ /unit

Figure 8-19 Sensitivity Analysis of Communication on Average Cost of Immature Products

Consider the impact of increasing or decreasing designer communication about cost. Each designer has a specific knowledge base. As this knowledge base is shared with other designers, they begin to learn from this shared knowledge, as indicated in Figure 8-20. Therefore, designers become more efficient at performing design for cost tasks because they have a broader knowledge about the factors that influence costs. As their
productivity of performing design for cost tasks improves, so does the process priority for these tasks, as evidenced by comparing Figure 8-21 and Figure 8-22.

Graph for Task Knowledge

Task Knowledge[DFCOST] : Half Cost Comm  \(1\) \(1\) dimensionless
Task Knowledge[DFCOST] : Base Disturbance  \(-2\) \(-2\) dimensionless
Task Knowledge[DFCOST] : Double Cost Comm  \(-3\) \(-3\) dimensionless

Figure 8-20 Sensitivity Analysis of Communication on Knowledge
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Graph for Design Productivity

Design Productivity[DFCOST] : Half Cost Comm $^{-1}$ Tasks/(Month*Worker)
Design Productivity[DFCOST] : Base Disturbance $^{-2}$ Tasks/(Month*Worker)
Design Productivity[DFCOST] : Double Cost Comm $^{-2}$ Tasks/(Month*Worker)

Figure 8-21 Sensitivity Analysis of Communication on Design Productivity of Design for Cost Tasks
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Graph for Relative Process Priority

0.2
0.165
0.13
0.095
0.06

Relative Process Priority[DFCOST] : Base Disturbance  -2-  dimensionless
Relative Process Priority[DFCOST] : Double Cost Comm  -3-  dimensionless

Time (Month)

0 60 120 180 240 300 360 420 480 540 600

Figure 8-22 Sensitivity Analysis of Communication on Relative Process Priority of Design for Cost Tasks

Increasing knowledge also stimulates the designer's personal priority weighting as attested to by Figure 8-24. As designers realize the importance of cost reduction and what it entails they are more likely to conduct cost reduction efforts. Therefore, the total priority assigned to design for cost tasks increases as shown in Figure 8-23.
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Graph for Relative Priority

0.04
0.03
0.02
0.01
0

0 60 120 180 240 300 360 420 480 540 600
Time (Month)

Relative Priority [DFCOST]: Half Cost Comm --1-- dimensionless
Relative Priority [DFCOST]: Base Disturbance --2-- dimensionless
Relative Priority [DFCOST]: Double Cost Comm --3-- dimensionless

Figure 8-23 Sensitivity Analysis of Communication on Relative Priority of Design for Cost Tasks

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As design productivity increases, the perceived effort required drops, Figure 8-25. The inverse is true when productivity decreases. When communication falls, the perceived effort required rises significantly due to a drop in productivity. Yet, the design allocation does not rise proportionally. Instead, the design allocation displayed in Figure 8-26 is well below perceived effort required. However, as shown in Figure 8-27, design allocation is constrained by the number of designers.
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Graph for Perceived Effort Required

Perceived Effort Required[DFCOST] : Half Cost Comm 1 1 Worker
Perceived Effort Required[DFCOST] : Base Disturbance 2 2 Worker
Perceived Effort Required[DFCOST] : Double Cost Comm 3 Worker

Figure 8-25 Sensitivity Analysis of Communication of Perceived Effort Required for Design for Cost Tasks
Graph for Design Allocation

Design Allocation[DFCOST] : Half Cost Comm 1 1 1 1 1 Worker
Design Allocation[DFCOST] : Base Disturbance 2 2 2 2 2 Worker
Design Allocation[DFCOST] : Double Cost Comm 3 3 3 3 3 Worker

Figure 8-26 Sensitivity Analysis of Communication on Design Allocation of Design for Cost Tasks
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Graph for Total Allocation

Total Allocation: Half Cost Comm 1 1 1 1 1 1 + Worker
Total Allocation: Base Disturbance -2 -2 -2 -2 -2 -2 Worker
Total Allocation: Double Cost Comm 3 3 3 3 3 3 Worker

Figure 8-27 Sensitivity Analysis of Communication on Total Allocation

Similar results could be shown for each of the other methods to increase knowledge.

Causal Tracing for Time to Fill Confidentiality Agreements

Although increasing supplier's willingness to communicate was listed as a method of improving communication, willingness to communicate is really a function of the time to fill confidentiality agreements. By decreasing the time to fill confidentiality agreements,
more agreements can be approved in the design phase. These agreements facilitate supplier communication, which increases supplier knowledge as shown in Figure 8-28 through Figure 8-30. The remainder of this causal tracing is not shown because it is similar to that shown above for communication. However, the impact of this knowledge increase is quantified in Figure 8-31 and Figure 8-32.

**Figure 8-28 Sensitivity Analysis of Time to Fill Confidentiality Agreements on Fraction Filled**

Fraction Filled : Half Fill Time  
Fraction Filled : Base Disturbance  
Fraction Filled : Double Fill Time  

Dimensionless
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Graph for Effect of Supplier Communication

Effect of Supplier Communication[DFCOST]: Half Fill Time  dimensionless
Effect of Supplier Communication[DFCOST]: Base Disturbance  dimensionless
Effect of Supplier Communication[DFCOST]: Double Fill Time  dimensionless

Figure 8-29 Sensitivity Analysis of Time to Fill Confidentiality Agreements on Supplier Willingness to Communicate
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Graph for Task Knowledge

Task Knowledge[DFCOST] : Half Fill Time dimensionless
Task Knowledge[DFCOST] : Base Disturbance dimensionless
Task Knowledge[DFCOST] : Double Fill Time dimensionless

Figure 8-30 Sensitivity Analysis of Time to Fill Confidentiality Agreements on Knowledge
Figure 8-31 Sensitivity Analysis of Time to Fill Confidentiality Agreements on Average Cost Immature Products
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Graph for Percent Margin

![Graph for Percent Margin](image)

- Percent Margin: Half Fill Time: dimensionless
- Percent Margin: Base Disturbance: dimensionless
- Percent Margin: Double Fill Time: dimensionless

Figure 8-32 Sensitivity Analysis of Time to Fill Confidentiality Agreements on Percent Margin

Causal Tracing for Changing Priorities

Cost reduction tasks are skipped because designers are not really accountable for cost. As a result, priority is skewed away from design for cost. Efforts designed to change the designer priorities have little impact on costs as evidenced by Figure 8-33. To achieve a
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significant impact on costs, not only does the priority for design for cost tasks need to be increased but also the priority for performance and backlog tasks has to be decreased. Figure 8-34 and Figure 8-35 illustrate that even doubling the personal priority has no impact. To achieve substantial gains the entire priority system needs to be changed.

Graph for Average Cost Immature

![Graph for Average Cost Immature](image)

Average Cost Immature: Half Pers Weight

Average Cost Immature: Base Disturbance

Average Cost Immature: Double Pers Weight

Figure 8-33 Sensitivity Analysis of Priorities on Average Immature Product Cost
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Graph for Design Allocation

Design Allocation[DFCOST]: Half Pers Weight - - - - - - Worker
Design Allocation[DFCOST]: Base Disturbance - - - - - - Worker
Design Allocation[DFCOST]: Double Pers Weight - - - - - - Worker

Figure 8-34 Sensitivity Analysis of Priorities on Design Allocation
To achieve this priority shift will require a paradigm shift in system architecture. The entire design and development process will have to be restructured to focus on cost. Achieving this paradigm shift will be extremely difficult, but the shift can be brought about in an incremental fashion as processes evolve. It will just take a number of years to see results. However, a couple of suggestions in Section 9 may be able to produce more immediate results, such as introducing pilot programs which focus on cost.
Comparison of Enterprise versus Project Models

Simulation was also used to estimate the impact of using cost tools to provide real-time feedback about costs. In effect the cost tools increase knowledge and reduce the time it takes to update cost status. Surprisingly, simulation shows that real-time feedback only had a small impact on cost, Figure 8-36. In hindsight, this outcome is not that surprising. First, cost tasks are so low in the designer's priorities that information delays have no impact. Second, the important aspect about cost tools is not the real time nature; it is the knowledge gain. If feedback about cost is slow in an enterprise level model the impact is negligible. Eventually the designers will learn. On a project basis, this time delay may have a significant impact. The designer may not learn fast enough to rectify cost problems on an individual project.
This result was surprising because initially it was thought that this information delay had a significant impact. The dual smooth was created because of this. In retrospect it seems obvious that the real time feedback is only important when considering a project by itself. Since the dual smooth formulation developed as part of this thesis works for both discrete and continuous inputs, the model was simulated assuming a one-time project pulse. In

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**Figure 8-36 Continuous Model: Impact of Time to Update Status on Average Cost of Immature Products**
this project model, changing the time to update status has a more significant impact on cost.

As shown in Figure 8-37, the average cost drops as the time to update status decreases. By increasing the time to update status, it takes longer for the optimism observed at project initiation to wear off. As a result, the estimated burn rate is slightly higher than when the time to update status is shorter, Figure 8-38. Since the estimated burn rate is higher fewer resources are allocated to performing cost tasks, Figure 8-39.
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Graph for Average Cost Immature

Average Cost Immature: Discrete Half Update

Average Cost Immature: Discrete Base

Average Cost Immature: Discrete Double Update

Figure 8-37 Project Model: Impact of Time to Update Status on Unit Cost
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Graph for Estimated Burn Rate

![Graph for Estimated Burn Rate](Image)

Estimated Burn Rate[DFCOST] : Discrete Half Update 4 Tasks/Month
Estimated Burn Rate[DFCOST] : Discrete Base 2 Tasks/Month
Estimated Burn Rate[DFCOST] : Discrete Double Update 3 Tasks/Month

Figure 8-38 Project Model: Impact of Time to Update Status on Estimated Burn Rate
The discrete simulation demonstrates the robustness of the model and the dual smooth structure. However, if the model described in the thesis is to be used as project model rather than an enterprise model, some additional fine-tuning is necessary. For example, first order controls need to be included to ensure that the stocks do not reach negative values as the project reaches completion. Furthermore, desired completion time needs to be a fixed time rather than a variable time.
Further Analysis

The model is fairly robust; however, a number of simplifications have been made to reduce complexity. The modeling process was stopped because the author believed that additional refinement would not yield substantial insight. However, with unlimited time and resources the author might relax the following assumptions:

- Target Costs and Baseline Costs Do Not Change Over Time,
- Staffing in the Testing and Test Manufacturing Phases Is Unconstrained,
- Manufacturing Ramp-up Costs Are Excluded from Cost Calculations,
- ECRs Are Not Initiated after the Testing Phase, and
- ECRs Have the Same Priority as New Design Work.

Each of these assumptions is described below.

**Target Costs and Baseline Costs Do Not Change Over Time**

In the existing formulation target costs and baseline costs must remain constant over time because the formulation for unit cost and adjusted gap size cannot account for changes in target costs, or baseline costs over time. In the current formulation, if the baseline or target gap change, the unit cost changes instantaneously. However, unit cost should not change until the design has completed the design process. The formulation for unit cost should be revised to account for this delay by using a smooth of target gap and baseline.
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The smooths should be represented using a coflow formulation similar to that used for the computation of probability of failing manufacturing. This model refinement was not added because this scenario is not central to the problem statement and was not expected to yield additional insight.

This assumption was made to maintain simplicity in the early model development process. The assumption was never revisited because it was not essential to the problem statement of reducing costs. While cost targets have changed over time and are expected to continue to change, these changes are really exogenous. Rather than tracing the dynamic behavior of these changes, the modeler is interested in identifying the dynamic behavior given the new cost targets. This refinement only becomes necessary, if the change in goals or cost targets were essential to the problem statement. For example, if the problem statement were to identify why cost targets have changed over time, this refinement might be necessary.

Staffing in the Testing and Test Manufacturing Phases Is Unconstrained

As mentioned in Section 7, the formulation of testing and test manufacturing work to do inherently assume that staffing levels are sufficient to complete incoming work in the desired time. Relaxing this assumption might yield additional insight. However, based
on observations at AEM this assumption seemed plausible because by most accounts
design was the bottleneck. Even if the test manufacturing and testing processes are
resource constrained, the insights developed regarding designer constraints would likely
apply to test manufacturing and testing. Furthermore, constraints in the testing or test
manufacturing phases are likely to compress the design process even more. If testing or
test manufacturing become the process bottlenecks, then by definition anything that
extends the cycle time of these bottleneck processes extends the cycle time of the entire
system. Since delivery date is fixed, the cycle time of another phase must be compressed
to compensate for bottleneck delays. The testing process has very rigid regulatory
requirements that cannot be bypassed. In addition, the test manufacturing process is
typically outsourced, and the supplier for these outsourced components dictates schedule.
As a result, when faced with continued bottleneck delays, design would be compressed
further to meet schedule. While the addition of this constraint would be interesting, it
was not necessary to yield insight about AEM's process and was omitted from the model.

Manufacturing Ramp-up Costs Are Excluded from Cost Calculations

Next, manufacturing ramp-up costs are excluded from cost calculations. In effect this
means that improving the manufacturability of a design has no impact on the
manufacturing ramp-up costs or profitability. In actuality, designs that consider
manufacturing have lower ramp-up costs. Engine unit cost targets are hard requirements
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of any engine design. While these targets do not have to be met in the design phase, they do have to be met once the product has reached maturity. As a result, when designers skip cost reduction tasks, manufacturing ramp-up requires more effort leading to higher labor costs. In addition, the time for a product to mature increases leading to lower production volumes due to the constant changes in the manufacturing process. Consequently, the model formulation used understates the cost impact of performing design for cost tasks. While this refinement would provide additional support for performing design for cost, it would not add any real dynamic behavior to the model. Therefore, this refinement was omitted due to the unlikelihood of adding insight to the problem of implementing DFM.

ECRs Are Not Initiated after the Testing Phase

The model only illustrates the impact of engineering change requests from the test manufacturing and testing phases. However, ECRs can be initiated at any phase of the product life cycle including product maturity. While any rework discovered in the later phases of a product life are more costly, they are less likely. The impact of this model change can be adequately estimated from the impact of rework in the testing and test manufacturing phases. Therefore, this refinement was not included.
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If additional investigation indicated that ECRs initiated in the later stages of a product life had an impact on the implementation of DFM, the model should be modified slightly. The chain of stocks describing the product design and development process should be extended to include this production ramp-up phase and the mature production phase. The average cost could then be computed as an auxiliary similar to immature unit cost already included in the model. The difference is that instead of being a function of the testing completion rate, unit cost would be a function of the stock of production ramp-up work to do and mature production work to do. It is interesting to note that this change in model structure actually results in a less complex model formulation. The author did not incorporate this change because it was not expected to yield additional insight. However, if any additional modeling effort is performed, this revision in model structure should be made to simplify future analysis.

ECRs Have the Same Priority as New Design Work

Finally, the model does not make any distinction between new work and rework. As a result, priorities do not take into account whether work is existing or new. In actual practice at AEM, priority is given to rework. As a result, it is possible that the majority of design effort focuses on correcting faulty designs rather than preventing future design problems. If too much emphasis is placed upon rework, design time will be overly
constrained. In the extreme, this emphasis can lead to design engineers being pulled from one design job in progress to one that has a higher priority.

Examples of this extreme scenario were discussed during the interview process. However, these examples only applied to drafting, cost estimating, and legal departments not design. Design engineers are dedicated to a project once they start. While they may work on more than one design project simultaneously, they have design deadlines for each design project. Design engineers might put less effort into a low priority project, but the low priority project cannot be put aside without repercussions to the design engineer. This less extreme example is adequately handled by the existing priority formulation. Time precluded further refinement of the priority formulation and investigation of this potential effect.

If priorities do lead to the extreme situation, policies used in lean production would be likely methods to eliminate the emphasis on rework. Implementing single piece flow to the design process is a possible candidate for such a scenario because it prevents designers from being pulled in multiple directions. A designer would not be able to begin another design job until the existing design job was complete. Due to delays that occur in the design process single piece flow may be too constraining. A similar result can be achieved by planning the long-term availability of resources. In this scenario, designers
can only be assigned to a design job, if they have time available given their projected workload. To implement this workload scheduling process, a more detailed breakdown of level of effort than currently used may be required. For example, at AEM design staff is allocated in terms of number of engineers for each functional requirement. However, this breakdown does not include any estimate of expected utilization of these resources. To adequately manage engineering resources, projects may need to be estimated in terms of engineering hours so that staff utilization can be factored into project staffing.
SECTION 9 CONCLUSIONS

This section describes insights developed by the author during the course of the modeling process. To describe these insights, this section is divided into six subsections as follows:

- Addenda to the Standard Method,
- System Dynamics Principles,
- New Model Formulations,
- Cost Reduction Principles
- Recommendations for AEM, and
- Concluding Thoughts.

The first three sub-sections describe the author's insights about the system dynamics process, while fourth and fifth sub-sections describe his insights about cost reductions. The final sub-section includes the author's thoughts about system dynamics and the model developed as a part of this thesis.
Addenda to the Standard Method

During the course of the modeling process, the author made several insights about the standard method described by Hines. In particular, three steps were explicitly added to the standard method as follows:

- Provide Examples,
- Simplify/Abstract, and
- Create Hybrid Causal Models.

Provide Examples

By actively seeking examples to describe each of the relevant variables, the modeler begins to develop a common language with the system insiders. If the modeler does not take the time to develop this language, miscommunication can ensue because the same words can be used to describe different things depending upon the context. For example, in the manufacturing setting, a commonly referred to term is cycle time. According to Rosenfield and Wein, the definition used for cycle time varies from one company to another. In some companies, cycle time refers to the time for one component to move through a production process. In other companies, cycle time refers to the average time to produce one unit. If one unit is manufactured at a time, then these definitions are
equivalent. However, if two or more units are produced at once, then these definitions vary (Rosenfield and Wein).

Furthermore, by actively seeking examples, the modeler gains a better understanding of the variables involved by having a more tangible definition. Moreover, these examples often contain background information that is useful to increase the modeler's understanding of the problem.

Simplify/Abstract

One of the lessons learned during the modeling process was the importance of simplification and abstraction. The simplification and abstraction process was essential to gaining modeling insight into the problem statement. Without this simplification, the model can become overly complex and yield little insight, as shown in Section 5. By periodically reflecting upon the model and attempting to simplify it, the model became less complex. Moreover, the abstraction process led to a more focused problem statement, which further simplified the problem.
Create Hybrid Causal Model

The final component added to the standard method was the creation of a hybrid causal model. By completing this step, the modeler is forced to think about the complexity that the causal loops generate. As a result, the modeler will realize that the causal loops may be too complex and embark upon the simplification/abstraction process. Furthermore, by creating this architectural vision, the modeler can more easily determine if the model formulation chosen for a particular loop will work within the context of the entire model. Having this vision reduces the likelihood that the formulation for one loop will not work with another.

System Dynamics Principles

From the modeling process several principles became apparent as follows:

- Spend Extra Time Defining the Problem Statement,
- Select Dynamic Characteristics Up-front, and
- Minimize Coupling for Addition of Loops

Spend Extra Time Defining the Problem Statement

By spending additional time defining the problem statement, complexity can be minimized. This principle can be directly derived from Nam Suh's *The Principles of*
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**Design.** In referring to the problem definition stage of the design process, Suh states the following:

*This is one of the most critical stages in the design process. This definitional step requires insight into the problem, and a knowledge base encompassing issues related to the problem. Poor problem definition leads to unacceptable or unnecessarily complex solutions.*

(Suh 30)

Although Nam Suh is referring to a traditional design process in this example, the applicability of this statement to system dynamics is demonstrated in Section 5 and Section 6 of this thesis. If additional time had been spent refining the problem statement, the complexity encountered in the initial phase of the modeling process and described in Section 5 could have been avoided.

In the early stage of the modeling process, emphasis should be placed on simplification and abstraction of the causal loops. The simplification/abstraction process will allow the revision of the problem statement. This iterative process should continue until the causal loops are simplified. As a heuristic, the simplification process should continue until the causal loops have been reduced to no more than six causal loops with no more than six distinct variables per loop. The simplification process should include more than discarding loops. The simplification process should follow the methods described in Section 3 and Section 6 such as searching for overarching themes. Only if modeling
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shows that these loops are too simple should additional complexity be added. However, the simplification process should not be abandoned in the causal loop development phase. As the model is specified, the modeler should continue to evaluate the modeling framework for a less complex solution.

Select Dynamic Characteristics Up-front

As part of creating an architectural vision, decisions need to be made about the dynamic characteristics of the model. A decision should be made early whether to create a model of a single project or a continuous stream of projects. To aid in this decision, the problem statement should be reevaluated. In this thesis, a decision was made to create an enterprise model rather than the single project model because an enterprise model was better suited to the problem statement. However, model complexity should also be reviewed. In many cases a project model will be created even though a continuous stream better represents the problem. The project model is often chosen to minimize complexity associated with a continuous stream. An assumption is then made that insights regarding a particular project can be applied to a continuous stream of projects. Although Section 8 illustrates with the variable time to update status, a discrete model will sometimes lead to different conclusions than a continuous model.
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Minimize Coupling for Addition of Loops

In creating the system dynamics model, chunks were added in a manner that minimized complexity. To reduce complexity, feedback was added incrementally. For example, a number of different design tasks were identified in the architectural vision; however, only two tasks were included at the outset of the modeling process because of the complexity of their feedback. This incremental addition of feedback could also be derived from Suh's design axioms. Suh states "The best design is a functionally uncoupled design that has the minimum information content" (Suh 48).

New Model Formulations

As part of the model development process, a unique model formulation, the dual smooth, was used. The dual smooth structure described in Section 7, represents the way expectations are reset at the beginning of a project. According to Hines, modelers trying to depict this behavior typically choose to use a discrete or project model due to the difficulty in representing this behavior in a continuous or enterprise model (Hines, Personal Discussion). One of the unique features of this formulation is that it works in both continuous and discrete models. A detailed description of this structure is included in Section 7.
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Cost Reduction Principles

By reflecting upon the simulation and observations at AEM, it is apparent that as designers become time constrained they skip cost reduction tasks because they have a low priority relative to other tasks. The fact that cost reduction tasks are skipped reveals two things, designers are time constrained and designer priorities are often different than company priorities. When a new process is implemented, it essentially replaces an existing process that is familiar and has momentum. As a result, the new process will not be used, unless it is architected in a manner that will allow it to take priority over the existing process. To meet this objective, the new process or procedure should have the following characteristics:

- Simplicity relative to the existing process, and
- Easy to learn, and
- Product and process goals must be aligned.

Without these three features, significant management intervention will be required to implement the new system.

The first two characteristics were identified as a means of working within the designers time constraints. As illustrated in Section 8 by the obsolescence of design for cost tasks, designers skip tasks as they become overbooked. Therefore, any new process or procedure must be simple relative to the existing process. If the new process takes more
time and/or involves extra steps, it will be bypassed in favor of existing processes. Moreover, the new process must be easy to learn. If implementing the new procedure requires significant time investment to learn, daily pressures will preclude learning.

Furthermore, to take precedent over existing policies and procedures, the designer must view the tasks as a priority. The designer has a number of different goals that drive these priorities. If these goals are not aligned, the designer's priorities may deviate from the company's priorities. However, due to the many factors that drive designers, aligning these goals may be an extremely difficult task. In addition, these policies must be implemented within an existing system that is difficult to change without starting an entirely new organization. Simulation illustrates the difficulty of realigning priorities by showing that changing designers' personal motivations to focus on cost has very little impact upon the overall priority of cost reduction tasks because the design process remains intact.

**Recommendations for AEM**

While the cost reduction principles are useful as a guide to ensure policy implementation, these principles do not provide much insight into the types of policies to implement at
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AEM. However, the simulations in Section 8 illustrate that to achieve cost reductions at AEM policies should focus on the following issues:

- Building Knowledge,
- Communicating Knowledge, and
- Alleviating Time Pressures.

By alleviating the time constraints on the designers, the designer is able to perform more tasks. As a result, even low priority tasks are completed. By focusing on policies that build knowledge or communicate knowledge, the designers increase their productivity allowing more tasks to be performed including low priority tasks.

The author has identified a number of recommendations aimed at these types of policies. The author uses the cost reduction principles as a basis for selecting these policies. Policies are described for each type of policy discussed above. In addition, one recommendation is made to assist in realigning priorities in the design process.

Many of the recommendations included in this section are pre-existing proposals at AEM. However, companies such as AEM have numerous policies being considered at any given time. Moreover, not all of these polices can be implemented with available time and
staff. As a result, the benefit of system dynamics simulation is often to identify which policy is most likely to succeed rather than identifying new policies. Therefore, the recommendations are included to provide focus at AEM as well as suggest new policies.

**Building Knowledge**

The policies selected to build knowledge were chosen for their simplicity relative to existing knowledge development processes. Typically, knowledge development has come through on the job training or through educational training. However, the time delay to gain this knowledge can take many years. As a result, many companies are looking at new ways to develop knowledge faster. To speed the process, the author recommends using benchmarking, employee rotation, outside review of the design process, and rule-based design.

Benchmarking allows for innovation without investing much time and effort in research. Reviewing what competitors have done allows for imitation as well as additional innovation. The innovations made by other companies can lead to insights that would not have been made if the competitor's product had not pulled them down another path.
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According to interviews with AEM personnel, AEM was able to successfully use benchmarking to reduce the costs associated with its gear box designs. Prior to resorting to benchmarking, AEM had initiated a number of design efforts to reduce production costs. However, the designers had only been able to achieve marginal gains. Managers began to suspect that the designers' knowledge of existing design forms was limiting their design solutions. Gearboxes in the aerospace industry are typically very contoured to match the shape of the gears. This contouring is very expensive to manufacture. Historically, this contoured shape was driven by pressures to improve efficiency by reducing weight with little regard for cost. The contoured design was so dominant that even when asked to radically redesign the gearbox to meet stiff cost targets, designers only considered the contoured shape (Bharath).

To move away from these expensive gearbox designs, AEM benchmarked the automobile industry because gearbox functionality is closely related in the two industries. Gearboxes in the automobile industry have been designed to meet very stringent cost requirements. As a result, the gearboxes have very little contouring and are essentially square boxes. The regular shape makes the design less expensive to manufacture. By looking at the automobile industry, AEM designers were able to expand their knowledge base of gearbox forms. Once aware of these other forms and their benefits, the designer began to consider these non-contoured shapes and changed the design paradigm (Bharath).
Similar results can also be achieved by benchmarking unrelated industries. When trying to improve material handling processes, Xerox benchmarked the logistic processes used by musical groups. When musical groups tour the country for live performances, they transport all of the equipment required for each concert with them. These groups travel with a team of people referred to as "roadies" that transport and set-up the equipment prior to each performance and dismantle the equipment after each performance. This process is rather complex, yet the entire process is accomplished in less than two days. Xerox hoped that by benchmarking roadies they could improve their own logistics (Elter).

Employee rotation is designed primarily to stimulate knowledge and innovation by increasing exposure to other areas of the industry. As a result of this multi-functional experience, the designer often develops system level innovations that lead to new or improved products and processes. Although not mentioned below, employee rotation also stimulates communication by building relationships and camaraderie across functional boundaries.

Outside review or hiring company outsiders is designed to challenge existing mentality. The phrase "bringing in new blood" is often used when hiring new staff or outsourcing and refers to bringing a fresh perspective to a problem. Since these people have not spent
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their life within the company and maybe not even in the industry, they do not have the same mindset as everyone else. As a result, they ask the one question that insiders fail to ask - "Why?".

Asking the simple question of why challenges the validity of a design or design concept, challenges the assumptions, and the boundaries. For example, AEM does not take full advantage of its manufacturing capabilities. Over the years, manufacturing processes have improved by adding features such as computer numerical control (CNC) machining. Due to these advances, processes that used to require three distinct steps now require one. However, AEM's design manuals were not updated to reflect the new capability. As a result, designs are prepared using the requirements of the older manufacturing process. Manufacturing engineers probably know that the designs are created using the capability specifications of the older equipment. Yet, if manufacturing engineers never reflect on the process, they will not realize that the design manual needs to be updated. Furthermore, process improvements will be futile because the designers will not create designs that utilize the process improvements. On the other hand, the outsiders will not have this knowledge and may ask the question leading to a moment of reflection and incorporation changes.
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The example above hints at another method of building knowledge: rule-based design. By creating the updated design manuals discussed above, the designer has lessons learned at his fingertips. These design manuals should be supplemented by creating lists of standard parts. These lists will outline the types of bolts and washers that should be used throughout the engine. By having these lists the designers will avoid creating custom designs for commodity parts.

Communicating Knowledge

As with the policies that focus on building knowledge, the author focuses on communication policies that are simple relative to the existing process. In addition, the author makes an attempt to identify communication policies that are easy to learn and align goals. The policies that are designed to increase communication of knowledge are relatively straightforward from the modeling process because many of the variables used in the modeling can be associated with a policy. In the modeling process, communication is represented by the variables: communication, IPT tasks, proximity, and supplier willingness to communicate. As a result, it seems obvious that policies to improve communication should focus on increasing IPT usage, improving supplier's willingness to communicate, and increasing proximity.
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The recommendations provided in this section go from small architecture changes to large ones. First, to stimulate the use of the IPT process, suppliers should be included in the performance evaluations of designers. In addition, a phase gate system should be implemented which requires supplier approval before proceeding to the next level. These two changes are relatively easy to implement. While they may take slightly more time than the existing process, they provide designers with additional incentives to ensure that the IPT process is followed.

AEM could also make significant strides by improving its methods of communication. AEM has not updated its communication techniques to keep pace with changes in technology. Conference rooms should be restructured to accommodate the electronic environment in which designs are created. According to Billy Fredriksson, SAAB has used technology to enhance communication. He suggests that companies are not taking full advantage of the tools that exist today to communicate information. SAAB has upgraded meeting rooms to take advantage of CAD/CAM technology. Meeting rooms for IPTs have been fitted an array of computer equipment that allows three-dimensional drawings of the design to be shown via computer projectors. He states that efforts such as these will greatly enhance communication (Fredriksson Class Lecture).
At a more fundamental level, procurement needs to be changed so that suppliers get involved in the design process earlier. To accomplish this goal, procurement needs to change its daily mode of operation. Procurement needs to empower designers to contact suppliers and negotiate costs. This interaction will stimulate designer knowledge about cost and reduce total time of designing a part. The direct interaction will also reduce information delays involved in obtaining cost estimates from cost engineering. Reducing cost engineering input will free them for more pressing cost estimating projects. However, to enable this communication, efforts must be made to speed the contracting process so that confidentiality agreements are finalized early in the design phase.

One method to speed this process is to apply lean principles to the legal department and implement principles such as single piece flow. Based upon interviews with AEM personnel, the contracts/legal group at AEM is resource constrained. In addition, work is prioritized by "whoever is screaming the loudest." As a result, the contracts staff may be working upon a confidentiality agreement for one supplier when another lands upon their desk with a higher priority. Consequently, the contracts staff will drop everything to work on the new higher priority contract. By the time the contract staff returns to the original contract agreement, they have to start over because they have forgotten what has already been done (Bharath, et al.). This scheduling method or lack of scheduling leads to unnecessary rework that further constrains the contracts group. Single piece flow
would eliminate much of this rework because the contracts staff would be forced to complete contract agreements before accepting new contract agreements.

The best way to improve communication with suppliers is by increasing accessibility to the supplier. Ideally, the supplier would be collocated with the designer. However, in order for collocation to be successful, the collocated supplier needs to be dedicated to its customers. Suppliers face the same time constraints that designers face. As a result, they may skip some of the IPT and cost reduction tasks. Electronic mail, electronic data interchange, or video teleconferencing can be used to speed this communication process. The method of collocation and communication, which is actually selected, depends upon existing infrastructure and willingness to invest. Furthermore, AEM should also consider providing incentives for collocation. The extra fee paid to suppliers should be counterbalanced by the long-term reduction in unit costs. Section 8 illustrates that reducing time constraints can lower unit costs.

*Alleviating Time Pressures*

To alleviate time pressures the author focuses on policies that do not require a substantial amount of learning. The author avoided recommending policies that focus on implementing productivity improvement tools to alleviate time pressures because use of
these tools often requires a substantial amount of learning before productivity gains can be achieved. In addition, these tools often introduce undiscovered error modes leading to rework. Therefore, the author focused recommendations on increasing staff size to alleviate time pressures.

Simulation indicated that one of the largest influences on unit cost is design staff size, yet cost cutting efforts have led to significant reductions in design staff. One of the things that the modeling process teaches is that cost of design staff is small relative to the long-term cost associated with a design. Designers can become so overwhelmed with backlog to the point that they cannot consider cost reduction tasks. Therefore, over the long term it is beneficial to err on the side of excess staff. The need for investment in design staff is often overlooked because cost cutting efforts often do not consider the impact to the system over the long term. Therefore, adding staff may not be a possibility due to corporate climate of cost cutting.

In a more abstract sense, the simulation indicates that the benefit of additional effort or investment in the design phase may outweigh the cost. Therefore, policies more acceptable in the corporate culture such as outsourcing to meet staffing needs or offering incentives for suppliers to work with designers to reduce costs, may achieve the same
results because they free designers to perform cost reduction tasks resulting in system wide cost reductions.

**Aligning Product and Process Goals**

The final recommendation is aimed at changing the underlying priorities in the design process so that they are aligned. While simulation and experience at AEM indicate that aligning priorities can be extremely difficult because of the number of different factors that influence priorities in the design process, one recommendation was included to realign these priorities. This recommendation was included despite the difficulty associated with aligning goals because it is also designed to increase knowledge and simplify the design process.

The author recommends initiating a limited number of engine design projects, or pilot projects, without an OEM contract. In addition, the metric used to assess these pilot projects should be knowledge gained. This is a somewhat radical departure from the existing design process. In the current system, engines are designed to meet a contract specification set by the OEM. The OEM contract dictates cost, schedule, weight, and performance. If performance, weight, and schedule goals are not met, harsh penalties are imposed. In addition, project managers are evaluated based upon meeting schedule,
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budget, and performance specifications. If schedule and performance goals are not met the project manager is held accountable. However, budget is a little more flexible. Budgetary goals are given for capital expenditures as well as final unit production cost. A manager can compensate for high production costs by reducing capital expenditures. Furthermore, unit production cost goals do not have to be met until the product has reached maturity. As a result, the burden of meeting unit cost can be shifted from the design phase to the manufacturing ramp-up phase.

By creating a design as a pilot project without an OEM contract, the process mechanisms that skew priorities away from cost can be eliminated. The schedule pressure can be alleviated because delivery date is not fixed. Instead of creating a design to specification, AEM could create a design to fill a market need. Eliminating the need for an OEM contracting process allows AEM to set its own design goals, which are consistent with product goals. In addition, the project does not need to be initiated until all of the AEM's suppliers have been selected. As a result, AEM can have suppliers involved in the initial phases of the design process.

However, this strategy is risky due to the possibility of missing the market needs. To eliminate risk, this strategy should only be applied to a small segment of AEM's engine market. The measure for success on the project should be knowledge gained. Whether
the engine is a commercial success is not as important as the knowledge gained from the
design process because this knowledge can be transferred to other engine lines. As a
result, a key part of the pilot project should be information dissemination so that
knowledge gained about cost reduction can be diffused to other engine designs.

Concluding Thoughts

The author believes that insights developed as part of this thesis will enable newcomers to
the field of system dynamics to be more successful in their modeling efforts because it
will allow newcomers to eliminate unnecessary complexity from their models. By
reducing the complexity, newcomers can gain a better understanding of the problem
being analyzed. As a result, the modeling effort is more likely to yield insight.
Moreover, increasing the success rate of newcomers should increase the likelihood that
they use system dynamics as an analysis tool in the future.

In addition, the author believes that model developed as a part of this thesis provides a
framework that can be used to implement cost reduction in design processes that have
constrained design resources. From simulation, the author was able to identify the
characteristics a policy must have to be implemented as well as the types of policies that
will have the greatest impact on reducing costs. As new policies are proposed to reduce
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costs, they should be evaluated based upon whether they meet these characteristics. As a starting point, the author describes a number of policies that meet these characteristics. However, AEM does not need to limit its policies to those described above. Instead, AEM should concentrate its attention on policies that meet the characteristics described above. AEM will have to evaluate its resources and goals further to determine which policies are best suited to AEM's environment.
BIBLIOGRAPHY

1. AEM web site (Name has been disguised to protect confidentiality). Accessed March 8, 2000.


4. Bharath, Keppel and AEM supplier development staff member. (The name of the supplier development staff member has been omitted to protect confidentiality). "Kickoff Meeting." Personal Interview. June 22, 1999.

5. Bharath, Keppel, et al. (The names of other AEM personnel have been omitted to protect confidentiality). "Block Interviews." Personal Interviews. 1999.


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APPENDIX A EQUATIONS FOR PREVENTIVE MAINTENANCE MODEL

(01) Actual Productivity = Effect of Yield on Productivity * Normal Productivity of Maintenance Staff
     Units: gears/(Month*Month*Worker)

(02) Actual Yield = Utilized Capacity / Maximum Rated Capacity
     Units: dimensionless

(03) Avg Rated Equipment Capacity = 100
     Units: gears/(Month*Machine)

(04) Change in Deterioration = (Deterioration Rate - Perceived Deterioration Rate) / Time to Update Status
     Units: gears/(Month*Month*Month)

(05) Degraded Capacity = INTEG( Deterioration Rate - Repair Rate , Maximum Rated Capacity * ( 1 - Desired Yield ) )
     Units: gears/Month

(06) Desired Gap Close Rate = Yield Gap / Maximum Desired Downtime
     Units: 1/Month

(07) Desired Yield = 0.6
     Units: dimensionless

(08) Deterioration Rate = Utilized Capacity / Time to Failure
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Units: gears/(Month*Month)

(09) Effect of Maintenance Staff on Time to Failure = Function of Staff on Time to Failure (Relative Maintenance Staff for Prevention)
Units: dimensionless

(10) Effect of Yield on Productivity = Function of Yield on Productivity (Relative Yield)
Units: dimensionless

(11) Effect Required Repair Effort on Allocation = Function Required Effort on Allocation (Relative Effort)
Units: dimensionless

(12) Effort Required to Maintain = (Maximum Rated Capacity * Desired Gap Close Rate + Perceived Deterioration Rate) / Actual Productivity
Units: Worker

(13) FINAL TIME = 100
Units: Month

(14) Function of Staff on Time to Failure ([(0,0)-(10,10)],(0,0.1),(0.5,0.3),(1,1),(2,1.5))
Units: dimensionless

(15) Function of Yield on Productivity ([(0,0)-(10,10)],(0,2),(1,1),(1.2,1e-006))
Units: dimensionless

(16) Function Required Effort on Allocation ([(0,0)-(10,10)],(0,0),(1,1),(2,1.5))
Units: dimensionless
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(17) Indicated Allocation = Effect Required Repair Effort on Allocation * Normal Effort Required for Repair
Units: Worker

(18) INITIAL TIME = 0
Units: Month

(19) Maintenance Staff Allocated To Repairs = min ( Total Maintenance Staff, Indicated Allocation )
Units: Worker

(20) Maintenance Staff Remaining for Prevention = Total Maintenance Staff - Maintenance Staff Allocated To Repairs
Units: Worker

(21) Maximum Desired Downtime = 2
Units: Month

(22) Maximum Rated Capacity = Avg Rated Equipment Capacity * Total Equipment
Units: gears/Month

(23) Normal Effort Required for Repair = 4
Units: Worker

(24) Normal Maintenance Staff for Prevention = 4
Units: Worker

(25) Normal Productivity of Maintenance Staff = 2500
Units: gears/(Month*Month*Worker)
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(26) Normal Time to Failure = 12
Units: Month

(27) Perceived Deterioration Rate = INTEG( Change in Deterioration, Maximum Rated Capacity * Desired Yield / Normal Time to Failure )
Units: gears/(Month*Month)

(28) Pulse Switch = 1
Units: dimensionless

(29) Pulse Variable = 1 - 0.2 * PULSE (2, 3) * Pulse Switch
Units: dimensionless

(30) Relative Effort = Effort Required to Maintain / Normal Effort Required for Repair
Units: dimensionless

(31) Relative Maintenance Staff for Prevention = xidz ( Maintenance Staff Remaining for Prevention, Normal Maintenance Staff for Prevention, 1e+006)
Units: dimensionless

(32) Relative Yield = Actual Yield / Desired Yield
Units: dimensionless

(33) Repair Rate = Actual Productivity * Maintenance Staff Allocated To Repairs
Units: gears/(Month*Month)

(34) SAVEPER = TIME STEP
Units: Month
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(35) TIME STEP = 1
Units: Month

(36) Time to Failure = Normal Time to Failure * Effect of Maintenance Staff on Time to Failure * Pulse Variable
Units: Month

(37) Time to Update Status = 3
Units: Month

(38) Total Equipment = 2000
Units: Machines

(39) Total Maintenance Staff = 8
Units: Worker

(40) Utilized Capacity = INTEG( Repair Rate - Deterioration Rate, Maximum Rated Capacity * Desired Yield )
Units: gears/Month

(41) Yield Gap = max ( Desired Yield - Actual Yield, 0)
Units: dimensionless
APPENDIX B EQUATIONS FOR DUAL SMOOTH

EXAMPLE

(01) Actual Burn Rate = Win/Actual Cycle Time
    Units: Tasks/Month

(02) Actual Cycle Time = Cycle Time Factor*Desired Cycle Time
    Units: Months

(03) Change in Burn = (1-Fraction Initialized)*(Actual Burn Rate-Est Burn)/Time to Update
    Units: Tasks/Month/Month

(04) Change in Initial = Fraction Initialized*(Initial Value-Est Burn)/TIME STEP
    Units: Tasks/(Month*Month)

(05) Cycle Time Factor = 2
    Units: dimensionless

(06) Desired Cycle Time = 10
    Units: Month

(07) Desired Tasks = (Win Rate-Actual Burn Rate)*TIME STEP+Work to Do
    Units: Tasks

(08) Est Burn = INTG (Change in Burn+Change in Initial, (1-Switch)*(Time to Update*Fraction Initialized*Initial Value-TIME STEP * Fraction Initialized*Win/Actual Cycle Time+TIME STEP*Win/Actual Cycle Time
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\[ \frac{(\text{TIME STEP}+\text{Time to Update}) \cdot \text{Fraction Initialized}}{\text{TIME STEP} \cdot \text{Fraction Initialized}} \]

Units: Tasks/Month

(09) \( \text{FINAL TIME} = 40 \)
Units: Month

(10) \( \text{Fraction Initialized} = xidz(\text{TIME STEP} \cdot \text{Win Rate}, \text{Desired Tasks}, 1) \)
Units: dimensionless

(11) \( \text{INITIAL TIME} = 0 \)
Units: Month

(12) \( \text{Initial Value} = \text{Desired Tasks} / \text{Desired Cycle Time} \)
Units: Tasks/Month

(13) \( \text{Pulse Time} = \text{Desired Cycle Time} \)
Units: Month

(14) \( \text{SAVEPER} = \text{TIME STEP} \)
Units: Month

(15) \( \text{Switch} = 1 \)
Units: dimensionless

(16) \( \text{TIME STEP} = 0.125 \)
Units: Month

(17) \( \text{Time to Update} = 2 \)
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Units: Month

(18) Win = 100
Units: Tasks

(19) Win Rate = (PULSE(Pulse Time, TIME STEP) * (Win / TIME STEP)) + PULSE(0, TIME STEP) * (Win / TIME STEP) + Switch * (1 - Switch) * Win / Actual Cycle Time
Units: Tasks/Month

(20) Work to Do = INTEG (+Win Rate - Actual Burn Rate, (1 - Switch) * Win)
Units: Tasks
APPENDIX C EQUATIONS FOR AEM MODEL

(001) Actual Burn Rate[TASKS] = Design Completion Rate[TASKS]
Units: Tasks/Month

(002) Actual Proximity = 10
Units: dimensionless

(003) Administrative Monthly Labor Cost = 3.2e+007
Units: $/Month

(004) Aging Rate = Mature Products / New Product Life
Units: Products/Month

(005) Agreement Inflow = Backlog Inflow[BLOG] * Agreements per Task
Units: Agreements/Month

(006) Agreements per Task = 0.25
Units: Agreements/Task

(007) Allocation Factor for Discrete = Total Allocation / Fraction of Design Time Available / Design Staff Size * Discrete Switch + 1 - Discrete Switch
Units: dimensionless

(008) Allocation Remaining = Total Effort Available - Total Allocation
Units: Worker

(009) Average Cost Immature = INTEG( Change in Immature Cost , ( Baseline[DFCOST] - XIDZ ( ( Backlog Inflow[DFCOST] * ( 1 - Mfg Failure

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\[ \text{Average Cost Mature} = \text{INTEG}( \text{Change in Mature Price} , ( \text{Baseline}[\text{DFCOST}] - \text{XIDZ} ( ( \text{Backlog Inflow}[\text{DFCOST}] * (1 - \text{Mfg Failure Fraction}) * (1 - \text{Testing Failure Fraction}) / (1 - \text{Mfg Failure Fraction} - \text{Testing Failure Fraction} + \text{Mfg Failure Fraction} * \text{Testing Failure Fraction}) ) * \text{Target Gap}[\text{BLOG}] , ( \text{Backlog Inflow}[\text{BLOG}] * (1 - \text{Mfg Failure Fraction}) * (1 - \text{Testing Failure Fraction}) / (1 - \text{Mfg Failure Fraction} - \text{Testing Failure Fraction} + \text{Mfg Failure Fraction} * \text{Testing Failure Fraction}) ) , \text{Baseline}[\text{DFCOST}] ) ) / \text{Products per Project} * \text{Cost Reduction Factor} * \text{Unit Conversion} \)

Units: $/\text{unit}

(010)

\[ \text{Average Cost Replacements} = \text{INTEG}( \text{Change in Replacement Cost} , (1 - \text{Fraction of Production Mature}) * \text{Average Cost Immature} * \text{Cost Reduction Factor} + \text{Average Cost Mature} * \text{Fraction of Production Mature} ) \]

Units: $/\text{unit}

(011)

\[ \text{Average MFF of Mfg Work To Do} = \text{INTEG}( \text{Change in TFF of Mfg WTD} , \text{Normal Testing Failure Fraction} ) \]

Units: dimensionless

(012)

\[ \text{Average Price} = 585000 \]

Units: $/\text{unit}

(013)

\[ \text{Average Product Cost Once Mature} = \text{Indicated Cost of Mature} * (1 - \text{Fraction of Production Mature}) + \text{Average Cost Mature} * \text{Fraction of Production Mature} \]

Units: $/\text{unit}

(014)
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(015) Backlog Inflow[TASKS] = Target Gap[TASKS] * Win Rate * Surge Factor * (1 - Discrete Switch) + Discrete Win Rate * Target Gap[TASKS] * Discrete Factor * Discrete Switch
Units: Tasks/Month

(016) Baseline[BLOG] = 0
Baseline[DFCOST] = 675000
Baseline[IPT] = 0
Baseline[PERF] = 800
Units: Tasks/Project

(017) Capital Cost Manufacturing = Capital Cost of Manufacturing Per Project * Manufacturing Projects Performed
Units: $/Month

(018) Capital Cost of Manufacturing Per Project = 5e+008
Units: $/Project

(019) Capital Cost of Testing Per Project = 1.5e+008
Units: $/Project

(020) Capital Cost Testing = Capital Cost of Testing Per Project * Testing Projects Performed
Units: $/Month

(021) Change in Burn Rate[TASKS] = (1 - Initialized Fraction) * (Actual Burn Rate[TASKS] - Estimated Burn Rate[TASKS]) / Time to Update Status[TASKS]
Units: Tasks/(Month*Month)

(022) Change in Demand = (Immature Unit Demand - Indicated Immature Unit Demand) / Time To Perceive Change in Demand
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Units: units/(Month*Month*product)

(023) Change in Immature Cost = ( Immature Unit Cost - Average Cost Immature ) / Immature Dilution Time
Units: $/(Month*unit)

(024) Change in Immature Production Rate = ( Indicated Immature Unit Demand * Immature Products - Production Rate Immature Products ) / Time to Adjust Production
Units: units/(Month*Month)

(025) Change in Initial[TASKS] = Initialized Fraction * ( Est Initial Burn[TASKS] - Estimated Burn Rate[TASKS] ) / TIME STEP
Units: Tasks/(Month*Month)

(026) Change in Mature Demand = ( Mature Unit Demand - Indicated Mature Unit Demand ) / Time To Perceive Change in Demand
Units: units/(Month*Month*product)

(027) Change in Mature Price = ( Indicated Cost of Mature - Average Cost Mature ) / Mature Dilution Time
Units: $/(Month*unit)

(028) Change in Mature Production Rate = ( Indicated Mature Unit Demand * Mature Products - Production Rate Mature Products ) / Time to Adjust Production
Units: units/(Month*Month)

(029) Change in MFF = XIDZ ( ( Indicated MFF - Mfg Failure Fraction ), Mfg Dilution Time, 1)
Units: 1/Month
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(030) Change in Perceived MFF = (Indicated Perceived MFF - Perceived MFF) / Indicated RT
Units: 1/Month

(031) Change in Replacement Cost = (Average Product Cost Once Mature - Average Cost Replacements) / Dilution Time Spares
Units: $/(Month*unit)

(032) Change in Replacement Rate = (Field Units to Be Replaced / Desired Time To Repair - Production Rate Replacements) / Time to Adjust Production
Units: units/(Month*Month)

(033) Change in RT[TASKS] = (Design Productivity[TASKS] - Expected Design Productivity[TASKS]) / Time to Update Status[TASKS]
Units: Tasks/(Month*Month*Worker)

(034) Change in Task Knowledge[TASKS] = (Indicated Designer Knowledge[TASKS] - Task Knowledge[TASKS]) / Time to Absorb
Units: 1/Month

(035) Change in TFF of Mfg WTD = XIDZ ((Indicated TFF - Average MFF of Mfg Work To Do), Mfg Dilution Time, 1)
Units: 1/Month

(036) Change in TFF of Testing WTD = XIDZ ((Average MFF of Mfg Work To Do - Testing Failure Fraction), Testing Dilution Time, 1)
Units: 1/Month

(037) Change Supplier Knowledge[TASKS] = (Indicated Supplier Knowledge[TASKS] - Supplier Knowledge[TASKS]) / Time to Change Suppliers
Units: 1/Month
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(038) \( \text{Chg in Perceived TFF} = \frac{\text{Indicated Perceived TFF} - \text{Perceived TFF}}{\text{Time to Mfg} + \text{Indicated RT}} \)

Units: 1/Month

(039) \( \text{Complete Designs[TASKS]} = \text{INTEG}( \text{Testing Completion Rate[TASKS]} - \text{Design Obsolesence[TASKS]} + \text{Backlog Inflow[TASKS]} / (1 - \text{Mfg Failure Fraction} - \text{Testing Failure Fraction} + \text{Mfg Failure Fraction} \times \text{Testing Failure Fraction}) + \text{Mfg Failure Fraction} \times (1 - \text{Testing Failure Fraction}) \times \text{Product Life Cycle} \)

Units: Tasks

(040) \( \text{Completed Design Phase} = \frac{\text{Confidential Agreements Filled}}{\text{Indicated RT}} \)

Units: Agreements/Month

(041) \( \text{Confidential Agreements Filled} = \text{INTEG}( \text{Fill Rate} - \text{Completed Design Phase} + \text{Agreements per Task} \times \text{Backlog Inflow[BLOG]} \times \text{Indicated RT} \times \text{Indicated RT} / (\text{Indicated RT} + \text{Time to Fill Agreements}) \)

Units: Agreements

(042) \( \text{Confidential Agreements Required} = \text{INTEG}( \text{Agreement Inflow} - \text{Fill Rate} - \text{Unfilled In Design Phase} + \text{Agreements per Task} \times \text{Backlog Inflow[BLOG]} \times \text{Indicated RT} \times \text{Time to Fill Agreements} / (\text{Indicated RT} + \text{Time to Fill Agreements}) \)

Units: Agreements

(043) \( \text{Contract Priority[TASKS]} = \text{Total Delay[TASKS]} \times \text{Delay Penalty[TASKS]} \)

Units: $

(044) \( \text{Contract Weighting Factor} = 1 \)

Units: dimensionless
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(045) Cost Reduction Factor = 0.67
Units: dimensionless

(046) Decommission Rate = Field Units / Product Life Cycle
Units: units/Month

(047) Delay Penalty[TASKS] = Average Price * Indicated Immature Unit Demand * Percent of Contract[TASKS] * Number of Products
Units: $/Month

Units: Worker

(049) Design Completion Rate[TASKS] = Design Allocation[TASKS] * Design Productivity[TASKS]
Units: Tasks/Month

(050) Design Monthly Labor Cost = Design Staff Size * Labor Rate
Units: $/Month

Units: Tasks/Month

Units: Tasks/(Month*Worker)

(053) Design Staff Size = 1700
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Units: Worker

(054) \[ \text{Design Work To Do[TASKS]} = \text{INTEG}( \text{Backlog Inflow[TASKS]} - \text{Design Completion Rate[TASKS]} - \text{Obsolete Rate[TASKS]} + \text{Rework Entering[TASKS]} \]

\[ + \text{Backlog Inflow[TASKS]} * \text{Desired Design Release Cycle Time} / (1 - \text{Mfg Failure Fraction} - \text{Testing Failure Fraction} + \text{Mfg Failure Fraction} * \text{Testing Failure Fraction}) \]

Units: Tasks

(055) \[ \text{Desired Completion Rate[TASKS]} = \text{Desired Status at End of Scheduled Release Cycle[TASKS]} / \text{Desired Design Release Cycle Time} \]

Units: Tasks/Month

(056) \[ \text{Desired Design Release Cycle Time} = 9 \]

Units: Month

(057) \[ \text{Desired Fraction of Gap to Close[TASKS]} = \text{If then else} (\text{Status Gap[TASKS]} > 0, \text{Status Gap[TASKS]} / \text{Time to Close[TASKS]}, 0) \]

Units: Tasks/Month

(058) \[ \text{Desired Initial Burn[TASKS]} = \text{Initial Tasks[TASKS]} / \text{Desired Design Release Cycle Time} \]

Units: Tasks/Month

(059) \[ \text{Desired Ratio of N to M[TASKS]} = \text{XIDZ} (\text{Target Gap[TASKS]}, \text{Target Gap[BLOG]}, 1e+006) \]

Units: dimensionless

(060) \[ \text{Desired Status at End of Scheduled Release Cycle[TASKS]} = \text{Design Work To Do[TASKS]} \]

Units: Tasks
(061) Desired Time To Repair = 1
Units: Month

(062) Dilution Time Spares = MAX ( XIDZ ( Field Units to Be Replaced , Wear Out Rate , TIME STEP ) , TIME STEP )
Units: Month

(063) Discrete Factor = Pulse ( Discrete Surge Start Time , TIME STEP )
Units: dimensionless

(064) Discrete Surge Start Time = 40
Units: Month

(065) Discrete Switch = 0
Units: dimensionless

(066) Discrete Win Rate = Projects in Discrete Case / TIME STEP
Units: Project/Month

Units: dimensionless

Units: dimensionless

Units: dimensionless
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Units: dimensionless

(071) Effect IPT on Designer Tasks Knowledge[TASKS] = Effect of Internal Team Knowledge on Designer[TASKS] * Effect of Supplier Team Knowledge on Designer[TASKS]
Units: dimensionless

Units: dimensionless

(073) Effect Knowledge on MFF[TASKS] = Function Knowledge on MFF[TASKS] ( Relative Knowledge[TASKS] )
Units: dimensionless

(074) Effect Knowledge on TFF[TASKS] = Function Knowledge on TFF[TASKS] ( Relative Knowledge[TASKS] )
Units: dimensionless

(075) Effect Knowledge on Weighting[TASKS] = Function of Knowledge on Weighting[TASKS] ( Relative Knowledge[TASKS] )
Units: dimensionless

Units: dimensionless

(077) Effect Min Knowledge on Max[TASKS] = Function of Knowledge on Productivity[TASKS] ( Min Knowledge )
Using System Dynamics to Understand Barriers to Cost Reduction

Units: dimensionless

(078) Effect of Average Time Spent on Task Knowledge[TASKS] = Function Task Time on Knowledge[TASKS] (Effective Completion Rate Per Person[TASKS])
Units: dimensionless

(079) Effect of Estimated Tasks Complete on Perceived MFF[TASKS] = Function Tasks on MFF[TASKS] (Estimated Fraction of Goal[TASKS])
Units: dimensionless

(080) Effect of Estimated Tasks Completed on Perceived TFF[TASKS] = Function of Tasks on TFF[TASKS] (Estimated Fraction of Goal[TASKS])
Units: dimensionless

(081) Effect of Internal Team Knowledge on Designer[TASKS] = Function Team Knowledge on Designer[TASKS] (Relative Team Knowledge Internal[TASKS])
Units: dimensionless

(082) Effect of Relative Accountability on Weighting[TASKS] = Function Prob on Accountability[TASKS] (Relative Accountability[TASKS])
Units: dimensionless

(083) Effect of Supplier Communication[TASKS] = Function of SComm on Designer[TASKS] (Rel SComm[TASKS])
Units: dimensionless

(084) Effect of Supplier Team Knowledge on Designer[TASKS] = Effect Supplier Team Knowledge[TASKS] * Effect of Supplier Communication[TASKS]
Units: dimensionless
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(085) Effect of Tasks Complete on Perceived Accountability[TASKS] = Function Tasks Complete on Accountability[TASKS] (Estimated Fraction of Tasks Completed[TASKS])

Units: dimensionless

(086) Effect of Tasks Perform on Mfg Failure[TASKS] = Function Tasks on MFF[TASKS] (Indicated Fraction of Goal Met[TASKS])

Units: dimensionless

(087) Effect of Tasks Performed on Testing Failure[TASKS] = Function of Tasks on TFF[TASKS] (Indicated Fraction of Goal Met[TASKS])

Units: dimensionless

(088) Effect on Max Est Initial Burn[TASKS] = Function of Relative Tasks Complete on Productivity[TASKS] (Min Fraction Complete)

Units: dimensionless


Units: dimensionless

(090) Effect Proximity[TASKS] = Function of Proximity[TASKS] (Relative Proximity)

Units: dimensionless

(091) Effect Supplier Team Knowledge[TASKS] = Function Supplier Knowledge on Designer[TASKS] (Relative Supplier Team Knowledge[TASKS])

Units: dimensionless

(092) Effect Task Time = Function of IPT Tasks on Knowledge (Effective Completion Rate Per Person[IPT])

Units: dimensionless
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(093) Effect Team Size[TASKS] = Function Team Size on Knowledge[TASKS] (Relative Team Size[TASKS])
Units: dimensionless

Units: dimensionless

(095) Effect WTC[TASKS] = Function Supplier Fraction Fill on WTC[TASKS] (Relative Fraction Filled)
Units: dimensionless

(096) Effective Completion Rate Per Person[TASKS] = Relative Ambitiousness of Goals[TASKS] * (Relative Completion Rate Per Person[TASKS])
Units: dimensionless

(097) Est Initial Burn[TASKS] = Fraction of Ceiling[TASKS] * Max Initial Burn[TASKS]
Units: Tasks/Month

(098) Estimated Burn Rate[TASKS] = INTEG( Change in Burn Rate[TASKS] + Change in Initial[TASKS], Backlog Inflow[TASKS] / (1 - Mfg Failure Fraction - Testing Failure Fraction + Mfg Failure Fraction * Testing Failure Fraction))
Units: Tasks/Month

(099) Estimated Delay[TASKS] = XIDZ (Status Gap[TASKS], Estimated Burn Rate[TASKS], 0)
Units: Month

(100) Estimated Fraction of Goal[TASKS] = XIDZ (Estimated Ratio of N to M[TASKS], Desired Ratio of N to M[TASKS], 0)
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Units: dimensionless

(101) Estimated Fraction of Tasks Completed[TASKS] = XIDZ (Indicated Status at End of Scheduled Release Cycle[TASKS], Desired Status at End of Scheduled Release Cycle[TASKS], 0)
Units: dimensionless

(102) Estimated Ratio of N to M[TASKS] = XIDZ (Estimated Burn Rate[TASKS], Estimated Burn Rate[BLOG], 1e+006)
Units: dimensionless

(103) Expected Design Productivity[TASKS] = INTEG(Change in RT[TASKS], Normal Design Productivity[TASKS])
Units: Tasks/(Month*Worker)

Units: units

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Units: units

(106) Fill Rate = Confidential Agreements Required / Time to Fill Agreements
Units: Agreements/Month

(107) FINAL TIME = 600
Units: Month

(108) Fraction Filled = XIDZ ( Confidential Agreements Filled , ( Confidential Agreements Required + Confidential Agreements Filled ), 0)
Units: dimensionless

Units: dimensionless

(110) Fraction of Design Time Available = 0.9
Units: dimensionless

(111) Fraction of Production Mature = XIDZ ( Production Rate Mature Products , ( Production Rate Mature Products + Production Rate Immature Products ), 0)
Units: dimensionless

(112) Fractional Size of Gap[TASKS] = XIDZ ( Target Gap[TASKS] , Target[TASKS] , 1e+006)
Units: dimensionless

(113) Func Prod on Process Priority[TASKS] ( [(0,0)-
(10,10)],(0,0),(0.5,0.75),(1,1),(2,1.5) )
Units: dimensionless
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(114) Function Diversity on Knowledge[TASKS]  ( (0,0)-(10,10),(0,0.8),(1,1),(2,1.5),(4,2) )
Units: dimensionless

(115) Function Fraction Complete on Priority[TASKS]  ( (0,0)-(10,10),(0.5,2),(1,1),(2,0.5) )
Units: dimensionless

(116) Function Int Comm on Knowledge[TASKS]  ( (0,0)-(10,10),(0,0),(10,10) )
Units: dimensionless

(117) Function Knowledge on MFF[BLOG]  ( (0,0)-(10,10),(0,1),(1,1),(2,1) )
Function Knowledge on MFF[DFCOST]  ( (0,0)-(10,10),(0,1),(1,1),(2,1) )
Function Knowledge on MFF[IPT]  ( (0,0)-(10,10),(0,1),(1,1),(2,1) )
Function Knowledge on MFF[PERF]  ( (0,0)-(10,10),(0.5,1.05),(1,1),(2,0.95) )
Units: dimensionless

(118) Function Knowledge on TFF[BLOG]  ( (0,0)-(10,10),(0,1),(1,1),(2,1) )
Function Knowledge on TFF[DFCOST]  ( (0,0)-(10,10),(0,1),(1,1),(2,1) )
Function Knowledge on TFF[IPT]  ( (0,0)-(10,10),(0,1),(1,1),(2,1) )
Function Knowledge on TFF[PERF]  ( (0,0)-(10,10),(0.5,1.1),(1,1),(2,0.95) )
Units: dimensionless

(119) Function of Fraction of Ceiling  ( (0,0)-(10,10),(0,0),(1,1),(2,1) )
Units: dimensionless

(120) Function of IPT Tasks on Knowledge  ( (0,0)-(10,10),(0,0.8),(1,1),(2,1.5),(4,2.5) )
Units: dimensionless
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(121) Function of Knowledge on Productivity [TASKS] ( [(0,0)-(10,10)],(0,0.8),(1,1),(5,5) )
Units: dimensionless

(122) Function of Knowledge on Weighting [BLOG] ( [(0,0)-(10,10)],(0,0.4),(1,1),(1.5,2) )
Function of Knowledge on Weighting [DFCOST] ( [(0,0)-(10,10)],(0,0.4),(1,1),(1.5,2) )
Function of Knowledge on Weighting [IPT] ( [(0,0)-(10,10)],(0,0.4),(1,1),(1.5,2) )
Function of Knowledge on Weighting [PERF] ( [(0,0)-(10,10)],(0,0.4),(1,1),(1.5,2) )
Units: dimensionless

(123) Function of Proximity [BLOG] ( [(0,0)-(10,10)],(1e-005,2),(0.0001,1),(1,1) )
Function of Proximity [DFCOST] ( [(0,0)-(10,10)],(1e-005,2),(0.0001,1),(1,1) )
Function of Proximity [IPT] ( [(0,0)-(10,10)],(1e-005,2),(0.0001,1),(1,1) )
Function of Proximity [PERF] ( [(0,0)-(10,10)],(1e-005,2),(0.0001,1),(1,1) )
Units: dimensionless

(124) Function of Relative Tasks Complete on Productivity [BLOG] ( [(0,0)-(10,10)],(0,1.5),(0.5,1.25),(1,1),(1.25,0.75),(1.5,0.5),(2,0.2) )
Function of Relative Tasks Complete on Productivity [DFCOST] ( [(0,0)-(10,10)],(0,1.5),(0.5,1.25),(1,1),(1.25,0.75),(1.5,0.5),(2,0.2) )
Function of Relative Tasks Complete on Productivity [IPT] ( [(0,0)-(10,10)],(0,1.5),(0.5,1.25),(1,1),(1.25,0.75),(1.5,0.5),(2,0.2) )
Function of Relative Tasks Complete on Productivity [PERF] ( [(0,0)-(10,10)],(0,1.5),(0.5,1.25),(1,1),(1.25,0.75),(1.5,0.5),(2,0.2) )
Units: dimensionless
(125) Function of SComm on Designer[TASKS] ( [(0,0)-(10,10)],(0,0.9),(0.5,0.95),(1,1),(2,2) )
Units: dimensionless

(126) Function of Tasks on TFF[BLOG] ( [(0,0)-(10,10)],(0,1),(1,1),(2,1) )
Function of Tasks on TFF[DFCOST] ( [(0,0)-(10,10)],(0,1),(1,1),(2,1) )
Function of Tasks on TFF[IPT] ( [(0,0)-(10,10)],(0,1),(1,1),(2,1) )
Function of Tasks on TFF[PERF] ( [(0,0)-(10,10)],(0.5,1.4),(1,1),(2,0.75) )
Units: dimensionless

(127) Function Perceived MF on Process Priority[BLOG] ( [(0,0)-(10,10)],(0,1),(1,1),(2,1) )
Function Perceived MF on Process Priority[DFCOST] ( [(0,0)-(10,10)],(0,1),(1,1),(2,1) )
Function Perceived MF on Process Priority[IPT] ( [(0,0)-(10,10)],(0,1),(1,1),(2,1) )
Function Perceived MF on Process Priority[PERF] ( [(0,0)-(10,10)],(0,0),(1,1),(2,2) )
Units: dimensionless

(128) Function Perceived TF on Process Priority[BLOG] ( [(0,0)-(10,10)],(0,1),(1,1),(2,1) )
Function Perceived TF on Process Priority[DFCOST] ( [(0,0)-(10,10)],(0,1),(1,1),(2,1) )
Function Perceived TF on Process Priority[IPT] ( [(0,0)-(10,10)],(0,1),(1,1),(2,1) )
Function Perceived TF on Process Priority[PERF] ( [(0,0)-(10,10)],(0,0),(1,1),(2,2) )
Units: dimensionless

(129) Function Prob on Accountability[TASKS] ( [(0,0)-(10,10)],(0,0.2),(0.5,0.3),(1,1),(2,2),(5,5),(10,10) )
Units: dimensionless
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(130) Function Supplier Fraction Fill on WTC[TASKS] ( [(0,0)-(10,10)],(0,0.8),(1,1),(2,2),(3,2.5) )
Units: dimensionless

(131) Function Supplier Knowledge on Designer[TASKS] ( [(0,0)-(10,10)],(0,0.8),(1,1),(2,2),(3,2.5) )
Units: dimensionless

(132) Function Task Time on Knowledge[TASKS] ( [(0,0)-(10,10)],(0,0.8),(1,1),(4,2) )
Units: dimensionless

(133) Function Tasks Complete on Accountability[TASKS] ( [(0,0)-(10,10)],(0.5,2),(1,1),(2,0.5) )
Units: dimensionless

(134) Function Tasks on MFF[BLOG] ( [(0,0)-(10,10)],(0,1),(1,1),(2,1) )
Function Tasks on MFF[DFCOST] ( [(0,0)-(10,10)],(0,1),(1,1),(2,1) )
Function Tasks on MFF[IPT] ( [(0,0)-(10,10)],(0.5,1.4),(1,1),(2,0.75) )
Function Tasks on MFF[PERF] ( [(0,0)-(10,10)],(0,1),(1,1),(2,1) )
Units: dimensionless

(135) Function Team Knowledge on Designer[TASKS] ( [(0,0)-(10,10)],(0,0),(10,10) )
Units: dimensionless

(136) Function Team Size on Knowledge[TASKS] ( [(0,0)-(10,10)],(0,0),(1,1),(2,1.2),(3,1.2) )
Units: dimensionless
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(137) Immature Dilution Time = MAX ( XIDZ ( Immature Products , Introduction Rate , TIME STEP ) , TIME STEP )
Units: Month

Units: Products

(139) Immature Spending = Average Cost Immature * Production Rate Immature Products
Units: $/Month

(140) Immature Unit Cost = ( Baseline[DFCOST] - XIDZ ( Testing Completion Rate[DFCOST] * Target Gap[BLOG] , Testing Completion Rate[BLOG] , Baseline[DFCOST] ) ) / Products per Project * Unit Conversion
Units: $/unit

(141) Immature Unit Demand = 4
Units: units/(Month*product)

(142) Indicated Complete per Person[TASKS] = Design Completion Rate[TASKS] / Design Staff Size
Units: Tasks/(Month*Worker)

(143) Indicated Cost of Mature = Average Cost Immature * Cost Reduction Factor
Units: $/unit
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Units: dimensionless

(145) Indicated Fraction of Ceiling[TASKS] = Desired Initial Burn[TASKS] / Max Initial Burn[TASKS]
Units: dimensionless

(146) Indicated Fraction of Goal Met[TASKS] = XIDZ ( Tasks Performed Per Backlog Task[TASKS] , Desired Ratio of N to M[TASKS] , 0)
Units: dimensionless

(147) Indicated Immature Unit Demand = INTEG( Change in Demand , Immature Unit Demand )
Units: units/(Month*product)

(148) Indicated Mature Unit Demand = INTEG( Change in Mature Demand , Mature Unit Demand )
Units: units/(Month*product)

(149) Indicated MFF = Normal Mfg Failure Fraction * PROD ( Effect of Tasks Perform on Mfg Failure[TASKS!] ) * PROD ( Effect Knowledge on MFF[TASKS!] )
Units: dimensionless

(150) Indicated Perceived MFF = Mfg Failure Fraction * PROD ( Effect of Estimated Tasks Complete on Perceived MFF[TASKS!] ) * PROD ( Effect Knowledge on MFF[TASKS!] )
Units: dimensionless
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(151) Indicated Perceived TFF = Testing Failure Fraction \* PROD (Effect of Estimated Tasks Completed on Perceived TFF[TASKS!] ) \* PROD (Effect Knowledge on TFF[TASKS!])
Units: dimensionless

(152) Indicated RT = XIDZ (Design Work To Do[BLOG] , Design Completion Rate[BLOG] , 8)
Units: Month

Units: Tasks

(154) Indicated Supplier Knowledge[BLOG] = 0.5
Indicated Supplier Knowledge[DFCOST] = 0.5
Indicated Supplier Knowledge[IPT] = 0.5
Indicated Supplier Knowledge[PERF] = 0.5
Units: dimensionless

(155) Indicated TFF = Normal Testing Failure Fraction \* PROD (Effect of Tasks Performed on Testing Failure[TASKS!] ) \* PROD (Effect Knowledge on TFF[TASKS!])
Units: dimensionless

(156) Initial Inflow Tasks[TASKS] = (Backlog Inflow[TASKS] + Rework Entering[TASKS]) \* TIME STEP
Units: Tasks

Units: Tasks
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(158) INITIAL TIME = 0
Units: Month

(159) Initialized Fraction = XIZ ( Initial Inflow Tasks[BLOG], Initial Tasks[BLOG], 1)
Units: dimensionless

(160) Introduction Rate = Testing Completion Rate[BLOG] / Target Gap[BLOG] * Products per Project
Units: Products/Month

(161) Labor Cost = INTEG( Monthly Labor Cost, 0)
Units: $

(162) Labor Rate = 16000
Units: $/(Month*Worker)

(163) Manufacturing Monthly Labor Cost = 3.2e+007
Units: $/Month

(164) Manufacturing Projects Performed = XIZ ( Manufacturing Tasks Performed, Target Gap[BLOG], 0)
Units: Project/Month

(165) Manufacturing Tasks Performed = Mfg Fail Rate[BLOG] + Mfg Completion Rate[BLOG]
Units: Tasks/Month

(166) Margin = Revenue - Total Cost
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Units: $

(167) \text{Marginal Delay} = 0.03
Units: \text{Month}

(168) \text{Market Priority[TASKS]} = \text{MarketP} \left( \text{Perceived Effort Required[BLOG]} , \text{Relative Priority[BLOG]}, \text{PERF, Width, Total Effort Available} \right)
Units: \text{dimensionless}

(169) \text{Mature Dilution Time} = \text{MAX} \left( \text{XIDZ (Mature Products, Maturing Rate, TIME STEP)}, \text{TIME STEP} \right)
Units: \text{Month}

Units: \text{Products}

(171) \text{Mature Spending} = \text{Average Cost Mature} \times \text{Production Rate Mature Products}
Units: \$/\text{Month}

(172) \text{Mature Unit Demand} = 8
Units: \text{units/(Month*product)}

(173) \text{Mature Volume} = 250
Units: \text{units/product}

(174) \text{Maturing Rate} = \text{Production Rate Immature Products} / \text{Mature Volume}
Units: \text{Products/Month}
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(175) \[ \text{Max Initial Burn[TASKS]} = \text{Normal Max Initial Burn[TASKS]} \times \text{Effect on Max Est Initial Burn[TASKS]} \times \text{Effect Min Knowledge on Max[TASKS]} \]
Units: Tasks/Month

(176) \[ \text{Mfg Completion Rate[TASKS]} = \frac{\text{Mfg Work To Do[TASKS]} \times (1 - \text{Mfg Failure Fraction})}{\text{Time to Mfg}} \]
Units: Tasks/Month

(177) \[ \text{Mfg Dilution Time} = \text{XIDZ} \left( \text{Mfg Work To Do[BLOG]}, \text{Design Completion Rate[BLOG]}, \text{TIME STEP} \right) \]
Units: Month

(178) \[ \text{Mfg ECR Time} = 2 \]
Units: Month

(179) \[ \text{Mfg Fail Rate[TASKS]} = \frac{\text{Mfg Work To Do[TASKS]} \times \text{Mfg Failure Fraction}}{\text{Time to Mfg}} \]
Units: Tasks/Month

(180) \[ \text{Mfg Failure Fraction} = \text{INTEG}(\text{Change in MFF}, \text{Normal Mfg Failure Fraction}) \]
Units: dimensionless

(181) \[ \text{Mfg Work To Do[TASKS]} = \text{INTEG}(\text{Design Completion Rate[TASKS]} - \text{Mfg Completion Rate[TASKS]} - \text{Mfg Fail Rate[TASKS]} \times \text{Backlog Inflow[TASKS]} / (1 - \text{Mfg Failure Fraction} - \text{Testing Failure Fraction} + \text{Mfg Failure Fraction} \times \text{Testing Failure Fraction}) \times \text{Time to Mfg}) \]
Units: Tasks

(182) \[ \text{Min Fraction Complete} = 0 \]
Units: dimensionless
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(183) Min Knowledge = 0.5
Units: dimensionless

(184) Min or Max[BLOG] = 1
Min or Max[DFCOST] = -1
Min or Max[IPT] = 1
Min or Max[PERF] = 1
Units: dimensionless

(185) Misc Costs = INTEG( Monthly Misc Costs , 0)
Units: $

* Allocation Factor for Discrete
Units: $/Month

Units: $/Month

(188) Monthly Revenue = Average Price * ( Production Rate Immature Products + Production Rate Mature Products + Production Rate Replacements )
Units: $/Month

(189) MTBR = 60
Units: Month

(190) New Product Life = Product Life Cycle - Residence Time Immature
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Units: Month

(191) New Production = Production Rate Immature Products + Production Rate Mature Products
Units: units/Month

(192) Normal Accountability Weighting[BLOG] = 1
Normal Accountability Weighting[DFCOST] = 0.3
Normal Accountability Weighting[IPT] = 0.1
Normal Accountability Weighting[PERF] = 0.9
Units: dimensionless

Units: Tasks/(Month*Worker)

(194) Normal Design Productivity[BLOG] = 0.4
Normal Design Productivity[DFCOST] = 60
Normal Design Productivity[IPT] = 10
Normal Design Productivity[PERF] = 0.053
Units: Tasks/(Month*Worker)

(195) Normal Fraction Filled in Design Phase = INITIAL( 0.375 )
Units: dimensionless

(196) Normal Max Initial Burn[TASKS] = Normal Design Productivity[TASKS] * Total Effort Available
Units: Tasks/Month
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(197) Normal Mfg Failure Fraction = 0.2
Units: dimensionless

(198) Normal Personal Knowledge Weighting[BLOG] = 0.9
Normal Personal Knowledge Weighting[DFCOST] = 0.3
Normal Personal Knowledge Weighting[IPT] = 0.2
Normal Personal Knowledge Weighting[PERF] = 0.9
Units: dimensionless

(199) Normal Probability of Accountability[BLOG] = 0.9
Normal Probability of Accountability[DFCOST] = 0.1
Normal Probability of Accountability[IPT] = 0.1
Normal Probability of Accountability[PERF] = 0.9
Units: dimensionless

(200) Normal Process Priority[BLOG] = 1
Normal Process Priority[DFCOST] = 0.2
Normal Process Priority[IPT] = 0.4
Normal Process Priority[PERF] = 0.9
Units: dimensionless

(201) Normal Proximity = 10
Units: dimensionless

(202) Normal Ratio[BLOG] = 1
Normal Ratio[DFCOST] = 0.5
Normal Ratio[IPT] = 1
Normal Ratio[PERF] = 0.2


**Using System Dynamics to Understand Barriers to Cost Reduction**

<table>
<thead>
<tr>
<th>Equation</th>
<th>Description</th>
</tr>
</thead>
</table>
| (203) | Normal Supplier Knowledge[BLOG] = 0.5  
Normal Supplier Knowledge[DFCOST] = 0.5  
Normal Supplier Knowledge[IPT] = 0.5  
Normal Supplier Knowledge[PERF] = 0.5  
Units: dimensionless |
| (204) | Normal Task Knowledge[BLOG] = 0.9  
Normal Task Knowledge[DFCOST] = 0.3  
Normal Task Knowledge[IPT] = 0.4  
Normal Task Knowledge[PERF] = 0.9  
Units: dimensionless |
| (205) | Normal Testing Failure Fraction = 0.05  
Units: dimensionless |
| (206) | Number of Products = \(( \text{Desired Status at End of Scheduled Release Cycle[BLOG]} / \text{Target Gap[BLOG]} \times (1 - \text{Discrete Switch}) + \text{Discrete Switch} \times \text{Projects in Discrete Case} \) \times \text{Products per Project}  
Units: Products |
| (207) | Obsolete Products = INTEG( Aging Rate , 0)  
Units: Products |
| (208) | Obsolete Rate[TASKS] = \( \text{MAX} (\text{XIDZ ( Design Work To Do[TASKS] , Indicated RT , 1e+006)} - \text{Design Completion Rate[TASKS]} , 0)) \)  
Units: Tasks/Month |
| (209) | Other Costs = 0 |
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Units: $/Month

(210) Perceived Effort Required[TASKS] = ( Desired Completion Rate[TASKS] + Desired Fraction of Gap to Close[TASKS] ) / ( Expected Design Productivity[TASKS] )
Units: Worker

(211) Perceived MFF = INTEG( Change in Perceived MFF , Normal Mfg Failure Fraction )
Units: dimensionless

(212) Perceived TFF = INTEG( Chg in Perceived TFF , Normal Testing Failure Fraction )
Units: dimensionless

(213) Percent Margin = XIDZ( Margin , Total Cost , 0)
Units: dimensionless

(214) Percent of Contract[BLOG] = 0.03
Percent of Contract[DFCOST] = 0
Percent of Contract[IPT] = 0
Percent of Contract[PERF] = 0.03
Units: dimensionless

(215) Personal Accountability Weighting[TASKS] = Effect of Relative Accountability on Weighting[TASKS] * Normal Accountability Weighting[TASKS]
Units: dimensionless

Units: dimensionless
(217) Personal Priority Weighting[TASKS] = Personal Knowledge Weighting[TASKS] * Personal Accountability Weighting[TASKS]
Units: dimensionless

Units: dimensionless

Units: dimensionless

Units: dimensionless

(221) Process Weighting Factor = 2
Units: dimensionless

(222) Product Life Cycle = 240
Units: Month

Units: $

(224) Product Weighting Factor = 1
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Units: dimensionless

Units: units/Month

Units: units/Month

Units: units/Month

(228) Production Spending = Immature Spending + Mature Spending + Replacement Spending
Units: $/Month

(229) Products per Project = 1
Units: Products/Project
(230) Projects in Discrete Case = 1
Units: Project

(231) Rate of Change Request[TASKS] = Work Failing Mfg[TASKS] / Mfg ECR Time
Units: Tasks/Month

Units: dimensionless

Units: dimensionless

Units: dimensionless

(235) Relative Communication[BLOG] = 1
Relative Communication[DFCOST] = 1
Relative Communication[IPT] = 1
Relative Communication[PERF] = 1
Units: dimensionless

(236) Relative Completion Rate Per Person[TASKS] = Indicated Complete per Person[TASKS] / Normal Completion Per Person[TASKS]
Units: dimensionless

Units: dimensionless
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(238) Relative Diversity[BLOG] = 1
Relative Diversity[DFCOST] = 1
Relative Diversity[IPT] = 1
Relative Diversity[PERF] = 1
Units: dimensionless

Units: dimensionless

(240) Relative Fraction Filled = Fraction Filled / Normal Fraction Filled in Design Phase
Units: dimensionless

Units: dimensionless

(242) Relative Perceived Mfg FF = Perceived MFF / Normal Mfg Failure Fraction
Units: dimensionless

(243) Relative Perceived TFF = Perceived TFF / Normal Testing Failure Fraction
Units: dimensionless

Units: dimensionless

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Units: dimensionless

(246) Relative Product Priority[TASKS] = XIDZ (Product Priority[TASKS], SUM (Product Priority[TASKS]), 0)
Units: dimensionless

(247) Relative Proximity = Actual Proximity / Normal Proximity
Units: dimensionless

(248) Relative Supplier Team Knowledge[TASKS] = Supplier Knowledge[TASKS] / Normal Supplier Knowledge[TASKS]
Units: dimensionless

Units: dimensionless

(250) Relative Team Size[BLOG] = 1
Relative Team Size[DFCOST] = 1
Relative Team Size[IPT] = 1
Relative Team Size[PERF] = 1
Units: dimensionless

(251) Repair Rate = Production Rate Replacements
Units: units/Month

(252) Replacement Spending = Average Cost Replacements * Production Rate Replacements
Units: $/Month
Residence Time Immature = \text{XIDZ} (\text{Immature Products}, \text{Maturing Rate}, \text{TIME STEP})

Units: Month

Revenue = \text{INTEG}(\text{Monthly Revenue}, 0)

Units: $

Rework Entering[TASKS] = \frac{(\text{Rate of Change Request}[BLOG] + \text{Testing Rate of Change Request}[BLOG])}{\text{Target Gap}[BLOG]} \times \text{Target Gap}[TASKS]

Units: Tasks/Month

SAVEPER = \text{TIME STEP}

Units: Month

Status Gap[TASKS] = \text{MAX}(\text{Desired Status at End of Scheduled Release Cycle}[TASKS] - \text{Indicated Status at End of Scheduled Release Cycle}[TASKS], 0)

Units: Tasks

Supplier Knowledge[TASKS] = \text{INTEG} (\text{Change Supplier Knowledge}[TASKS], \text{Indicated Supplier Knowledge}[TASKS])

Units: dimensionless

Surge Amplitude = 2

Units: dimensionless

Surge Duration = 5

Units: Month
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(261)  Surge Factor = 1 * ( 1 - Surge Switch ) + Surge Switch * ( ( Surge Amplitude - 1) * Pulse ( Surge Start Time , Surge Duration ) + 1)
Units: dimensionless

(262)  Surge Start Time = 4
Units: Month

(263)  Surge Switch = 1
Units: dimensionless

(264)  Target[BLOG] = 1500
Target[DFCOST] = 450000
Target[IPT] = 72
Target[PERF] = 1000
Units: Tasks/Project

(265)  Target Gap[TASKS] = MAX ( Min or Max[TASKS] * ( Target[TASKS] - Baseline[TASKS] ) , 0)
Units: Tasks/Project

(266)  Task Knowledge[TASKS] = INTEG( Change in Task Knowledge[TASKS] , Normal Task Knowledge[TASKS] )
Units: dimensionless

(267)  TASKS : BLOG, DFCOST, IPT, PERF

(268)  Tasks Performed Per Backlog Task[TASKS] = XIDZ ( Design Completion Rate[TASKS] , Design Completion Rate[BLOG] , 0)
Units: dimensionless
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(269) Testing Completion Rate[TASKS] = Testing Work To Do[TASKS] * (1 - Testing Failure Fraction) / Time to Test
Units: Tasks/Month

(270) Testing Dilution Time = XIDZ (Testing Work To Do[BLOG], Mfg Completion Rate[BLOG], TIME STEP)
Units: Month

(271) Testing ECR Time = 2
Units: Month

(272) Testing Fail Rate[TASKS] = Testing Work To Do[TASKS] * Testing Failure Fraction / Time to Test
Units: Tasks/Month

(273) Testing Failure Fraction = INTEG(Change in TFF of Testing WTD, Normal Testing Failure Fraction)
Units: dimensionless

(274) Testing Monthly Labor Cost = 1.6e+007
Units: $/Month

(275) Testing Projects Performed = XIDZ (Testing Tasks Performed, Target Gap[BLOG], 0)
Units: Project/Month

Units: Tasks/Month
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(277) Testing Tasks Performed = Testing Fail Rate[Blog] + Testing Completion Rate[Blog]
Units: Tasks/Month

(278) Testing Work To Do[TASKS] = INTEG( Mfg Completion Rate[TASKS] -
Testing Completion Rate[TASKS] - Testing Fail Rate[TASKS] ,
Units: Tasks

(279) TIME STEP = 0.0625
Units: Month

(280) Time to Absorb = 9
Units: Month

(281) Time to Adjust Production = 2
Units: Month

(282) Time to Change Suppliers = 12
Units: Month

(283) Time to Close[BLOG] = 1
Time to Close[DFCOST] = 3
Time to Close[IPT] = 3
Time to Close[PERF] = 3
Units: Month

(284) Time to Fill Agreements = 15
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Units: Month

(285) Time to Mfg = 10
Units: Month

(286) Time To Perceive Change in Demand = 2
Units: Month

(287) Time to Test = 6
Units: Month

(288) Time to Update Status[BLOG] = 1
Time to Update Status[DFCOST] = 3
Time to Update Status[IPT] = 1
Time to Update Status[PERF] = 1
Units: Month

(289) Total Allocation = SUM ( Design Allocation[TASKS!] )
Units: Worker

(290) Total Cost = Labor Cost + Misc Costs + Total Manufacturing Cost
Units: $

(291) Total Delay[TASKS] = Estimated Delay[TASKS] + Marginal Delay
Units: Month

(292) Total Effort Available = Design Staff Size * Fraction of Design Time Available
Units: Worker
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(293) **Total Manufacturing Cost** = \( \text{INTEG} \left( \text{Production Spending} , 0 \right) \)

Units: $

(294) \text{Trade Factor}[\text{BLOG}] = 1
\text{Trade Factor}[\text{DFCOST}] = 0.0011
\text{Trade Factor}[\text{IPT}] = 0.83
\text{Trade Factor}[\text{PERF}] = 1.2

Units: $/Task

(295) **Unfilled In Design Phase** = Confidential Agreements Required / Indicated RT

Units: Agreements/Month

(296) **Unit Conversion** = 1

Units: $*\text{product}/(\text{unit}*\text{Task})

(297) **Wear Out Rate** = Field Units / MTBR

Units: units/Month

(298) **Width** = 0.75

Units: dimensionless

(299) **Win Rate** = 0.1

Units: Project/Month

(300) **Work Failing Mfg[TASKS]** = \( \text{INTEG} \left( \text{Mfg Fail Rate[TASKS]} - \text{Rate of Change Request[TASKS]} , \text{Backlog Inflow[TASKS]} \right) / \left( 1 - \text{Mfg Failure Fraction} - \text{Testing Failure Fraction} + \text{Mfg Failure Fraction} * \text{Testing Failure Fraction} \right) * \text{Mfg Failure Fraction} * \text{Mfg ECR Time} \)

Units: Tasks
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(301) \[
\text{Work Failing Testing[TASKS]} = \text{INTEG( Testing Fail Rate[TASKS] - Testing Rate of Change Request[TASKS], Backlog Inflow[TASKS] / ( 1 - Mfg Failure Fraction - Testing Failure Fraction + Mfg Failure Fraction \times Testing Failure Fraction ) \times ( 1 - Mfg Failure Fraction ) \times Testing Failure Fraction \times Testing ECR Time )}
\]

Units: Tasks