Staying Nimble: A Flexible Approach to Complex Product Development in a Rigid Environment

by

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B.S. Mechanical Engineering
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Submitted to the System Design and Management Program
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ABSTRACT

Incorporating flexibility into business processes can provide organizations with increased agility to respond to uncertainty within complex product development projects spanning across many years and many organizations. Current methods used for determining value in order to justify associated costs for implementing and maintaining process flexibility are not sufficient in capturing the full worth of flexibilities within processes.

A framework is developed which builds upon on prior research to assess value of flexibility within product development processes, combining benefits of rigid constraints with flexible options. Valuation of a simple potential flexibility within an aircraft development project is used to demonstrate the use of the framework in practice and to evaluate strengths and weaknesses of the framework.

The method of valuation provides benefit of capturing hidden value that would otherwise be ignored or left on the table and provides further insight into the behavior of the process flexibility in a manner which leads to optimization of that flexibility. However, adoption of the framework is hindered by the skillset required in practice along with the inherent inability to demonstrate its full value, as measured by actual performance.

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1 Introduction

1.1 Motivation

Over the past eight years, the oldest privately-owned aircraft manufacturing company in New York transformed from a small fully vertically-integrated company into an extension of a very large major enterprise with subsidiaries spanning across the world. The transition had provided the former privately-owned company with many more capabilities and opportunities than it once had. However, many great capabilities were also lost in the process.

Before some of the major transformations took place, I recall testing the landing gear of an unmanned helicopter in development. Several aircraft had already been built and were bound for customer flight testing later that year. Qualification of the aircraft was being completed concurrently with production. Resources and time were significantly constrained. The majority of the test fixture was designed based on material already in-house. In those days, an engineer could take a short walk from their desk to the metals department and see exactly what was available to work with. It was almost like taking a walk through your dad's workshop, assuming that your dad happened to have hundreds of metal extrusions, bars, rods, sheets and plates of varying alloys and tempers lying around. The test fixture and set-up may not have been the most elegant, but it worked. Unfortunately, the initial design of the landing gear did not. The test article failed during dynamic testing. But after some analysis and redesign, the next test article was built and ready for testing within just over a week. Without internal capabilities, testing could have been delayed for months due to all the processes associated with the complex machining, routing, drilling, forming, heat treatment, assembly, instrumentation, and calibration. Instead, we quickly recovered, qualified the new design, and replaced the landing gear on the previously built aircraft in time for the first flight milestone. The success of this rapid response in product development was primarily attributed to the existence of excess inventory of raw material, as well as the vertically-integrated manufacturing capability that permitted complete manufacture of the finished product from raw material without the use of any processes outside the walls of the company.

There is a high cost associated with having vertically-integrated manufacturing capabilities, excess inventory of material to "play with", and other such flexibilities. There are also high costs associated with not having what you need, when you need it. It can sometimes be difficult to comprehend the full extent of value provided by flexibilities within an organization's operating processes and procedures. To be able to accurately assess the worth of those flexibilities and to clearly communicate that value across all stakeholders and decision makers assessing whether or not to incorporate or retain those flexibilities can present an even greater challenge.

Just before the majority of in-house manufacturing capabilities were sold off and eliminated from the small NY facility, I remember taking one last walk thru the plant with the Director of Engineering. We couldn't help but look around and reflect upon the unique capabilities that we were about to part with. Today, not many aircraft manufacturing plants in the United States receive raw sheet metal at one end of the factory and fly aircraft out the other. I would be surprised if I see anything like it again.

This dramatic change and loss of what I perceived as extremely valuable assets led me to wonder if decision makers responsible for eliminating such a wealth of capability could have truly understood the full value of those flexibilities. Could I even reasonably justify the cost of maintaining such flexibility? Through my coursework within the System Design and Management program at MIT, I have been exposed to methods for assessing value of flexibility within the design of products and systems. But what about the business processes within highly structured companies that govern the development of those products and systems. As processes evolve and mature over many years, many rigid constraints are added as an attempt to provide focus, increase efficiency, and eliminate waste. However, it often feels that such constraints have an opposite effect, which may ultimately hinder the speed of product development. It is believed that flexibility within processes can be incorporated to improve the agility of a company and improve the likelihood of success within product development. However, to do so, one must first have a means of quantifying value in a manner in which decision makers can justify the incorporation and maintenance of such flexibility within their product development processes.

1.2 The Importance of Assessing Value

Adapting to uncertainties in the constraints of a rigid environment is difficult, at best. Highly structured corporate environments provide efficiency and stability in a dynamic world. These environments often possess valuable resources which can be tapped to address a wide range of challenges. However, the very principles which have built up such a wealth of resources may also constrain them from adapting and seizing new and unexpected opportunities. Requirements change as the voice of the customer adapts to changing environments, or as new customers become available with different voices. Regulations change and alter technological playing fields. New manufacturing technologies and design capabilities become available which can change the method of development. New suppliers may become available as existing ones become obsolete. Corporate organizations and partnerships change, creating new possibilities and/or alter existing capabilities. Some rigidity may help avoid falling into the trap of amplifying dynamics. Although, too much rigidity may also prevent seizing opportunities.

Many organizations strive to become more agile in order to respond faster to changes in customers' needs and desires. Every engineer developing a new product must do so in an environment filled with uncertainty. The longer it takes to develop a product, the more likely that the needs of the customer will change over that time period. For complex products requiring significant time to develop, such as aircraft or even larger systems of systems, what the customer truly wants at the time of the product launch may be quite different from what they told the developer years or decades before when the project started and when requirements were initially defined.

The difficulty many companies face is the ability to effectively place value on a particular flexibility and justify the costs associated with the incorporation and the maintenance of that flexibility. The story of the small aircraft company discussed in the previous section did not end with it simply losing unique capabilities. It ended a year later when the NY facility was shut down. The larger organization needed to downsize due to forecasted reductions in market demand. The NY facility was purchased at a time when it was nimble and able to quickly react to changes in manufacturing demand. The value of maintaining flexibilities within its manufacturing processes was not perceived sufficient to justify associated costs. The value of the

NY facility degraded as flexibilities were eliminated over time without understanding their true worth. At the time of the shutdown, the NY facility was much more integrated with the larger company and operated under similar processes and procedures, but was no longer considered valuable enough to remain in operation.

As companies become larger and systems become more complex, aircraft systems are typically developed between many companies and across multiple organizations within the same enterprise. Standard processes can improve the efficiency and quality of interactions between the many different organizations thru commonality. However, processes that work well for one group may hinder the performance of another. Each organization has different needs, which may change over time. Differences in processes and procedures may provide a diverse network of complementary competences and capabilities. For example, procedures that benefit the rapid development of new aircraft may hinder the manufacture of mature models in production, and vice versa. Likewise, processes that improve the high volume production of aircraft with few configuration variations may certainly not work quite as well with low volume production of aircraft with many types of configurations.

Some companies valuate flexibilities in processes similar to process improvements intended to address known problems. They may use metrics to compare the performance of a process before and after a change to quantify the difference and associate value with the actual outcome. Such metrics only measure known outcomes that occurred within circumstances of the past. The danger in relying solely on past outcomes is that similar outcomes may not be experienced in the future as environments and circumstances change. Many flexibilities are intended to improve the likelihood of success of events in the future which have an infinite number of outcomes, and may not be valued in the same manner. Thus different methods of assessing their value are needed.

1.3 Thesis Context

This thesis is intended to provide product developers with a framework for evaluating the value of incorporating and maintaining flexibility in operating procedures and processes within their organizations to improve the likelihood of success of product development projects. This proposed framework is intended for individuals and organizations that develop complex projects spanning several years or decades. In particular, this framework is intended to provide the most benefit for highly structured organizations which may struggle with balancing flexibility within rigid constraints to provide the best possible outcomes.

This thesis focuses primarily on the product development of aircraft. The aircraft industry is a "show-me" industry. In order to develop aircraft and aircraft systems, one must build functional prototypes to demonstrate performance and capabilities. Developers build prototypes not only to better understand issues early in the development process, but also to retain the interests of customers during the very long development process. Therefore, it is appropriate to focus much attention on principles, processes and flexibilities related to manufacturing with special consideration to very low production quantities with a high level of variation, lead time, and uncertainty. Single quantity production orders of aircraft presents an extreme test of manufacturing flexibility due to the thousands of unique parts.

The term "flexibility" varies considerably depending on the audience, despite the significant amount of research on the subject. Some define flexibility loosely as simply meaning "leeway", or the opposite of "firmness" inherent in formalities (Tatikonda, 1999). For the purpose of this research, the term "flexibility" will simply be defined as an ability to either exercise options or refrain from exercising options, with relative ease at some point in the future. Flexibilities may be incorporated into many different aspects of product development, including the resources, business processes and procedures, and the product itself. Typically, there is a cost associated with incorporating or maintaining a flexibility within a process that must be carefully considered and weighed against the benefits created by that flexibility. Throughout this paper, the term "rigidities" will also be used. Rigidities refer to constraints within processes or procedures which must be strictly adhered to under all conditions. Examples of flexibilities and rigidities are presented in Table 1.

Process	Flexibility	Rigidity
Supply Chain Process	**Multiple Manufacturing Options** The capability of being able to form and heat treat a metal bracket either using in-house resources or offloading the work to an outside supplier depending on capacity.	**Sole Manufacturing Option** Constraint of outside processes as a sole option (if the company has no applicable internal manufacturing capability).
Drawing Review & Release Process	**Configurable Design Review Workflow** The option of selecting specific design reviewers and approvers and assigning the sequence in which the reviews occur within a sequence or parallel path.	**Predefined Design Review Workflow** Standard work that defines the work flow of design reviews by automatically selecting engineering disciplines and individuals to review the design regardless of unique qualities within the design.
Design Validation Process	**Deferred Interface Validation** Option of being able to reduce the level of interface validations prior to design release and defer a complete evaluation of interfaces upon build of a prototype or test article. Organizations which are capable of building and testing components very quickly may defer some validation efforts from within the upfront design scope to the testing phase in order to release a design faster, build it, and test it as quickly as possible to determine if the design is sufficient.	**Upfront Interface Validation** Requirement for upfront conduct of an exhaustive fit check of interfacing features within design tolerances prior to manufacture. Organizations which are faced with greater costs in build and testing may place more stringent requirements upfront, requiring more time and effort during the pre-release design phase to reduce downstream risks.

Table 1: Examples of Flexibilities and Rigidities

This thesis discusses why conventional methods of assessing process improvements is not sufficient for assessing the value of flexibilities within those processes. Significant value may go unnoticed, ignored, or left on the table without considering impacts of system dynamics or risks and opportunities. The process of assessing value may also expose detrimental or adverse effects of incorporating flexibilities within process changes.

1.4 Thesis Structure

This thesis presents a framework based on prior published research. The framework is then utilized to assess the value of flexibility in a sample product development process under various conditions. The flexibility example is used to demonstrate how the framework can be used, as well as to assess strengths and weaknesses of the framework itself. The ultimate intent of this thesis is to develop and demonstrate a useful framework for assessing value of flexibilities within product development processes and procedures.

This framework utilizes previously developed analytical tools and methods in a manner intended to guide the decision of whether or not to incorporate flexibilities into product development processes. Monte Carlo simulations are used to assess the value of flexible options within the product development processes. System dynamics models are used to understand the behavior within systems resulting from fluctuations within parameters along reinforcing and balancing causal loops. Business processes within product development projects can be highly integrated with other processes that have complicated dynamic relationships that can be modelled in a manner that defines the behavior of that system or process. This approach was developed as a practical means to analyze a complex system with many interrelationships and a wide range of possibilities.

2 Literature Review

2.1 Valuation of Processes

It would not be appropriate to discuss value within product development processes used in aircraft development without first considering the conventional approach of utilizing Value Stream Analysis and Mapping (VSA/M). As Hugh McManus and Richard Millard discuss in their 2002 research, "Value Stream Analysis (VSA) is a method by which lean principles are applied in the examination of business processes". In their research, improvements within product development processes were measured across nine U.S. aerospace development sites to assess the impact of VSA/M within the aerospace industry. Following the increasingly popular lean methodology developed by the Toyota Motor Corporation and applied in MIT's Lean Aerospace Initiative, VSA/M is intended to identify and eliminate waste within business processes. Within VSA/M, waste falls within the categories defined in Table 2.

	Waste	Description
1	Overproduction	too much detail, unnecessary information, redundant development, over-dissemination, pushing rather than pulling data
2	Transportation	information incompatibility, communication failure, multiple sources, security issues
3	Waiting	information created too early or unavailable, late delivery, suspect quality
4	Processing	unnecessary serial effort, too many iterations, unnecessary data conversions, excessive verification, unclear criteria
5	Inventory	too much information, poor configuration management, complicated retrieval
6	Unnecessary Movement	required manual intervention, lack of direct access, information pushed to wrong sources, reformatting
7	Defective Product	lacking quality, conversion errors, and incomplete, ambiguous, or inaccurate information, lacking required tests/verification

Table 2: Categories of Waste within Value Streams (McManus and Millard, 2002)

In a 2010 research conducted as part of the Lean Advancement Initiative (LAI) at MIT, Dr. Josef Oehmen and Dr. Eric Rebentisch have concluded that, on average, 77% of product development activities are waste, based on prior research and experience. This is shown in Figure 1 as a combination of waste due to idle activity and waste within executed activity. Oehmen and Rebentisch use the definition of waste presented by Taiichi Ohno in the "Toyota Production System", that waste is "all elements that only increase cost without adding value". (Oehmen and Rebentisch 2010)

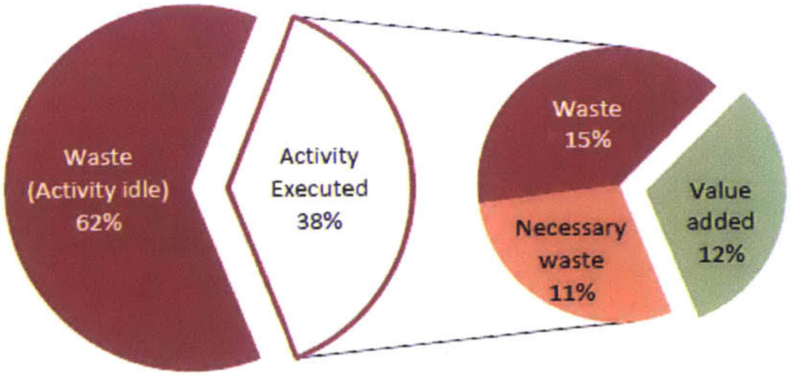


Figure 1: Waste within Product Development (Oehmen and Rebentisch, 2010)

Several tools have been observed to have been used in practice in the aerospace industry to aid in the mapping of value streams, including Gantt charts, Ward/LEI maps, process flow maps, "Learning to See" methods, system dynamics modeling, and design structure matrices. Based on McManus and Millard's research at the nine aerospace sites, it was concluded that there was not a single "best practice" or tool that yields success, but rather an integration of varying tools that best fit the individual circumstances. These tools or combination of tools were utilized within the following VSA/M steps;

1) Assemble and train VSA/M team
2) Select Value Stream to improve
3) Define Value Stream elements
4) Analyze and map Current State
    a. Analyze and map Future State
    b. Analyze and map Ideal State
5) Implement new process
6) Continuous Improvement

The VSA/M team would assess predicted improvements based on comparing the Future State Map to the Current State Map. Actual success was determined based on demonstrated performance improvements after the Future State was incorporated, as compared to the prior state. The difficulty observed was in the collection of necessary data used to compare metrics of current process states, which was used to consider the value of the activity. In addition, McManus and Millard indicate that the quantification of value of activities within VSA/M efforts have ranged across different levels of subjectivity from simple categorization (value added, necessary non-value added / enabling, and non-value added) to scaled ratings. (McManus and Millard 2002)

It is important to highlight that improvement observed by McManus and Millard is quantified based on demonstrated abilities. Prior to incorporation, a future state is mapped out and compared to the current state. After incorporation, the process is analyzed based on behavior in conditions present at that time. The value is either based on metrics obtained during actual conditions or expected behavior within assumed or forecasted conditions in which the process will be executed. Furthermore, value of tasks within value steam map can be subjective and based on the perception of VSA/M team members. A potentially valuable element under different conditions could be removed if perceived to create waste and be of little value within the process being evaluated under specific conditions.

From my experience, what may be considered waste by one group, and which may fall under one of the seven waste categories within Table 1, may be considered valuable to others. Considering the example of rapid development capabilities described Section 1.1, the excess inventory of raw material could easily be categorized as a waste due to excess inventory with no apparent need. However, the readily available material became overwhelmingly necessary for the test team to recover from a failed test in order to support critical development milestones.

McManus and Millard also assess the impact of context quantification on the success of VSA/M. In this study, "context quantification" refers to a quantifiable value or rating used to represent how much the lean trait addressed the extent of the process's environment. As shown in Figure 2, increased context quantification tended to yield an increase in success, as observed across the nine sites. A high-level view of the product development process tended to provide the necessary context needed at a lower level analysis. The high level analysis provided context but considered most processes as value-added, rather than identifying processes with little or no value to be removed. Whereas the lower level analysis provided insight into process improvements but failed to provide success without context. A combination of utilizing a high-level representative tool, along with detail-level process flow map and a design structure matrix was suggested to combine benefits (McManus and Millard 2002). This approach appears to align with the philosophy that without a "big-picture" map, one can easily go very far down a path in the wrong direction.

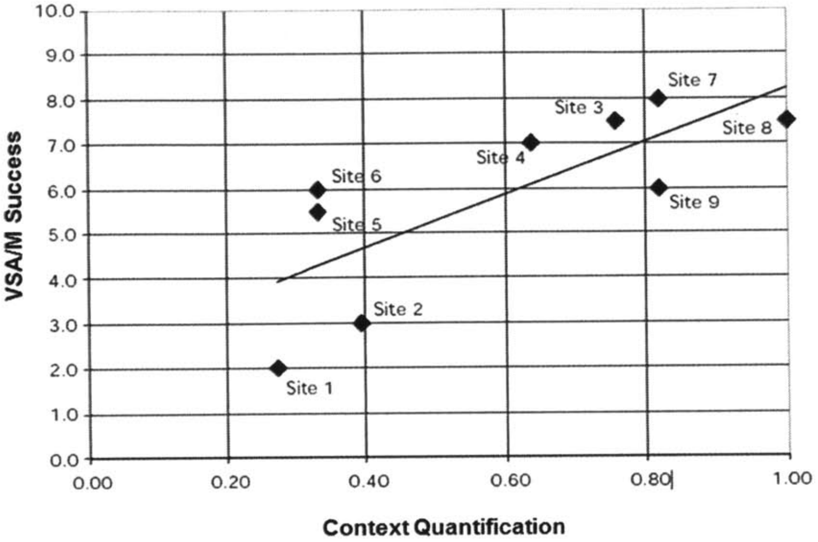


Figure 2: Correlation between Lean Context and Process Improvement Success (McManus and Millard 2002)

Research conducted by Ryan Whitaker further summarizes prior work in the area of VSA/M and Lean conducted by Slack, Millard, Chase, McManus, and Rebentisch, which indicates that although value definition is difficult, value stream mapping is a powerful means of evaluating value which should be utilized as a first step for optimizing the product development process as well as an enhancement to other optimization tools. (Whitaker 2005)

2.2 Uncertainty in Product Development Process

Continuous failures within complex and large product development projects indicate that conventional methods and approaches of improving design efficiency by eliminating waste and creating value may not be sufficient due to the uncertainties inherent within processes. More than often, product development projects are planned based on static forecasts. (Oehmen and Seering 2011)

Product development projects face many forms of uncertainty, including uncertainties in technology, requirements, demand, cost, resources, quality, etc. (Tatikonda 1999; de Neufville

2011). Planning is an essential part of product development in order to secure necessary resources and provide direction. Tatikonda reminds us that the number of steps required and exact method to develop a new product may not be known at the start of the project. In most cases, the complete set of requirements and precise means of creating a product to meet the changing needs of the customer are seldom fully known at the start of any project. Often, insufficient planning is blamed for project failures. The health of a project is often measured based on the execution of a plan, which is likely to be base-lined during a time of high uncertainty. The planning phase is often separated from the execution phase even though phases may overlap and contain iterative steps. The more effort expended during the planning phase may produce a higher likelihood of project success to some extent, but will never eliminate uncertainty. Forecasts associated with product developments are fundamental and important for planning purposes, but are almost always wrong (de Neufville 2011). And yet, the success of most projects is measured relative to some initial estimate. Many managers add buffers or "management reserves" to estimated project parameters to account for the unknown. However, too much buffer could be difficult to justify, result in missed opportunities, reduce confidence in management's competence, and negatively impact business relationships. Too little buffer may result in excessive cost over-runs, delays, penalties, and reduced future business opportunities. Regardless of the means, all development projects must account for uncertainty, primarily in the execution phase.

Although product development is typically considered separate from production in the product lifecycle, uncertainties associated with manufacturing certainly impacts the product development process during the development of prototypes, test articles, and manufacturing processes and techniques for production. Uncertainties associated with manufacturing variation, raw material costs, and process flow are typically evaluated during product development, but often do not have as much impact on initial fabrication of low quantities as they do with production of high quantities. Whereas uncertainties associated with interface coordination (fit), process variables, and material availability may not have as much impact on production of high quantities as they do with initial fabrication of lower quantities.

A significant amount of prior work surrounds the description and classification of different types of uncertainties including known uncertainties, ambiguous uncertainties (unknown probability distributions), unforeseeable uncertainties, endogenous uncertainties, and exogenous uncertainties (Oehmen an Seering 2011; Halpern 2005; Knight 1964; Lindley 2006; Morgan and Henrion 1992; Paté-Cornell 1996; Taleb 2010; Pich et al. 2002; Chalupnik et al. 2009; de Weck and Eckert 2007; McManus and Hastings 2005). Uncertainty may be either negative or positive, such as new markets, improved manufacturing technologies, and increased demand. Regardless of the where the uncertainty originates from, processes within product development are subject to their associated risks and opportunities.

2.3 Flexibility within Processes

Flexibility in product development and manufacturing processes can be incorporated by an organization to respond to the many uncertainties that exist in their operating environments (de Treville, 2007). Flexible options may exist without being utilized. For example, a flexible aircraft design may accommodate the ability to be configured for operations in the hot mountainous terrain of Afghanistan or be easily reconfigured for operations aboard naval vessels in cold arctic oceans. Although the design may require additional complexity and some degree of modularity, some cost and performance penalties can be avoided with the flexible configuration. Alternatively, a robust design would accommodate a much larger range of environmental extremes with a single configuration. The aircraft may never operate in the arctic, but if needed in the future for some unknown demand or mission requirement, it can.

Both flexibility and robustness can be used to address uncertainty. In early 1990's, the term "rigid flexibility" was made popular by Collins and Schmenner, which describes a strategy to produce manufacturing flexibility thru rigidity in simple, fool-proof processes and concomitant procedures designed to be followed by a dedicated and disciplined workforce. For example, design practices and modelling techniques may be standardized, which then provides an ease of transferring designers onto a project who use the same standardized procedures on other work. The rigidity would be the constraints defined within standard work for designing and modelling components. The flexibility would be the ability to easily transfer resources across projects as needed. Collins, et. al. tested the concept of rigid flexibility and determined that companies with higher simplicity and discipline can achieve a higher degree of flexibility, based on an empirical study involving over 800 manufacturers across 17 industries and 5 countries.

The concept of rigid flexibility naturally follows common principles associated with lean manufacturing of eliminating waste by streamlining business processes concerned with the flow of material and information thru the supply chain, with consideration to the full product development process, from conception to production (Collins et. al., 1998). The empirical study mentioned above was generalized across many different types of manufacturing industries and companies. Strategies that work for some or most companies, may not be appropriate for all, and should therefore be evaluated in accordance with the unique needs of the individual group. The rigid flexibility model requires procedures to be simple and rigid, including the standardization of procedures. Although, there is certainly benefit in improving the efficiency of inter-organizational interactions, the question still remains how should procedures be standardized? Should one group adopt the procedures of another based on the level of previous success of each party? Should groups with conflicting needs negotiate potential trade-offs to develop standard procedures which are suboptimal for one or both groups? Or should some procedures remain standard and rigid, while others incorporate flexibility?

Many believe that there is some optimal balance between rigidity and flexibility in the development process, rather than leaning all towards one side or the other. When evaluating success of a project's execution, Tatikonda et. al. argue that firmness is achieved through project management formality, whereas flexibility is achieved by project management autonomy and resource flexibility. Figure 3 illustrates this framework of rigidity and flexibility within project execution methods leading to success within project execution. Similar metrics to Collins et. al. were used when evaluating the success of a project.

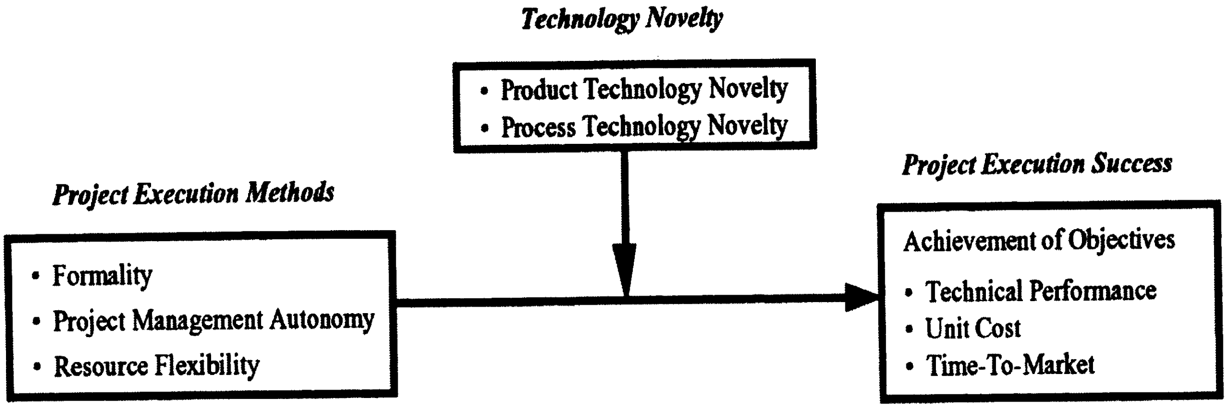


Figure 3: Conceptual framework of project execution effectiveness in product development projects (Tatikonda et. al. 2000)

2.4 Difficulty of incorporating flexibility

In 1995, David Upton conducted a study of North American manufacturing firms that revealed 40% of flexibility-improvement efforts at the companies studied were considered to have been unsuccessful or disappointing. He observed several issues when incorporating flexibility in practice. Flexibility is difficult to measure. In practice, the full value may not be realized due to the difficulties associated with quantifying potential abilities as compared to demonstrated abilities. Many of the unsuccessful attempts he observed were due to the inability to effectively measure the flexibility or due to failure of identifying what kind of flexibility was needed (Upton, 1995). Dolek points out that "despite the work produced by academia regarding the subject of flexibility, there are few firms that have achieved the mastery required to make the flexibility a key source of competitive advantage" (Dolek, 2007).

Comparing empirical data before and after incorporation of process changes is useful in understanding the actual impacts resulting from those changes within the specific conditions. However, many times the primary intent of flexibility is to mitigate a wide range of uncertainties, rather than to simply address a set of pre-determined conditions or known environments. The value of such options often resides within the ability to adapt to specific circumstances that may or may not occur in the future. Improved or degraded performance measured upon implementation of flexibility can fail to capture the true worth of that flexible option incorporated within a process.

Measuring the relationship between flexibility and performance will vary from one project to another based on the unique project parameters. In addition to differences between project definitions, the valuation of flexibility will differ between projects, preventing true "apples to apples" comparisons (Chen, 1996; Dolek, 2007). Therefore, perhaps actual performance is not a true measure of the flexibility's value. And if the value of the flexibility changes with each project, then perhaps the value can be considered from multiple lenses or system boundaries. There may be one value when considering the flexibility at the project level. There may be a different value associated with the flexibility when looking at it from the company level in which multiple projects are impacted. And there may be another value when considering the flexibility incorporated at a completely different company working on the same project.

Furthermore, McConnell highlights several additional inadequacies within current approaches for designing flexibility into a system, including;

- The ability for quantitative tools to account for parameters which are considered difficult to quantify.
- Limitations within qualitative tools to determine effects of system interrelationships.
- Lack of training in practice for responsible professionals to design, evaluate, and manage flexible systems.
- Questionable ability of institutions to incorporate and maintain flexible systems in practice. (McConnell 2007)

Thus, the primary concern with incorporating flexibility seems to center around the need for a reliable means of quantifying the value with consideration to potential outcomes across different environments in a manner which can be easily determined by trained professionals and easily explained to stakeholders.

2.5 Valuation of Flexibility

Many agree that it is appropriate to evaluate flexibility as a real option. Flexibility is undervalued when using cost-based or passive net present value analyses while only considering deterministic conditions. One method may be to evaluate economic trade-offs between the costs incorporating and maintaining a flexibility and the benefit of being able to respond to uncertainties, such as the variation of demand. Based on Fine and Freund's economic model, they argue that flexibility should be incorporated when the expected value of its best usage in each state, summed over the states, exceeds its cost (de Treville et al, 2007). Another approach is to incorporate a Monte Carlo simulation which transforms distributions of uncertain inputs into distributions of outputs based on the process of repeatedly sampling uncertain inputs and recording the corresponding results. Monte Carlo simulations certainly provide a clear understanding of the impact that various flexibilities may have on projects with respect to the full range of possibilities. In addition to understanding the expected value that a flexibility strategy may provide, the distribution of outcomes can be analyzed to help management determine which option is best. Some flexibilities may exhibit risk adverse behaviors which help a project to better avoid potential failures. Others may exhibit the ability to have higher likelihoods of obtaining new opportunities (de Neufville and Scholtes, 2011).

Research conducted by Joshua McConnell presents a framework which included the use of a system dynamics model and options valuation approach to quantitatively evaluate flexibility in complex systems. A case study involving the evaluation of flexibilities within an aircraft development project was analyzed by generating probabilistic distributions of benefits (output) resulting from a system dynamics model that incorporated inputs with probability distributions, as shown in Figure 4.

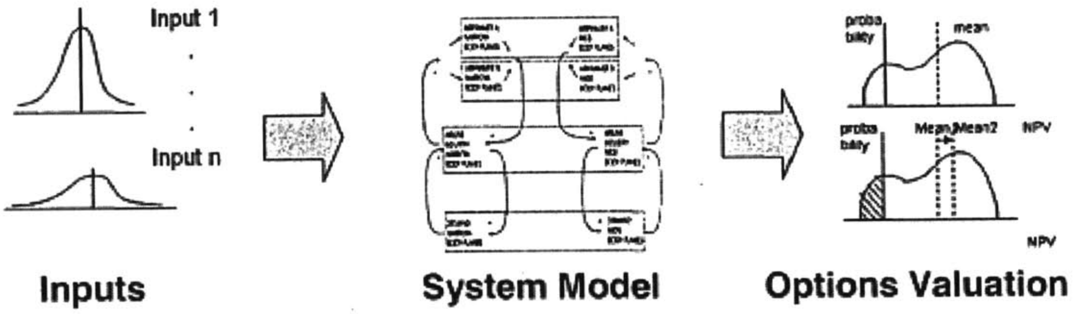
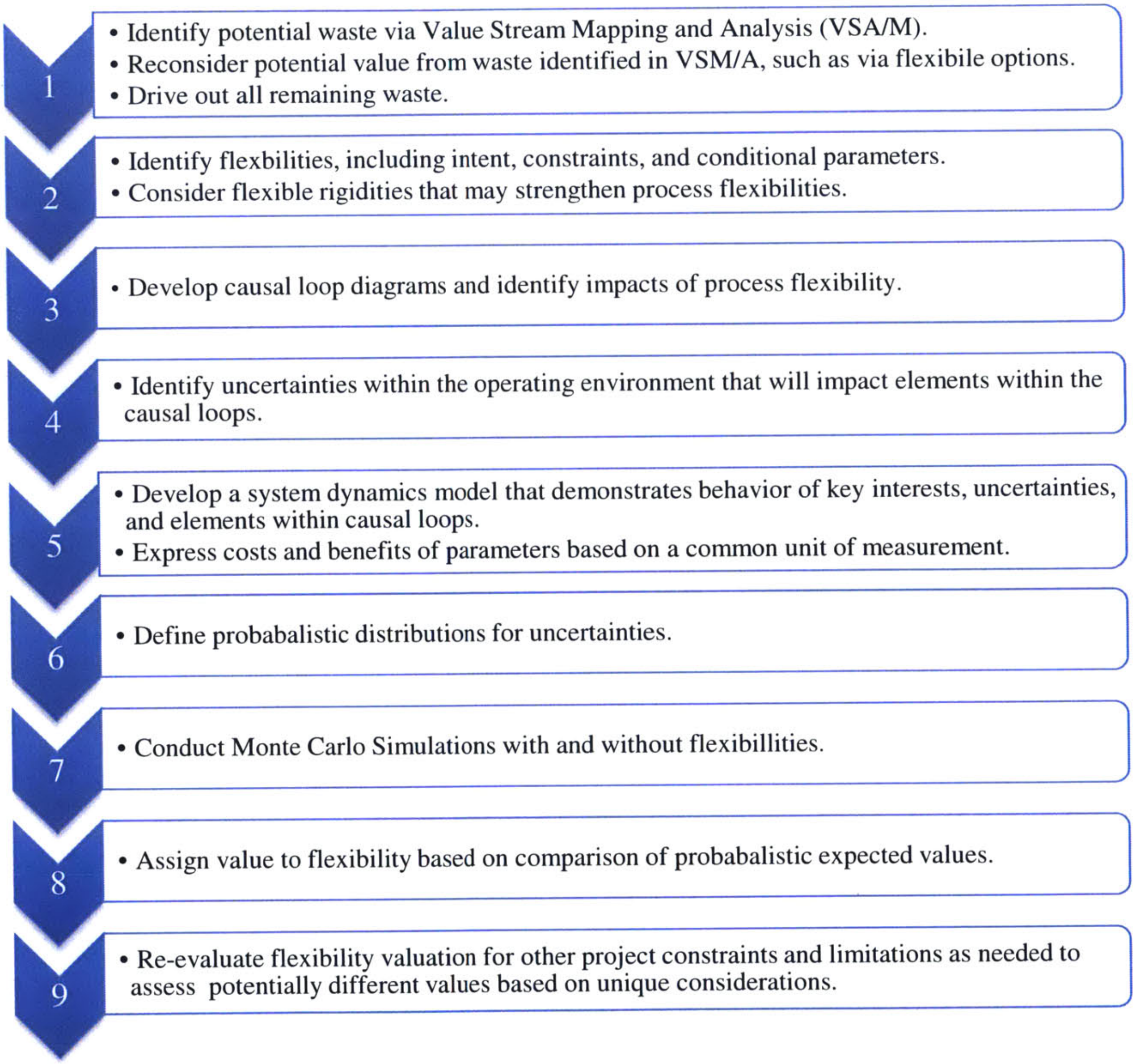


Figure 4: Quantitative Analysis Approach using System Dynamics Model (McConnell 2007)

Value of the flexibility was determined by comparing the probability distribution function averages for systems with flexibility and without flexibility, which followed prior work (Tufano and Moel 1997; Clemons and Gu 2003; Greden et al. 2005; Miller 2005). McConnell points out that the valuation of the flexibility was considered to vary as a function of the selected metric. Within the case study being analyzed, multiple goals existed across varying corporate strategies. This presented multiple possible metrics which could have led to different rules with exercising the flexibility, and ultimately different quantitative values for the flexibility. He also points out that multiple stakeholders have trade-offs when it comes to benefits and costs that must be considered. When evaluating flexibility in a case study of a transportation system, he observed how a flexible option created value for one stakeholder at the expense of another. He concludes that the benefits and costs are disturbed differently. (McConnell 2007)

3 A New Flexibility Valuation Framework

This thesis proposes a framework for assessing the value of flexibilities within processes, as presented in Figure 5. This builds upon the significant amount of research and practical implementation of process valuation used in practice and the relatively low, but growing, experience in valuation of flexibilities within systems and products.



1
- Identify potential waste via Value Stream Mapping and Analysis (VSA/M).
- Reconsider potential value from waste identified in VSM/A, such as via flexibile options.
- Drive out all remaining waste.

2
- Identify flexbilities, including intent, constraints, and conditional parameters.
- Consider flexible rigidities that may strengthen process flexibilities.

3
- Develop causal loop diagrams and identify impacts of process flexibility.

4
- Identify uncertainties within the operating environment that will impact elements within the causal loops.

5
- Develop a system dynamics model that demonstrates behavior of key interests, uncertainties, and elements within causal loops.
- Express costs and benefits of parameters based on a common unit of measurement.

6
- Define probabalistic distributions for uncertainties.

7
- Conduct Monte Carlo Simulations with and without flexibillities.

8
- Assign value to flexibility based on comparison of probabalistic expected values.

9
- Re-evaluate flexibility valuation for other project constraints and limitations as needed to assess potentially different values based on unique considerations.

Figure 5: Valuation Framework

As discussed in the prior section, there are certainly benefits to utilizing design efficiency approaches such as the VSA/M approach which incorporates methods from lean manufacturing to drive out waste and non-value added elements within a process. This is true for manufacturing processes, as well as business processes used in product development. However, waste should not be eliminated without careful consideration of potential value. Therefore, it is recommended to use VSA/M as an initial step of trimming out the "fat" to develop a streamlined and efficient process. As waste and non-value elements are identified, consider whether those elements or parts of those elements can be used or modified into a potential flexibility which may then provide value to the organization under different conditions or environments. This first step is considered an important means of developing simple and straight-forward processes without automatically rejecting *potential* value. The value of potential flexibilities will later be determined.

When evaluating a process during the design efficiency phase, consider potential rigidities or formalities such as standard work or procedures that can be coupled with flexible options. These "flexible rigidities" can lay out a simple foundation that can develop a significant amount of agility with other flexibilities. For example, a group of multiple organizations designing a large scale system should have a common language in which to communicate. It may not be practical or make sense for all companies involved to use the same drawing format, but it may make sense to develop constraints for modelling conventions, shared design standards, a common configuration management practices, and a common repository for shared data. These constraints would provide operating rules of engagement across organizations. Expectations are understood upfront and organizations have a common ground on which to collaborate. These constraints could still provide flexibility within which software to use based on available resource skills or upgrades to design software within companies, but provides minimum compatibility requirements to ensure designer A's detail part can be used in designer B's assembly model. A potential flexible option that can be utilized in combination with this rigidity could be to utilize another design house if demand increases beyond current capacity, which may otherwise be limited based on budget constraints associated with acquiring design software capabilities at the design house.

Too much rigidity or formalities may burden developers with excessive constraints which may significantly hinder speed and drive exceedingly high costs. On the other hand, too much flexibility will create chaos and reduce efficiency. An integrated approach which balances simple and robust forms of rigid constraints that still leaves room open for some flexibility to address uncertainties can provide an efficient agile process that can adapt to changes.

The framework discussed herein combines a system dynamics approach with Monte Carlo simulations to analyze behavioral impacts attributed to uncertainties and causal relationships within processes. This analytical approach assesses value based on a comparison of theoretical expectations within a wide range of probabilities. Algorithms within a system dynamics model with various random parameters are repeated across many simulations in order to obtain a distribution of probabilistic behaviors. Similar to McConnell's framework (McConnell 2007), a system dynamics model is utilized to understand the effects and behaviors of interrelationships within key attributes of the process. This model is used to provide both a high level context of the different elements within the development process, as well as sufficient granularity to capture value. The model or elements within the model can then be adjusted to ascertain the value of flexibility under different conditions.

All potential costs and benefits are evaluated based on a common unit for ease of comparison. Typically, costs are defined in terms of monetary values, although any unit can be used. This is utilized to provide a comparative measure to characteristics that are generally difficult to measure. The cost of poor quality may include a dollar value per defect which factors in costs associated with rework or recalls, as well as downstream impacts such as schedule delays, idle time if parts are on hold, damage to reputation for escapes to the customer, etc. Each of these elements may be expressed in terms of dollar value with careful consideration. This is similar to defining the value of a pound within aircraft development, where each pound added takes away fuel or equipment from a mission and can be assigned a dollar value in terms of what the company will pay to reduce weight. Schedule delays may be represented in terms of monetary losses due to contractual penalties, opportunity losses to other potential contracts, and reputation.

It is important to consider potential differences in value based on different uses for the process. For example, a product development process developed by a company is typically used across all or most projects. The value of the flexibility for project A may not be the same for project B based on unique circumstances. Similarly, if processes are common across multiple organizations or within different divisions of an organization, the value of the process may be different due to differences in behaviors of other elements within the individual groups that may promote or degrade the effectiveness of the flexibility.

4 Valuation of Process Flexibility in Practice

For the purposes of illustration, consider a relatively simple and straight forward process flexibility that is often utilized at aircraft manufacturing companies. This section assesses the value of a drawing redline option that provides a means of circumventing the full drawing revision release process in order to provide rapid response to the production floor during initial development. The term "redline" typically refers to a physical paper drawing on the production floor which is literally marked up with design changes by an authorized engineer using a red pen or pencil. The master drawing and future copies are then revised to incorporate the changes for future production. Although complex process flexibilities which are integrated throughout many more business processes can be evaluated in a similar manner, this simplified example has been selected as a means of walking through the methodology defined in the previous section without getting distracted by too many nuances of the selected flexibility itself.

4.1 Waste within Value Stream

The redline option behaves as a "fire-fighting" response which provides manufacturing with authorized engineering direction on how to proceed with discovered issues observed in development in advance of releasing a revised drawing. It is essentially a documented promise from an engineering authority indicating that a released revision of the drawing is on its way and will be released prior to final buy-off of the delivered product. The released drawing will ultimately match the marked up drawings that parts are built in accordance with.

From the perspective of the design engineering team, who is trying to make the most efficient use of a designer's time, the redline provides a significant amount of waste by creating additional work and distracting engineers from current work already in progress. Not only will the engineer need to provide a redline document that defines new engineering requirements to the manufacturing floor, but they will also need to revise the master design data with the same information in order to buy-off the product being built. The redline is not part of the current design until it's incorporated into a revision. Thus, design errors resulting from hidden changes may arise as additional engineers interfacing with the design are unaware of the authorized redlined changes. The redline process may fall under the waste category of "defective product" in terms of design quality. It may also fall under the waste category of "processing" in terms of the redundant processing effort required to design, review, and approve a change. When trying to streamline the design process, it would appear wise to eliminate the redline process and focus on a means of improving speed and accuracy of design work to ensure designs are completed correctly the first time and as quick as possible in order to avoid rework in the first place. Any streamlining that can be accomplished for the design process, will likely be beneficial in improving turn-around times and reducing the need for redlines or other corrective measures. But even the streamlined process may not be sufficient. After all it is quite difficult to find ways to improve both speed and quality, as improving design quality typically means more upfront effort and time. When considering the detailed design creation and release process within product development from a value stream perspective, there is little value associated with the redline process.

From a manufacturing perspective, however, the redline process actually helps to reduce idle time by improving the response rate from engineering to keep the manufacturing line flowing. As more issues arise and more parts are put on hold pending engineering direction, the manufacturing team will be limited to smaller amounts of workable work. In an ideal world, a supervisor would be able to level load the manufacturing team based on having all parts available when needed and can make the most efficient use of resources. In a low rate build, such as a one-off development design, any issue or defect can have significant ramifications to the flow due to accumulated delays. Thus a fast response from the redline process provides a means of reducing delays. This will ultimately provide benefit to the downstream engineering team who needs a manufactured test article to validate their designs. Thus, what is considered a waste from one perspective provides value when considered from another perspective that is indirectly tied to the upstream processes.

4.2 Flexibility Definition

Consider a drawing redline option within a product configuration process. Authorized engineering changes can be provided to manufacturing via "red-lined drawings". In this case, consider a process in which all design data utilized by manufacturing is digital, and "redlines" are simply authorized design changes available to manufacturing which have not yet been incorporated into the master drawing or future production copies via the full drawing revision process. For example, a redline could be a simple digital drawing file released to manufacturing that permits the use of alternate hardware which has not yet been modelled into the production assembly drawing or bill of material.

The primary intent of the flexibility is to bring a product or product change to market as quickly as possible. The specific purpose of the redline process is to minimize manufacturing delays associated with the discovery of design issues.

Consider the constraints, or rigidities, within the redline process flexibility presented in Table 3. Within redline incorporation constraints, the redline flexibility does not eliminate the need to make formal design changes, but simply delays the need date for incorporation. This delayed need can be particularly useful if manufacturing is on hold and if the time to incorporate a formal design change is significantly greater than the time required to release a redline in order to keep the manufacturing line moving. This flexibility can also useful if there are not enough engineering resources immediately available to respond to urgent production needs. Within the redline approval constraint, the redline does not circumvent necessary reviewers. The likelihood of rework and delays increases if additional people are required to approve future redline incorporations than were present when approving the initial redline released to manufacturing. Within the standard work constraint, resources can easily be transferred across programs without additional training for program-specific nuances within the redline process. This is one standard process for all programs. The flexibility resides within *when* the process may be used.

Redline Incorporation	• All redlines must be incorporated into released production drawings prior to customer delivery or qualification testing. • Delivered products must be defined by released engineering drawings and associated design data without any redlines. • A product cannot be delivered to a customer with open redlines that have not been incorporated into master design data.
Redline Approval	• The redline must be approved by all authorities required to approve associated formal design revision.
Standard Work	• The redline process must be a well-defined documented procedure which can be utilized across all projects. • There will only be one type of redline process within the company (standardization)

Table 3: Rigidity within Redline Flexibility

Also, consider conditional parameters, or policies, presented in Table 4 that further define the redline process flexibility. If the redline process were utilized under all conditions, incorporation of the redline process would be considered as a standard process change rather than a flexibility within the process. The response rate benefit policy may be further optimized by selecting a threshold which defines a minimum redline benefit required in order to utilize the flexibility (i.e. improved response rate to manufacturing). The build completion policy may be further optimized by further reducing the time period in which redlines can be exercised. Prior to build completion, all redlines must be incorporated through formal drawing revisions. This build completion policy avoids effort associated with redline activity when the project is estimated to be completed within the time it would take to simply revise a drawing.

Response Rate Benefit	In order to exercise the redline flexibility on a specific drawing, the effort estimated for releasing the redline must be less than the effort estimated for releasing a full drawing revision that would alternatively correct the design error.
Build Completion Pressure	In order to exercise the redline flexibility on a specific drawing, the expected duration for releasing the redline due to estimated effort must be less than the estimated remaining time until build completion (i.e. deadline for incorporating redlines through full drawing revision).

Table 4: Redline Flexibility Policies

Other flexible rigidities within the design process could also be explored to further contribute to the effectiveness of the redline process flexibility. One potential flexible rigidity would be to create a standard flow of reviewers and alternate reviewers required to authorize engineering changes based on a pre-defined set of criteria that address design change attributes, disciplines impacted, etc. Not only does this rigid flexibility of standardization make it straightforward for designers to know who needs to approve what, it can also be used to ensure that the upcoming design revision which incorporates the redline is reviewed and approved by the same reviewers who authorized the initial redline. This will ultimately help to avoid discrepancies between the redline "promise" and the official design change incorporation resulting from potential differences in reviewer preferences.

4.3 Causal Loop Diagrams

Visualize the impacts of the redline process flexibility within business operations of the company by developing causal loop diagrams. To begin, we start with the causal loops that define the intended behavior of the redline flexibility. In this case, consider the desire to reduce time to market (duration of product development).

The initial causal loop defined in Figure 6 represents a reinforcing behavior in which the ability to develop a solution that satisfies customer needs is impacted by the overall development time. Projects with long development times are prone to additional scope that further extends the time-to-market even further. The likelihood of scope creep increases as time-to-market lengthens due to changes in customer needs and desires over the course of the product development. Upon completion of an aircraft development after many years, consider the possibility of changes to customer needs and desires and improvements in competing and complementary technologies as compared to expectations at the start of the project when initial product requirements were being developed. As time increases, so does the likelihood that the customer will request change to initial scope.

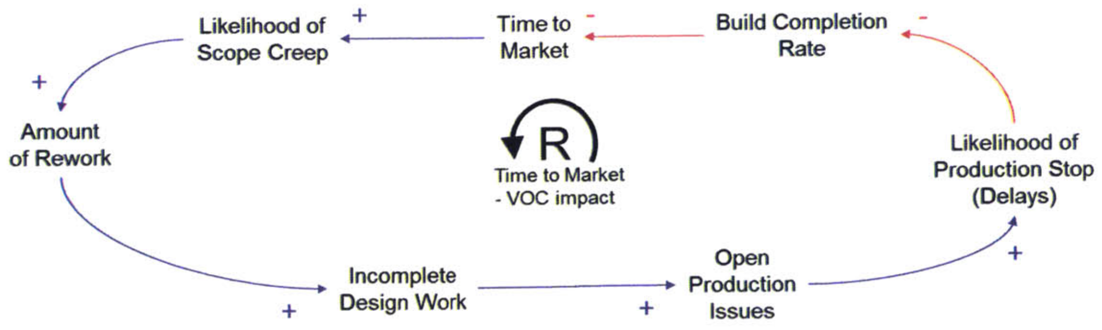


Figure 6: Causal Loop Diagram of Product Development with respect to Time to Market

As the likelihood of scope creep increases, the amount of rework increases. Previously released features within the design must now be revised in order to accommodate the new desires of the customer. Increased rework directly increases the amount of incomplete design work. Design revisions (rework) are simply added to the existing amount of design work that remains left to be completed. As more incomplete design work is discovered, the amount of production issues with unresolved engineering solutions increases. As amount of open production issues increase, the chances are greater that production will stop until issues are resolved, resulting in manufacturing delays. As likelihood of a production stop increases, the rate of build completion slows down. As the rate of build completion slows down, the time to market is further lengthened, and so-on. On the contrary, if time-to-market of product is reduced, the causal loop is reinforced in the opposite direction from what was described above.

The primary intent of the redline process is to reduce the likelihood of production delays by reducing the amount of open production issues, as shown in the balancing "Fire-Fighting" loop presented in Figure 7. The need for immediate response to open production issues increases as the likelihood of a production stop goes up. As the need for immediate response is increased, the amount of redline releases will increase, when then reduces the amount of production issues. This provides a balanced behavior to the product development process.

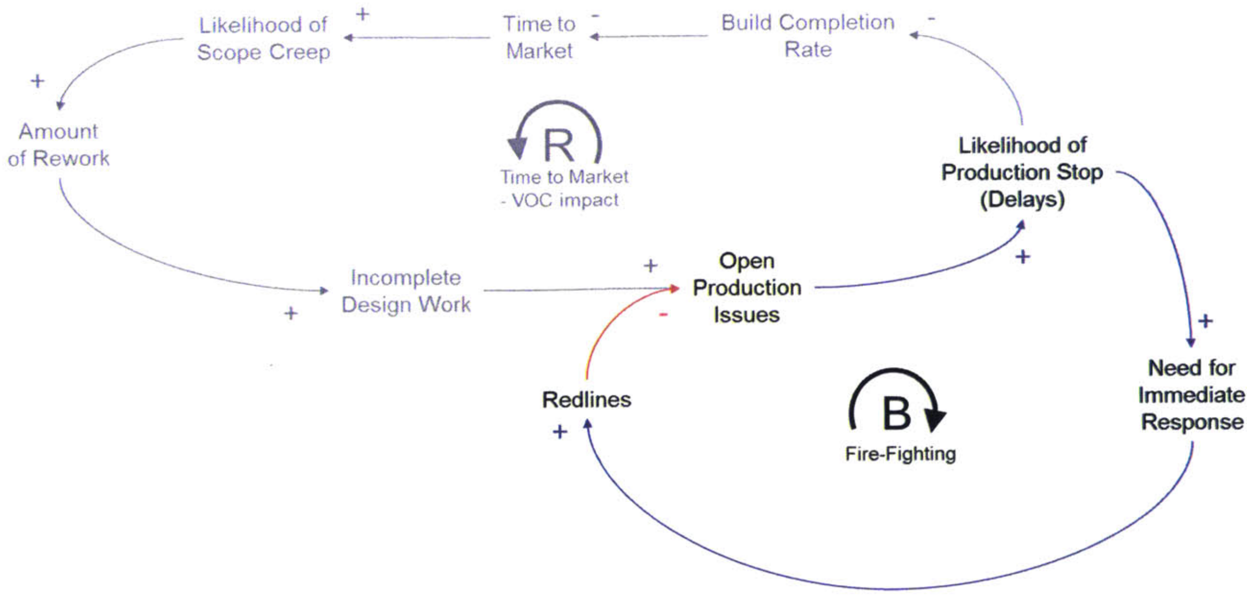


Figure 7: Causal Loop Diagram with Fire Fighting Balancing Loop

However, the presence of a redline process impacts other business areas, as shown in Figure 8. In order to release a redline, design resources are pulled from other activities in order to investigate the open production issues, develop solutions, and release redlines to manufacturing. When design changes are incorporated on redlines in advance of full design revisions, additional rework may result due to lack of current design features visible to other designers who may be developing features that interface with or are in the proximity of the recently changed design. In other words, there is a false sense of completed work or defined design available to engineers who may be unaware of the released redline. As quantity of redlines increase, the actual design configuration becomes less visible to other designers, thus increasing the likelihood of interface errors and creating additional rework.

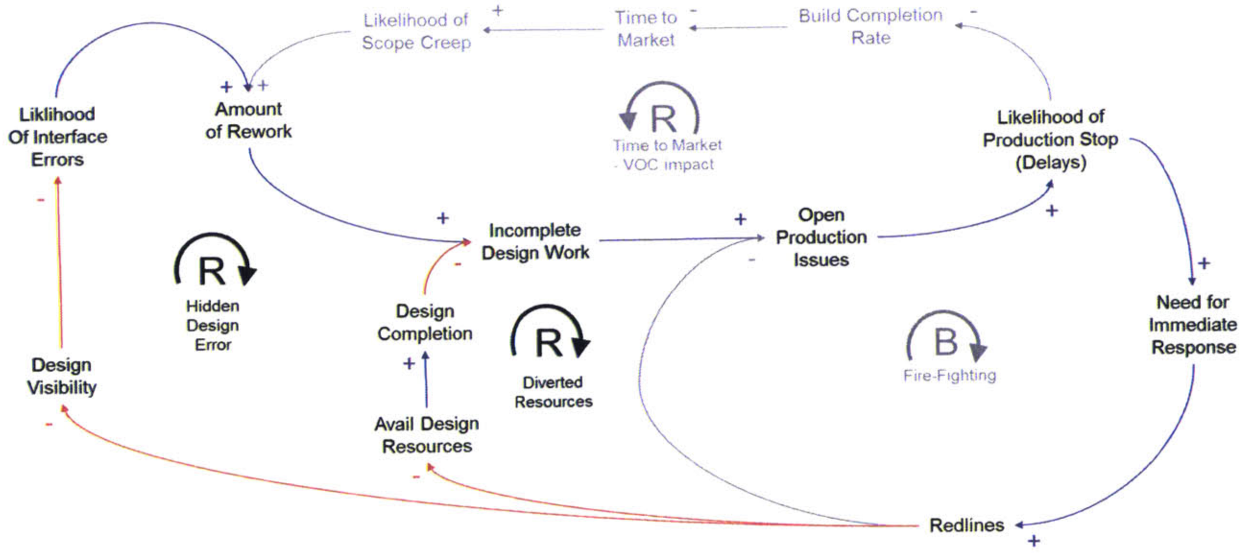


Figure 8: Complete Causal Loop Diagram of Design Processes with Redline Flexibility

4.4 Identification of Uncertainties

Uncertainties that could profoundly impact elements within the causal loops described in Section 4.3 need to be identified. For the example of the redline flexibility, environmental conditions within a small vertically integrated organization, as well as a larger organization, are considered. Within the small vertically integrated organization, engineers are fewer in number, responsible for a wide range of tasks, and have easy access to the product being manufactured. Within the large organization spread across multiple locations, a large pool of specialized engineering talent is available with relative ease of transferring resources across projects as needed. The two environments may fall under the umbrella of a single organization with differences across locations or subsidiaries. The environments can also represent the growth of a small organization into a much larger organization, as viewed by two opposite ends of the spectrum.

The following uncertainties have been identified;

- Scope Growth (in terms of scope increase per year)
- Design resource limitations (in terms of availability)
- Ability to staff up/down with design resources as needed (in terms of response to changes in staffing requirements)

- Design Efficiencies (design expertise)
- Designer Capacity (number of resources that can concurrently work on a design, limited to type of design and level of integration or modularity)
- Redline & Revision effort / durations
- Manufacturing Rates (capacity / efficiency)
- Design Quality (errors discovered during initial build)
- Mfg Prep Duration (time needed after release of design to be ready to manufacture, such as processing time for work instructions and procurement)

4.5 System Dynamics Model

The behavior of the product development process, as it relates to the redline process flexibility, has been modelled using a system dynamics approach in the Vensim DSS software that can carry out a Monte Carlo Simulation. Several iterations were attempted prior to selecting the current model presented in Figure 9. The primary reasons why earlier versions were abandoned were due to the unnecessary level of granularity and resulting complexity. It can be difficult to determine how much detail should exist when developing a system dynamics model to represent a process. Initially, every step of the process associated with the release of designs was attempted to be modeled, including different elements of review cycles, and so-forth. Essentially every step in a detailed process flow diagram was considered. However, the primary intent was lost. The primary reason for developing a system dynamics model is to understand behavior. It is certainly possible to model behavior of certain elements of the product development process that relate to the redline process without getting distracted by all the nuances of the many steps detailed in standard process flow charts.

Relationships of elements within the causal loops were modelled in an interconnected dynamics model consisting of four primary categories; Initial Engineering Design Completion, Initial Product Build, Engineering Design Corrections, and Design Resource Staffing. The system dynamics model is shown in Figure 9 for general reference. Each segment is later discussed in greater detail with an enlarged figure for ease of viewing. Definition of variables within the model is presented in Appendix A.

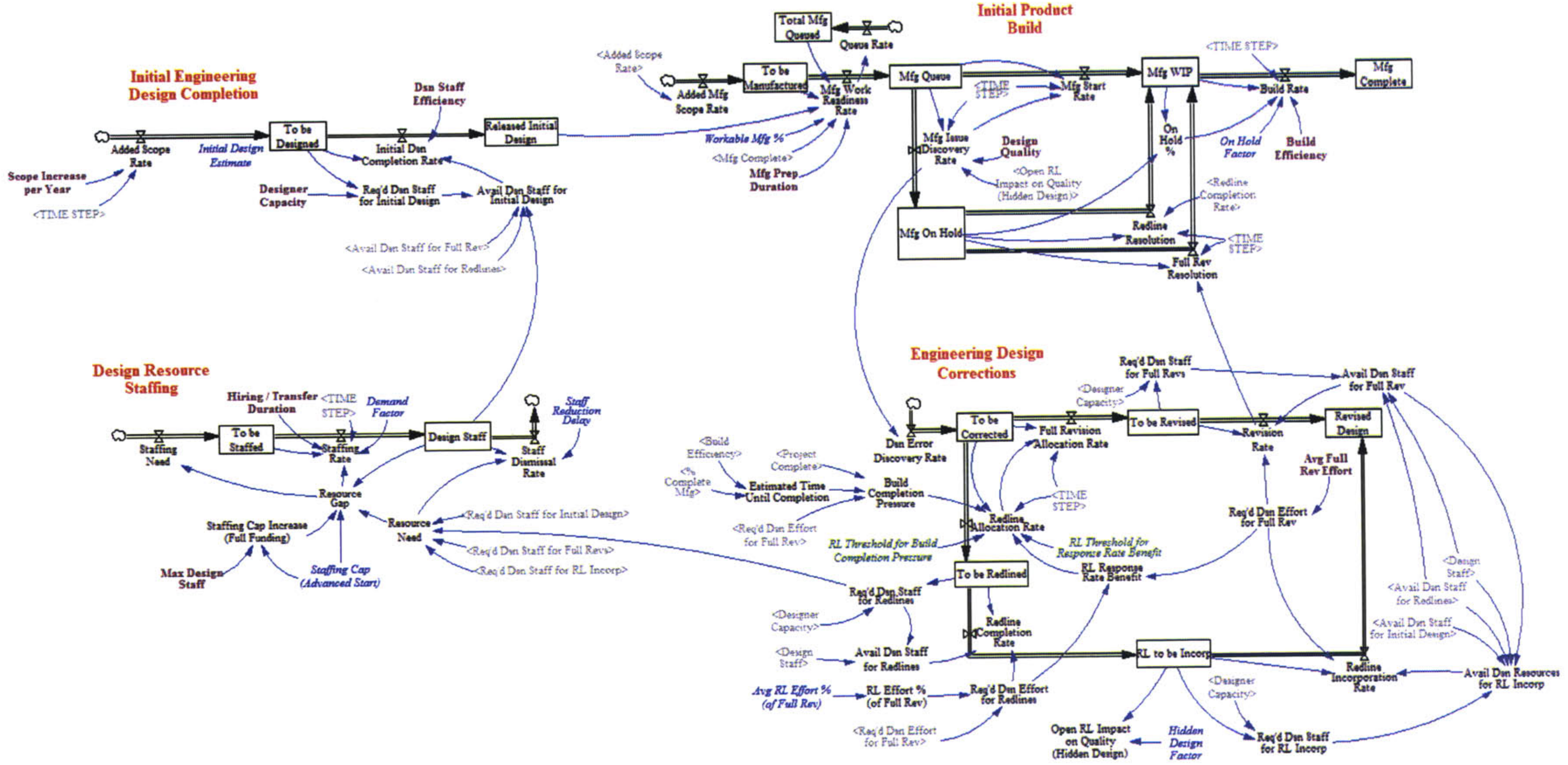


Figure 9: System Dynamics (SD) Model of Redline Process within Product Development

Initial designs are released in the Initial Engineering Design Completion segment, presented in Figure 10a. Primary factors that affect the release rate are the number of available resources, the efficiency of those resources, and additional scope requested by the customer that is incurred prior to project completion. As design issues arise, resources are pulled from this pool of design resources in order to address higher priorities, thus temporarily slowing progress until the other priorities are resolved or until additional resources can be added.

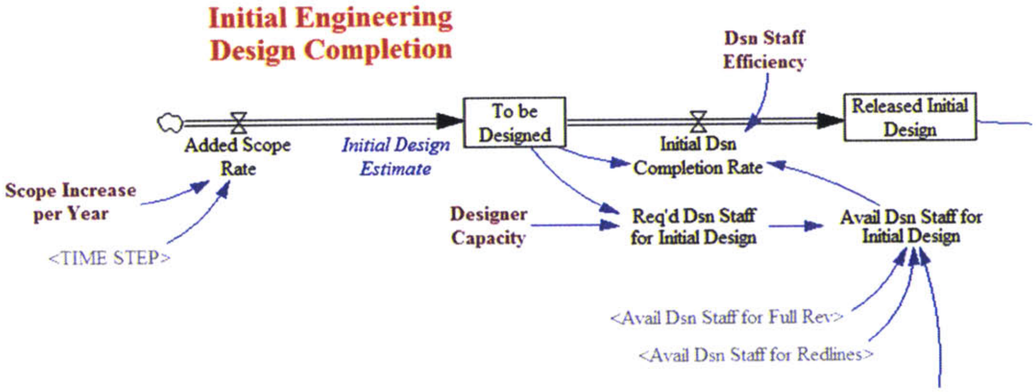


Figure 10a: Initial Engineering Design Completion Segment, SD Model

Elements attributed to the redline flexibility are highlighted orange in Figure 10b. Within the initial design segment, staff available to work initial design is impacted as resources are pulled to support higher priority issues to keep the manufacturing flowing.

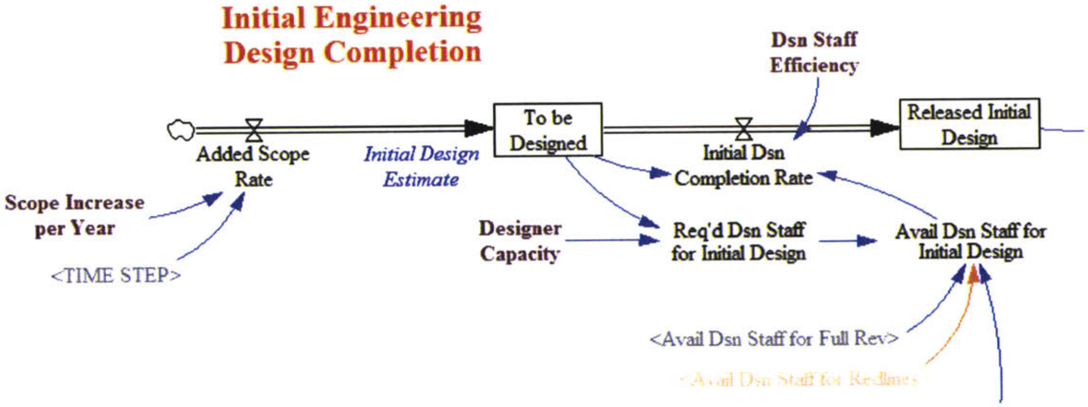


Figure 10b: Initial Engr Dsn Segment with Flexibility Factor Highlighted, SD Model

As designs are released, the build of the initial product occurs in the Initial Product Build segment, presented in Figure 11a. Primary factors affecting the build completion are delays associated with identifying and correcting of production issues.

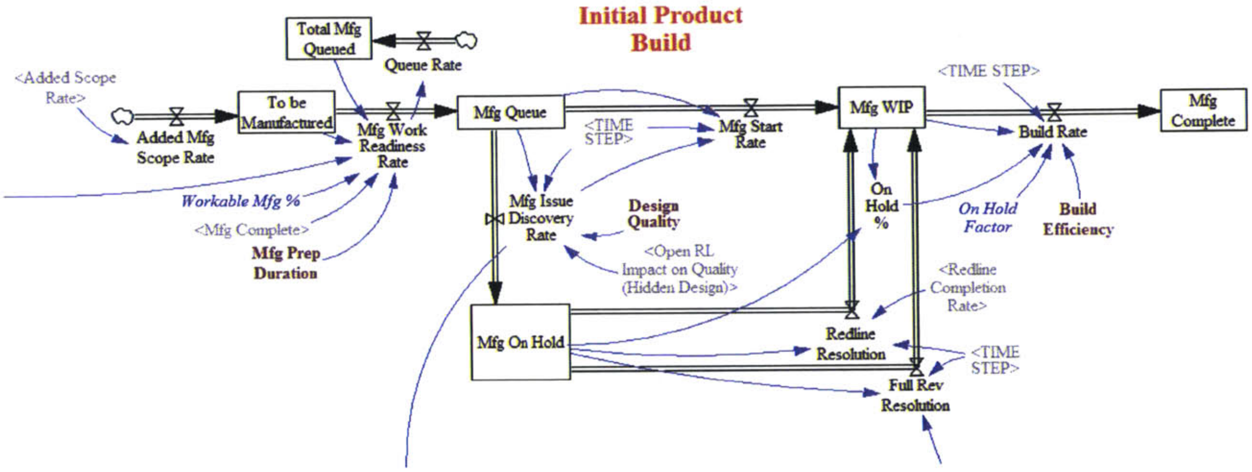


Figure 11a: Initial Product Build Segment, SD Model

Elements attributed to the redline flexibility are highlighted orange in Figure 11b. Within the initial product build segment, manufacturing work on hold is reduced, as redlines provide resolution to manufacturing in advance of full revisions. In addition design quality is impacted as while redlines remain unincorporated in master design data and hidden to other designers.

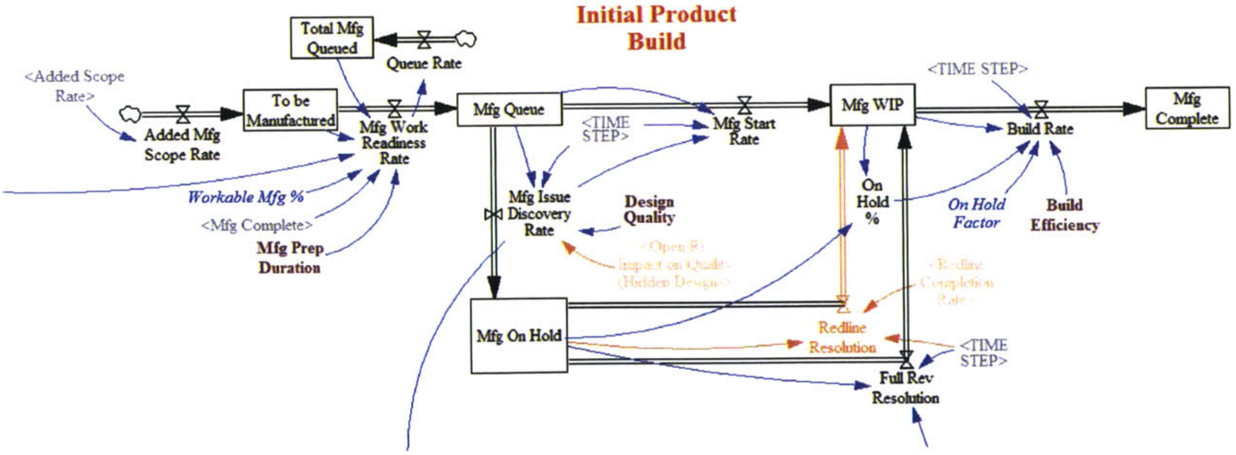


Figure 11b: Initial Product Build Segment with Flexibility Factors Highlighted, SD Model

Throughout the product development process, errors are likely to be found based on the level of design completion prior to build and the amount of design that is visible to all other designers. Complex systems are developed by many different engineering disciplines. In an ideal world, all physical and spatial interfaces would be defined upfront. However it is not uncommon for designers to learn as they go. As drawings, specifications, or interface documents are released, these interface requirements then become visible to the many other engineers designing components in the same proximity. An airframe engineer may release a design of a structural frame without full knowledge of other electrical wiring and attachments that will later need to be accommodated for. Ideally, these issues would be worked out prior to build. However, depending on the level of schedule pressure to build concurrently in advance of full design completion, interface errors are sometimes unavoidable. As designs are released, the design becomes defined and visible to others.

As errors are discovered, they are then resolved by one of two primary paths; full design revision or redline process, as shown in Figure 12a. Design resources are pulled from other tasks in order to identify a solution and release a full design revision. Alternatively, a redline drawing can be released to manufacturing and later followed up with a redline incorporation (design revision) as resources are freed up after higher priority design work is completed or additional resources are obtained. Full drawing revisions are to be completed unless criteria satisfied within redline threshold policies are satisfied. As mentioned in Section 4.2, policies defining the redline process flexibility govern when the flexibility may be executed. These factors are highlighted green in Figure 12a.

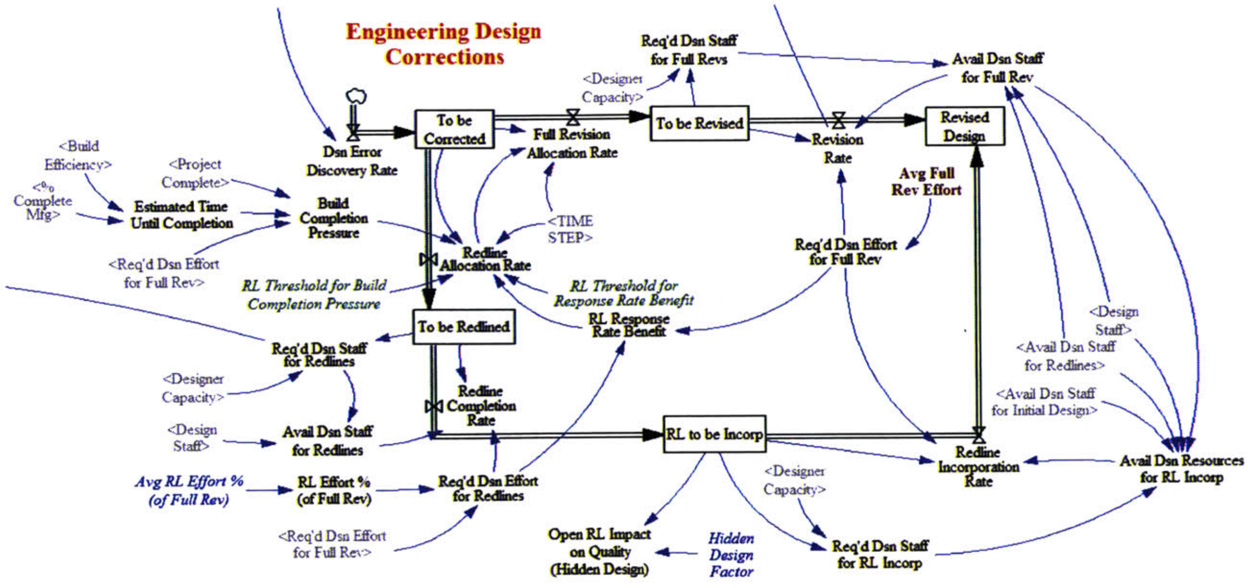


Figure 12a: Engineering Design Correction Segment, SD Model

Elements attributed to the redline flexibility are highlighted orange in Figure 12b. Within the engineering design correction segment, the lower loop defines the redline flexibility. As redlines are completed and drawings requiring full revisions are revised, components are released from "on hold" status in Figure 11a and moved to work in progress.

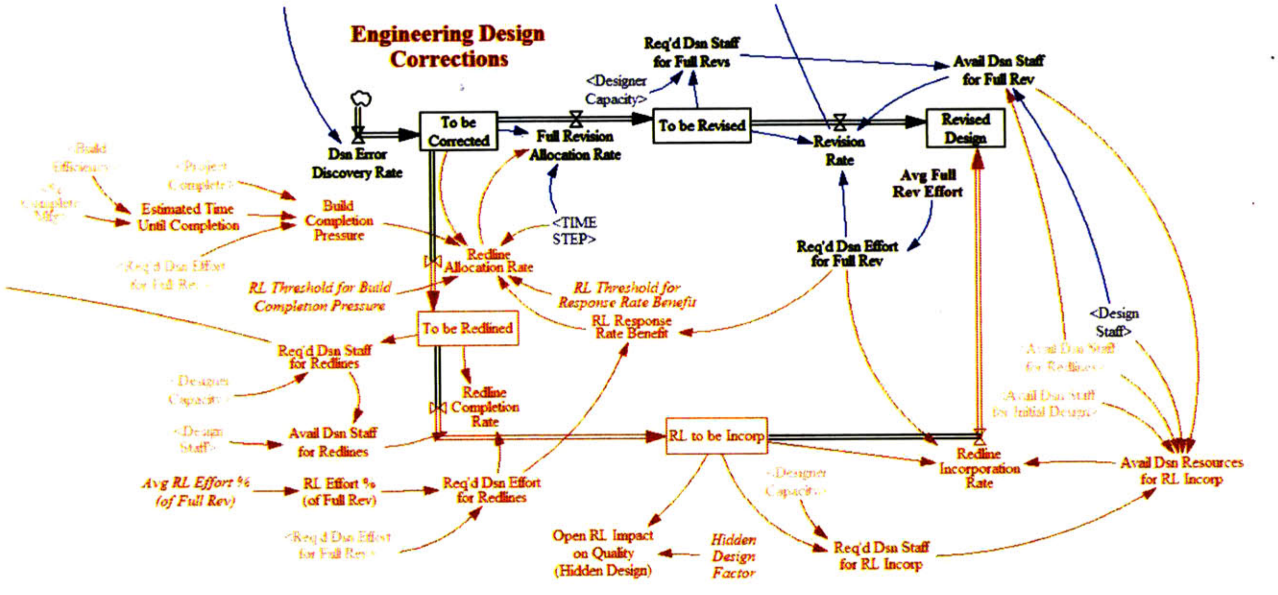


Figure 12b: Engr Dsn Correction Segment with Flexibility Factors Highlighted, SD Model

The remaining Design Resource Staffing segment presented in Figure 13a models the behavior for hiring or transferring resources onto the project based on identified resource gaps as new work becomes available for designers to work on.

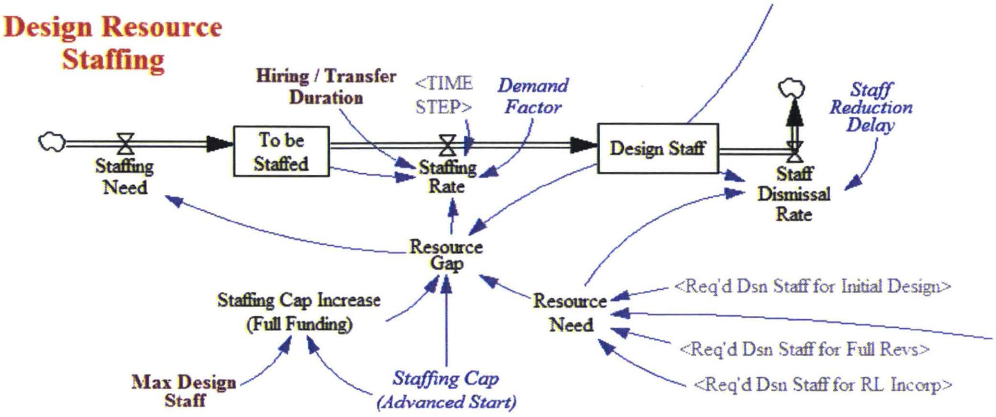


Figure 13a: Design Resource Staffing Segment, SD Model

Elements attributed to the redline flexibility are highlighted orange in Figure 13b. As engineering corrections are identified, resource needs increase to backfill resources borrowed from other activities.

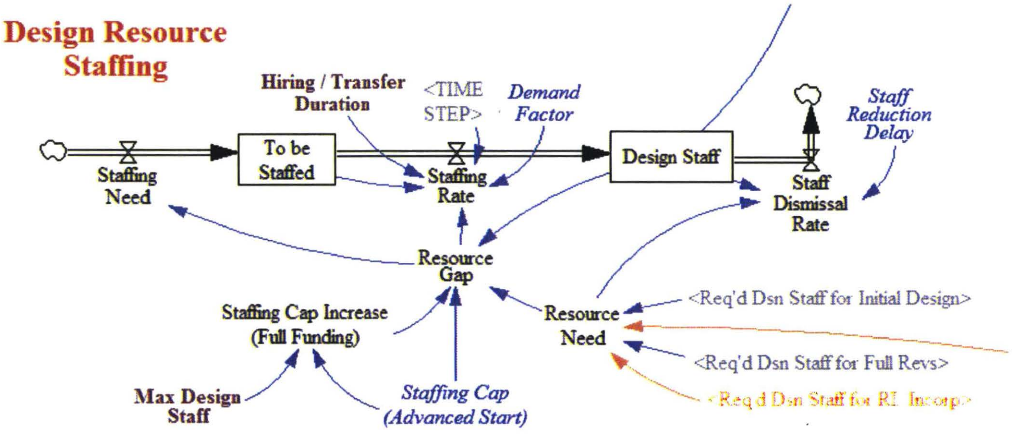


Figure 13b: Dsn Resource Staffing Segment with Flexibility Factors Highlighted, SD Model

The primary concerns impacted by the incorporation or avoidance of the redline flexibility is overall project schedule delays and costs associated with additional resources. The redline process provides a short term relief, which ultimately needs to be addressed by standard drawing revision processes prior to the project completion. If redlines go unnoticed, they create additional errors due to hidden design and additional work late in the project. In addition they add additional tasks to design resource workloads and divert resources from other design work. For ease of assessing value, all concerns are converted to monetary values. Schedule impacts are rolled up into penalty costs if the project is completed late, or rewards if the project is completed early. As shown in Figure 14, resource costs are added to the schedule costs as a total cost which will be compared across multiple scenarios. Elements within the system dynamics model that calculate costs and project completions are shown in Figure 15.

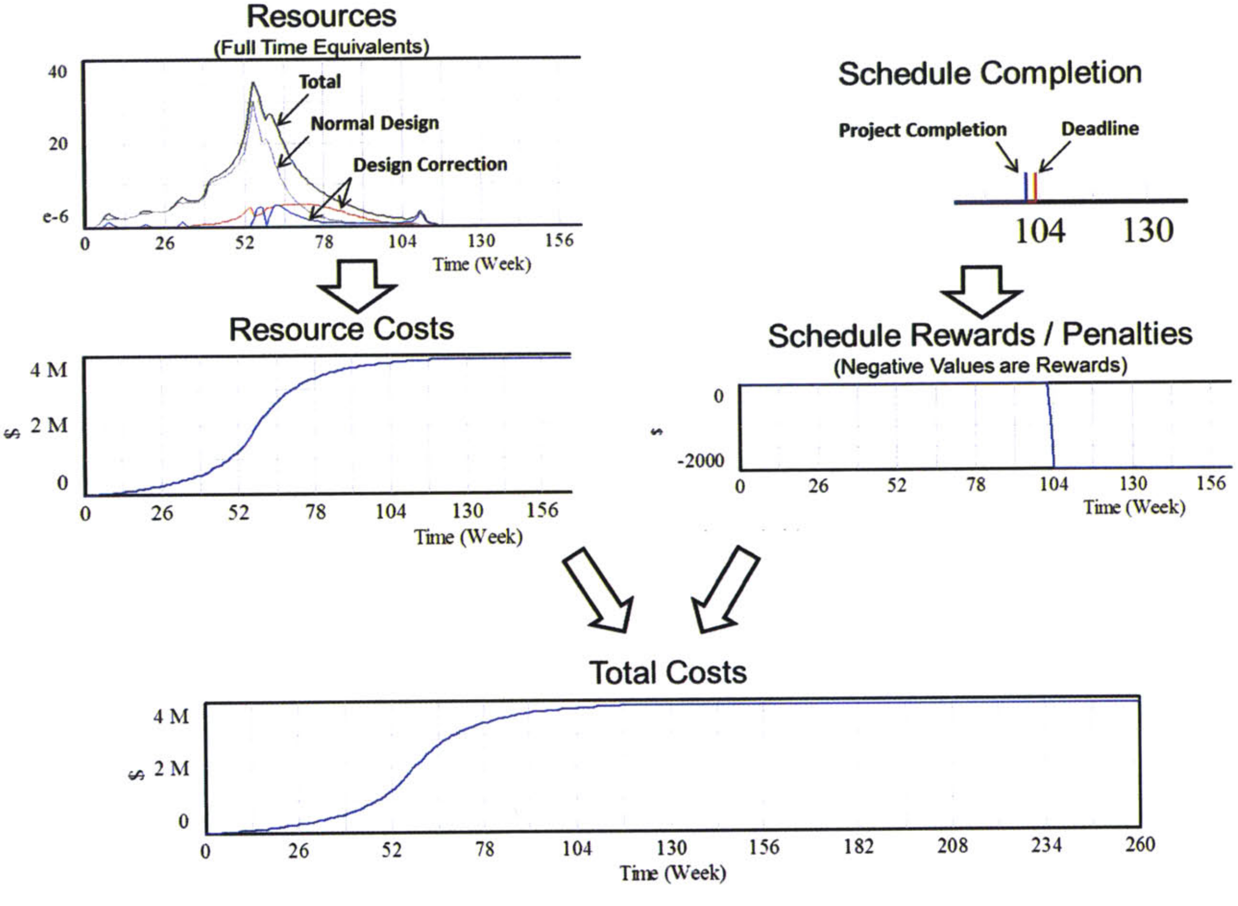


Figure 14: Total Project Cost (used for value comparison)

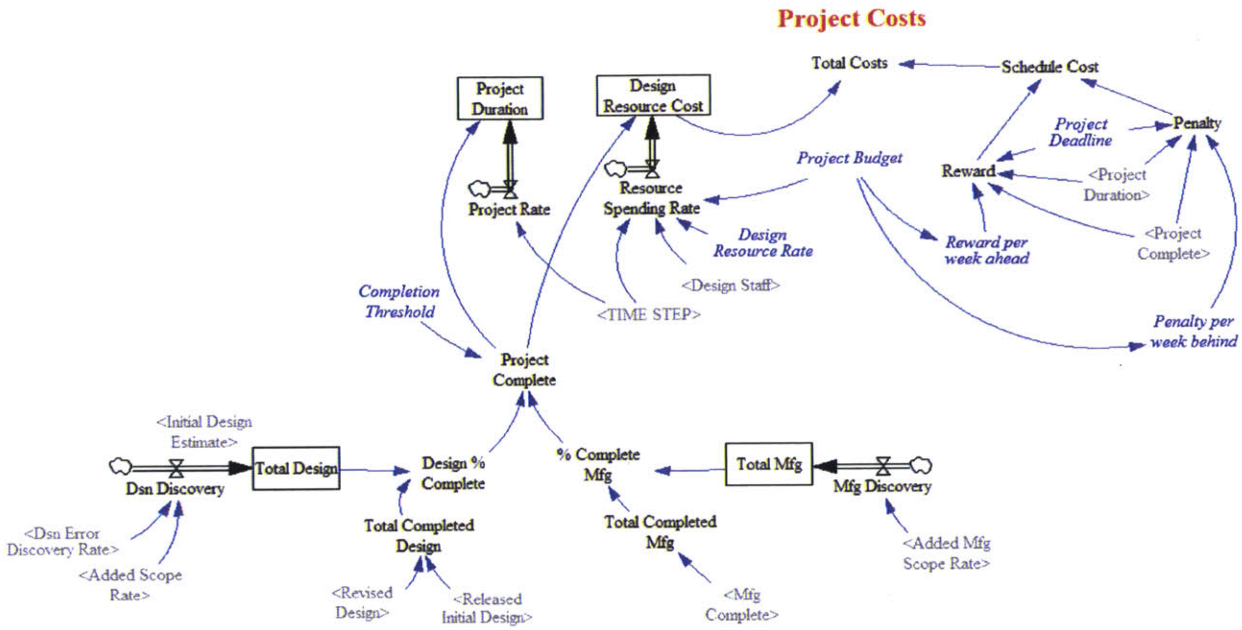


Figure 15: Project Cost Segment, SD Model

Furthermore, the system dynamics model presented in this section compares the performance if redline flexibility is incorporated and the performance if no redline flexibility is incorporated. Essentially, the model presented in Figure 9 (with redline flexibility) is compared to the model presented in Figure 16 (no flexibility), which depicts all orange elements removed from Figures 10b, 11b, 12b, and 13b.

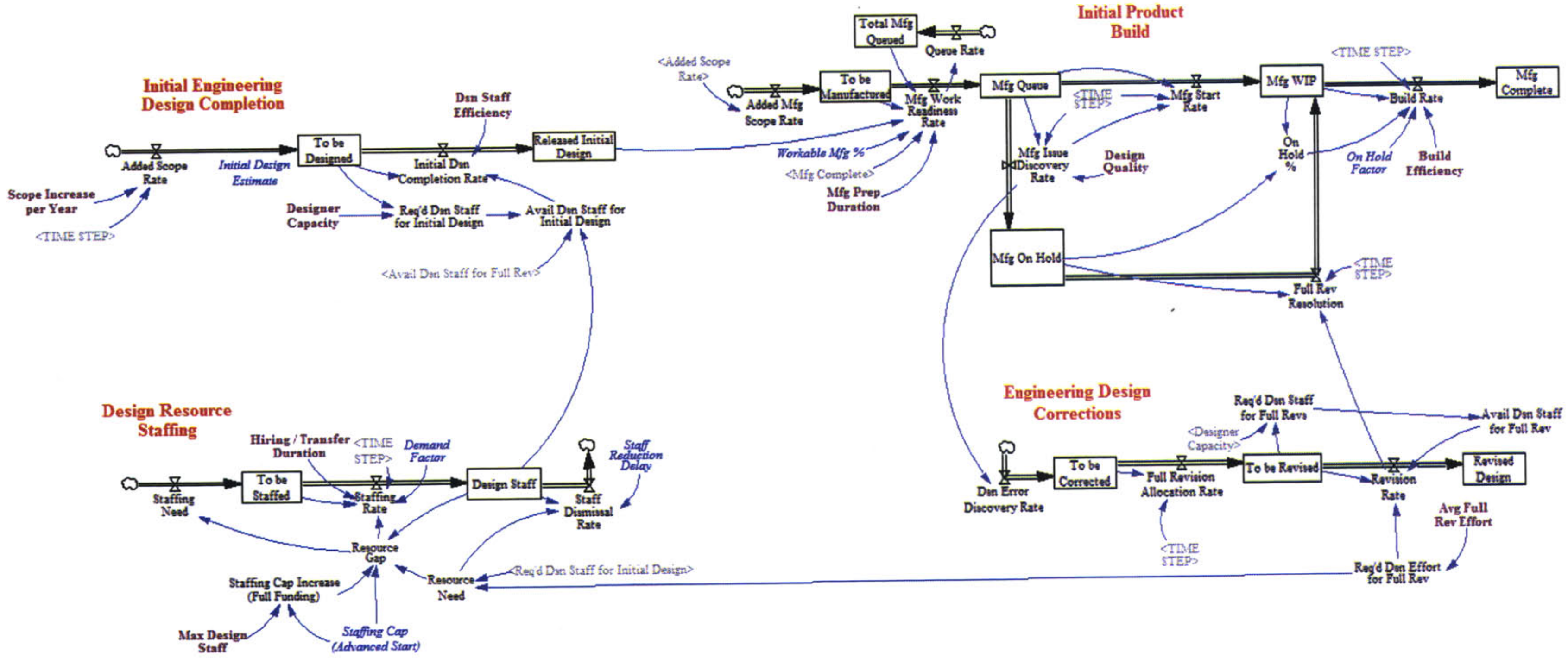
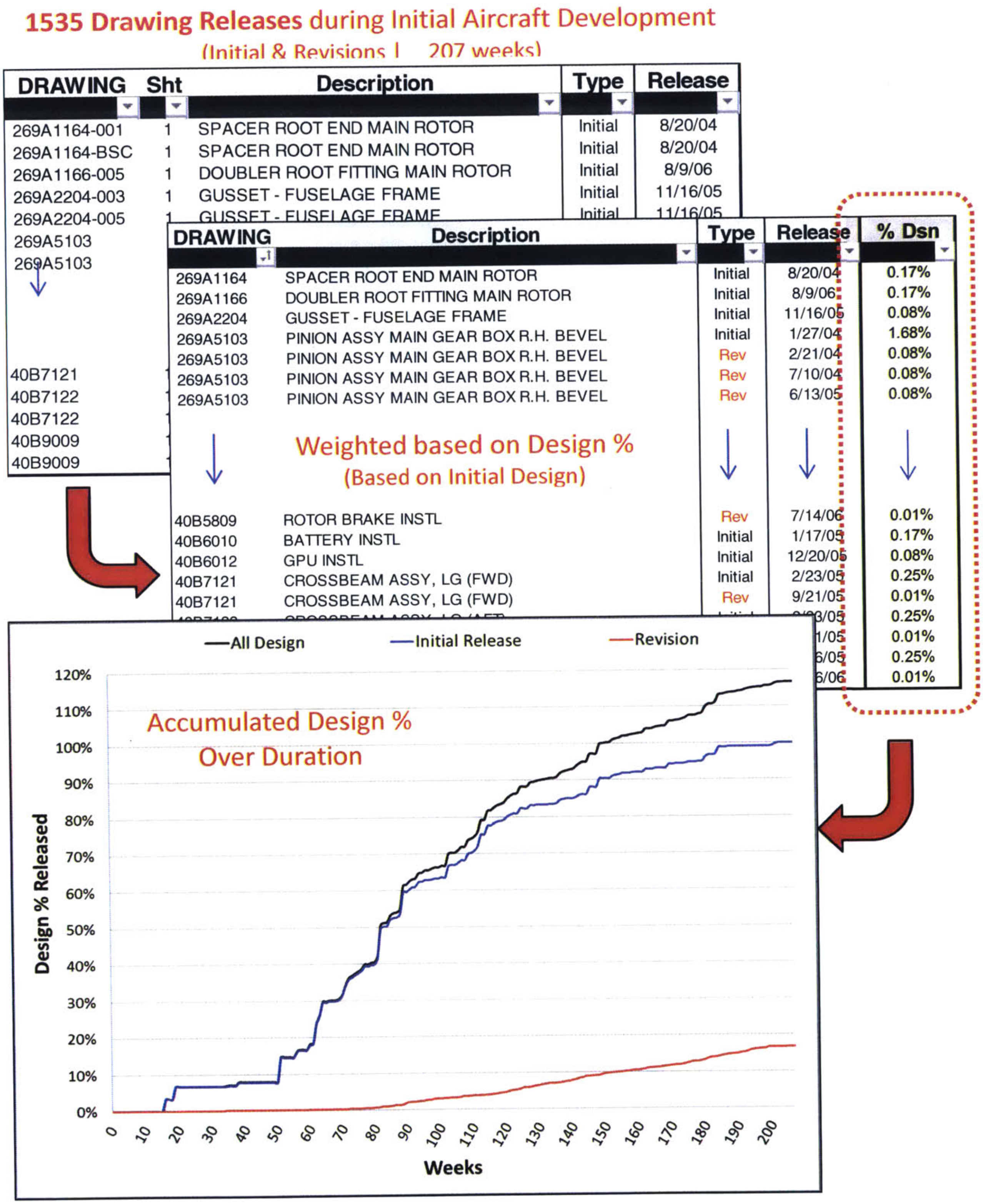


Figure 16: System Dynamics (SD) Model without Redline Flexibility

4.6 Model Validation

Validating the system dynamics model based on historic behaviors with known conditions provides confidence that the relationship of elements within the model are correct. If the model is exposed to input conditions similar to what has been experienced in the past, it is expected to obtain outputs from the model similar to actual results that have been observed under those same conditions. Thus it is important to ensure that input variables are independent from actual output data used for validation.

In order to validate the system dynamics model, data from an aircraft development project (actual project output) was compiled and compared to output from the model. Actual project output was based on 1,535 drawings released during the initial development period, as shown in Figure 17. Model inputs were based on known conditions and parameters that existed during the time in which the project was executed, as presented in Table 5. During this development project, no redline process was in place, thus historic data can only validate the model presented in Figure 16 (no flexibility). No project data is currently available for the proposed redline process flexibility presented in Figure 9 (redline flexibility). If the redline process were to be incorporated, it would be recommended to validate elements within that model as part of a continuous periodic flexibility reassessment (step 9 of the validation framework presented in Figure 5).



1535 Drawing Releases during Initial Aircraft Development

(Initial & Revisions | 207 weeks)

DRAWING	Sht	Description	Type	Release
269A1164-001	1	SPACER ROOT END MAIN ROTOR	Initial	8/20/04
269A1164-BSC	1	SPACER ROOT END MAIN ROTOR	Initial	8/20/04
269A1166-005	1	DOUBLER ROOT FITTING MAIN ROTOR	Initial	8/9/06
269A2204-003	1	GUSSET - FUSELAGE FRAME	Initial	11/16/05
269A2204-005	1	GUSSET - FUSELAGE FRAME	Initial	11/16/05
269A5103				
269A5103				
40B7121				
40B7122				
40B7122				
40B9009				
40B9009				

DRAWING	Description	Type	Release	% Dsn
269A1164	SPACER ROOT END MAIN ROTOR	Initial	8/20/04	0.17%
269A1166	DOUBLER ROOT FITTING MAIN ROTOR	Initial	8/9/06	0.17%
269A2204	GUSSET - FUSELAGE FRAME	Initial	11/16/05	0.08%
269A5103	PINION ASSY MAIN GEAR BOX R.H. BEVEL	Initial	1/27/04	1.68%
269A5103	PINION ASSY MAIN GEAR BOX R.H. BEVEL	Rev	2/21/04	0.08%
269A5103	PINION ASSY MAIN GEAR BOX R.H. BEVEL	Rev	7/10/04	0.08%
269A5103	PINION ASSY MAIN GEAR BOX R.H. BEVEL	Rev	6/13/05	0.08%
↓		↓	↓	↓
40B5809	ROTOR BRAKE INSTL	Rev	7/14/06	0.01%
40B6010	BATTERY INSTL	Initial	1/17/05	0.17%
40B6012	GPU INSTL	Initial	12/20/05	0.08%
40B7121	CROSSBEAM ASSY, LG (FWD)	Initial	2/23/05	0.25%
40B7121	CROSSBEAM ASSY, LG (FWD)	Rev	9/21/05	0.01%
			3/05	0.25%
			1/05	0.01%
			6/05	0.25%
			6/06	0.01%

Weighted based on Design %
(Based on Initial Design)

Figure 17: Actual Aircraft Development Project Data (Actual Output)

Input Parameter	Source of Input Data
Initial Design Estimate	This is automatically set as 100%. NOTE: The SD model is based up percentage of initial design, rather than quantity of drawings or components.
Scope Increase per Year	The average amount of scope added during the initial development of this particular aircraft development project was zero.
Design Staff Efficiency	Static value based on average efficiency measured during the initial development of this particular aircraft development project.
Designer Capacity	Based on maximum number of engineers able to work on a single group of drawings (design %). This estimate was based on the complexity of the design during the initial development of this particular aircraft development project.
Mfg Preparation Duration	Static value based on average duration measured as the delay between drawing release and production order release during the initial development of this particular aircraft development project.
Workable Mfg Percentage	Factor based on Bill of Materials during the initial development of this particular aircraft development project
Design Quality	Reported issues requiring design changes (as a % of initial design) during the initial development of this particular aircraft development project.
Build Efficiency	Static value based on average time it took to build components (as a % of build completion) during the initial development of this particular aircraft development project.
On Hold Factor	Assumed linear inverse relationship of manufacturing % on hold and build efficiency. As the percent of manufacturing on hold increases with respect to released manufacturing work in progress, the build rate is assumed to decrease equally.
Average Full Revision Effort	Static value based on average duration measured as the delay between issue identification and release of revised design during the initial development of this particular aircraft development project.
Hiring / Transfer Duration	Based on average time required to fulfill project resource requisitions during the initial development of this particular project.
Demand Factor (Staffing)	Based on hiring/transfer constraints during the initial development of this particular aircraft development project.
Staff Reduction Delay	Based on average time required to transfer staff onto other projects during the initial development of this particular aircraft development project.
Maximum Design Staff	This was set as zero during the model validation, since there were not hiring freezes or capacity constraints during the initial development of this particular aircraft development project.
Staffing Cap (Advanced Start)	This factor was used to capture the fact that initial development occurred within the first year in advance official project turn-on. Initial development was limited to a small set of engineers within the company.

Table 5: Source of Validation Input Data

The output data of released designs per week was used to validate the behavior resulting from the independent source inputs. As shown in Figure 18, the output of design releases and revisions resulted in a similar behavior to what was actually observed when exposed to similar conditions.

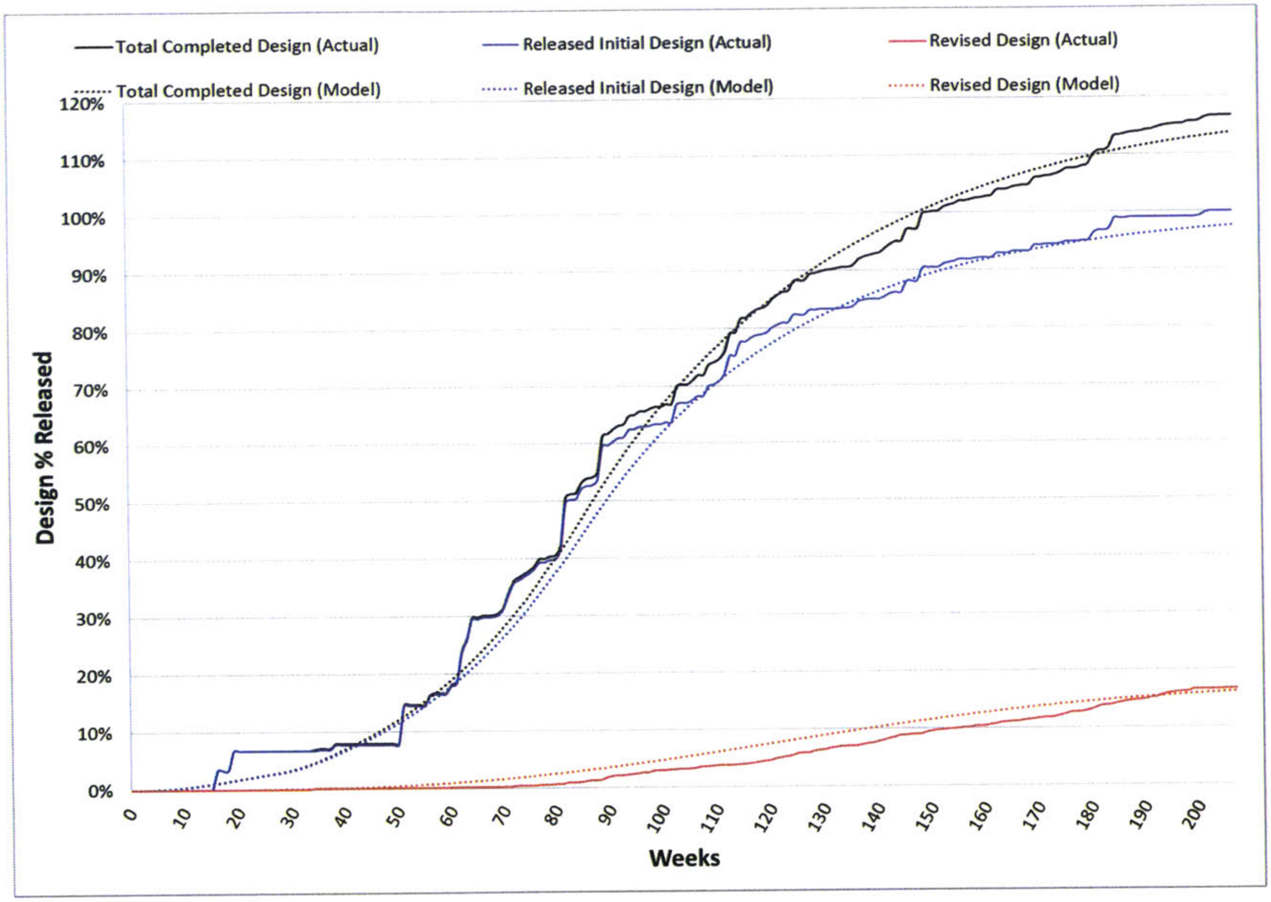


Figure 18: Comparison of SD Model Output to Actual Historic Data

4.7 Uncertainty Definitions

Processes are often evaluated based on expected values of input conditions, rather than a range of possibilities. This provides a deterministic method of evaluating the future state performance based on specific conditions within a single environment. Alternatively, performance can be evaluated within a wide range of uncertainty by considering probabilistic distributions of multiple input variables. Methods of determining probabilistic distributions that define uncertainty within input variables may certainly vary across organizations and by the nature of the input variable itself. Some inputs may have well defined probabilistic distributions based on a significant amount of historic data and sophisticated forecasting tools. Other variables may be ambiguous and not very well understood based on past history. These variables may be difficult to quantify, thus reducing the level of confidence within the forecast. It is important to document the probabilistic distributions of input variables considered, since the value of the flexibility is based on the range of possibilities within these input conditions. The quantified value of flexibility will change as uncertainty within input variables change.

This section does not focus on the development of uncertainties for the redline flexibility, but simply provides the definition of the considered inputs for which the value of the flexibility is ultimately be considered. These were developed as combination of past history as well as consideration of forecasts over the duration in which an upcoming aircraft development project may be conducted. These uncertainties are specific to a project and an organization in which the project is intended to be conducted. As previously mentioned, the value from the flexibility will change as uncertainties change. Therefore it is recommended to re-evaluate the value of flexibilities on a periodic basis to determine whether or not it is worthwhile to maintain the flexibility.

Added Scope Rate is an exogenous uncertainty based on changes in customer demands as time progresses. Within the system dynamics model, this is reflected in terms of added design % per year. A uniform distribution was considered since it is very uncertain how much additional scope may be added. The probabilistic distribution for uncertainty of this input variable is presented in Figure 19.

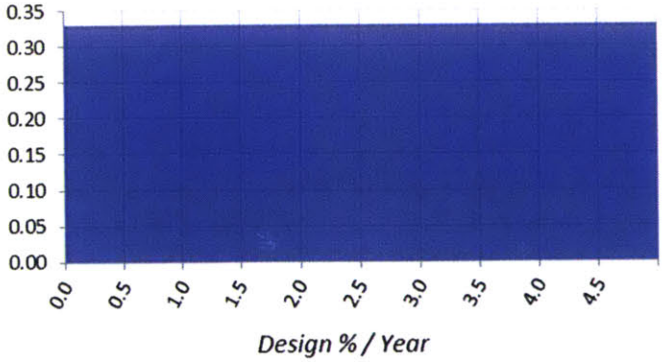


Figure 19: Added Scope Rate, Probabilistic Distribution (Input)

Design Staff Efficiency is based on the combination of available design resources and talent in terms of how quickly a full time equivalent engineer can complete a portion of the design. The probabilistic distribution for uncertainty of this input variable is presented in Figure 20.

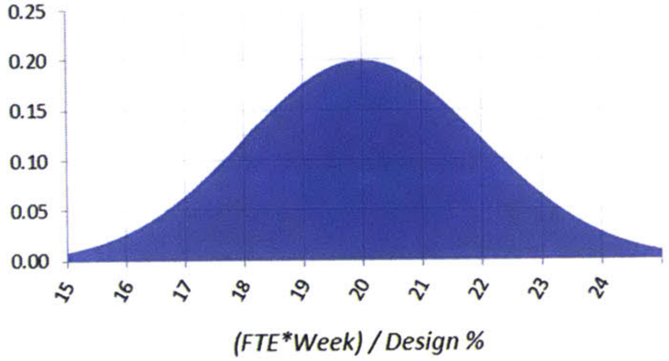


Figure 20: Design Staff Efficiency, Probabilistic Distribution (Input)

Designer Capacity is based upon number of resources that can concurrently work on a design, limited to type of design and level of integration or modularity. Some designs may be more susceptible to allowing more "chefs in the kitchen" depending on complexity and how integrated the particular design is. The probabilistic distribution for uncertainty of this input variable is presented in Figure 21.

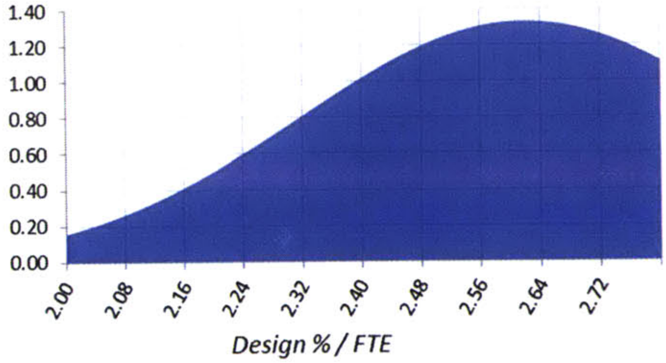


Figure 21: Designer Capacity, Probabilistic Distribution (Input)

Manufacturing Preparation Duration is based upon uncertainty within the processing time to have everything ready for build after designs are released. This is based on time needed to release production orders with manufacturing instructions, prepare tools, obtain raw material or detail parts used in the build, etc. The probabilistic distribution for uncertainty of this input variable is presented in Figure 22.

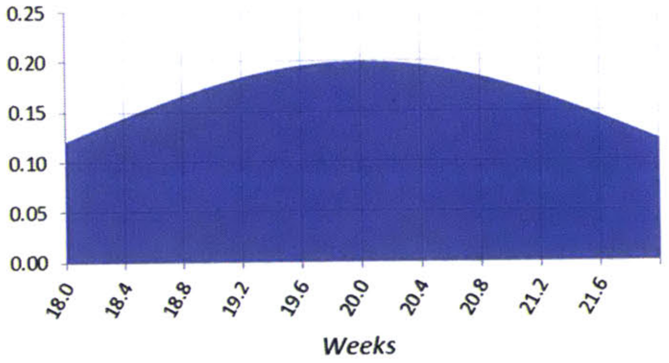


Figure 22: Manufacturing Preparation Duration, Probabilistic Distribution (Input)

Design Quality is based upon number of design-related issues discovered during the manufacturing phase. This can be attributed to interface issues that were not addressed during the detail design phase, or even alternate hardware that may be needed due to availability. The probabilistic distribution for uncertainty of this input variable is presented in Figure 23.

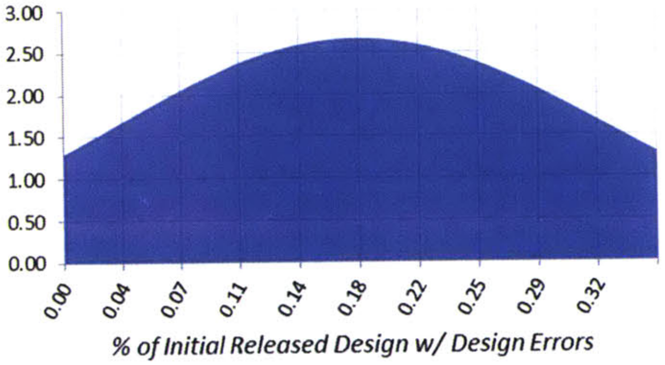


Figure 23: Design Quality (Initial Build), Probabilistic Distribution (Input)

Build Efficiency is based on the combination of available manufacturing resources and talent in terms of how much of the product can that can be completed per week. Other factors such as transitioning, learning, competing resources are also factored in. The probabilistic distribution for uncertainty of this input variable is presented in Figure 24.

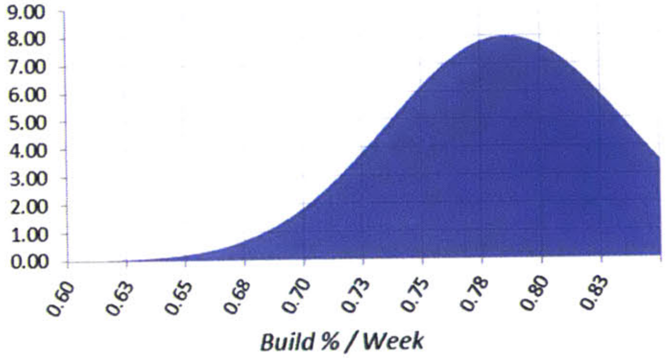


Figure 24: Build Efficiency, Probabilistic Distribution (Input)

Average Full Revision Effort defines the average amount of time it will take to release a fully revised design to the manufacturing floor after the issue is first identified and reported. The probabilistic distribution for uncertainty of this input variable is presented in Figure 25.

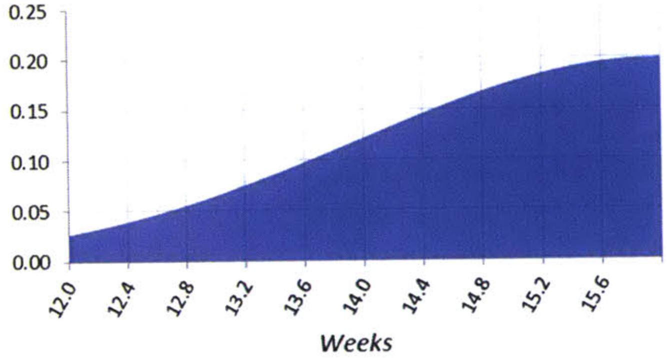


Figure 25: Average Full Revision Effort, Probabilistic Distribution (Input)

Maximum design resources defines uncertainty associated with availability of design resources due to competing projects within an organization or hiring freezes or other considerations. This is presented in terms of Full Time Equivalents (FTEs), which represents 40 hours per week. The probabilistic distribution for uncertainty of this input variable is presented in Figure 26.

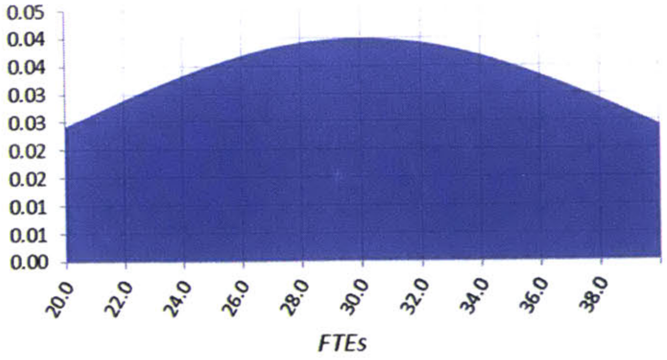


Figure 26: Max Design Resources, Probabilistic Distribution (Input)

Hiring / Transfer time is also associated with the staffing processes in terms of how quickly resources can be hired or transferred onto a project once staffing demand signals indicate a resource gap within the project. The probabilistic distribution for uncertainty of this input variable is presented in Figure 27.

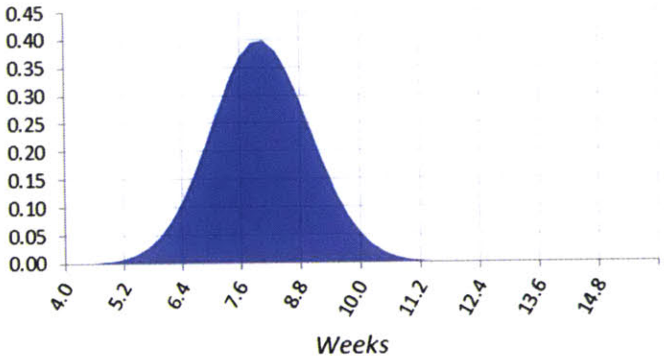


Figure 27: Hiring / Transfer Time, Probabilistic Distribution (Input)

4.8 Valuation of Redline Process Flexibility

To better understand the impact that uncertainty has on the value of flexibility, valuations were conducted in two manners. First, a comparison of total costs was conducted using only expected values (probabilistic means). In other words, outputs from models in Figure 9 (redline flexibility) and Figure 16 (no flexibility) were compared based on deterministic input values only. Second, a comparison of total costs was conducted using a Monte Carlo simulation to assess the impact of uncertainties defined in Section 4.7.

As shown in Table 6, by incorporating the redline flexibility within known environments, the flexibility appears to reduce the overall project cost by 2.0% and reduces duration by 14 weeks. For a $10M project, this would equate to a benefit of $200,000 for incorporating the redline flexibility into this project under specific conditions that were evaluated.

Deterministic Comparison	Cost (% Budget)	Duration (weeks)
No Flexibility	119.9%	222.0
Redline Flexibiity	117.9%	208.0
Flexibility Benefit	**2.00%**	**14.0**

Table 6: Deterministic Comparison of Flexibility, not optimized

As discussed in Section 4.2, redline policies could be optimized to provide further benefit. Values for *RL Threshold for Build Completion Pressure* and *RL Threshold for Response Rate Benefit* values were varied across a range from 0 to 10. Outputs for cost were monitored as the values were adjusted through a series of iterative evaluations. As shown in Figure 28, these factors determined whether or not the redline flexibility would be utilized.

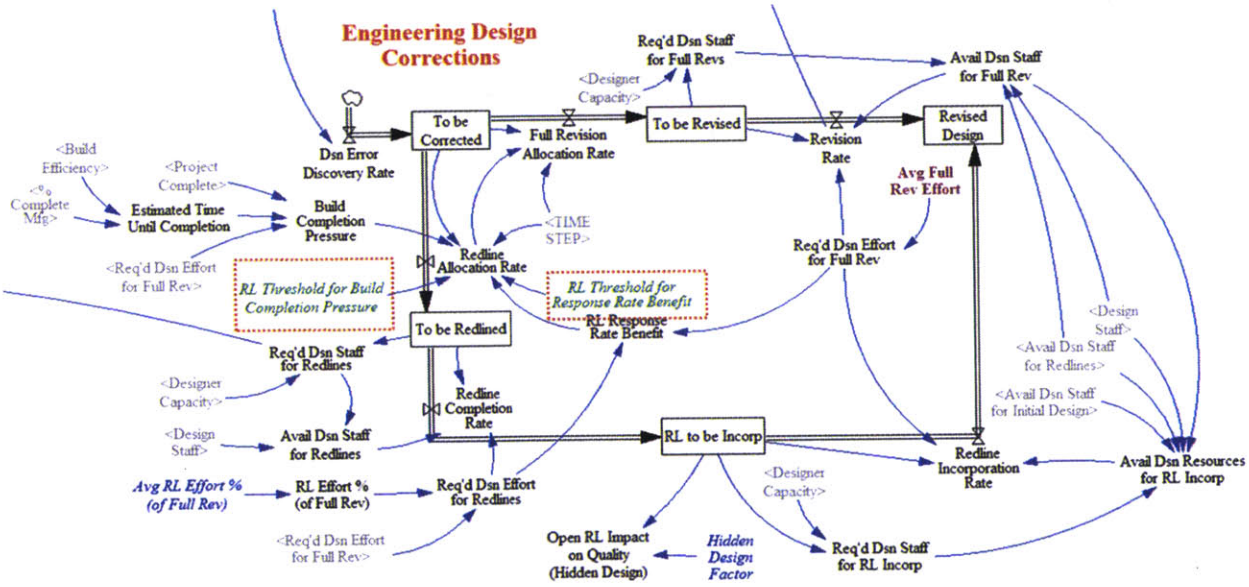


Figure 28: Variables Adjusted to Optimize Redline Flexibility

Ultimately, a combination of values for *RL Threshold for Build Completion Pressure* and *RL*

Threshold for Response Rate Benefit of 1.1 and 3.25, respectively, were determined to provide the most benefit. As shown in Table 7, an additional 1.5% benefit was achieved by optimizing the flexibility. For a $10M project, this would equate to a benefit of $350,000 for the optimized redline flexibility, as compared to the $200,000 for the non-optimized redline flexibility. It certainly makes sense that there would be an optimal value which provides the maximum benefit of utilizing redlines with minimal costs for use of that flexibility. For example, a *RL Threshold for Response Rate Benefit* value of 3.25 ensures that the effort required release a redline is at least 3.25 times less than the effort required to release a full drawing revision.

Deterministic Comparison	Cost (% Budget)	Duration (weeks)
No Flexibility	119.9%	222.0
Optimized Redline Flexibility	116.4%	207.0
Flexibility Benefit	**3.50%**	**15.0**

Table 7: Deterministic Comparison of Flexibility, optimized

When evaluating the behavior of the redline flexibility within uncertain environments, the value is different. A comparison of models in Figure 9 (redline flexibility) and Figure 16 (no flexibility) using Monte Carlo simulations was conducted with results shown in Table 8 and Figures 29 and 30. Values for *RL Threshold for Build Completion Pressure* and *RL Threshold for Response Rate Benefit* were varied in the same manner as described earlier to identify the optimized redline flexibility during a series of Monte Carlo simulations. Based on expected values of outputs, the value for the optimized redline flexibility yields an additional 1.6% of the project cost, within the boundaries of the uncertain environment defined in Section 4.7. For a $10M project, this would equate to a benefit of over $450,000 for the optimized redline flexibility, as compared to the $350,000 previously assessed within a deterministic environment.

Monte Carlo Comparison (Mean Values)	Cost (% Budget)	Duration (weeks)
No Flexibility	122.1%	264.4
Optimized Flexibility	117.6%	247.3
Flexibility Benefit	**4.55%**	**17.0**

Table 8: Comparison of Flexibility w/ consideration to Uncertainties

A comparison of the cumulative distribution functions (CDFs) are presented in Figures 29 and 30, which indicates a significant improvement in avoiding high budget overruns (NOTE the gap between 95th percentiles). Thus, the expected improvement of using the redline process is much different when considering a full range of uncertainties, rather than only the expected value of each condition.

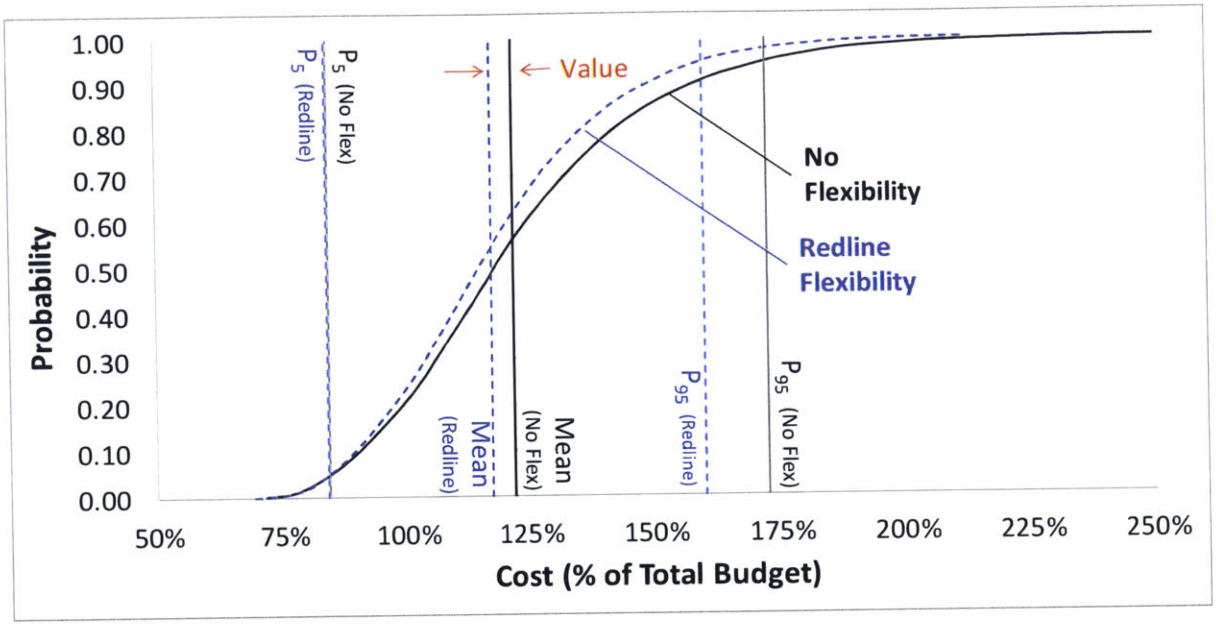


Figure 29: CDF of Total Project Costs

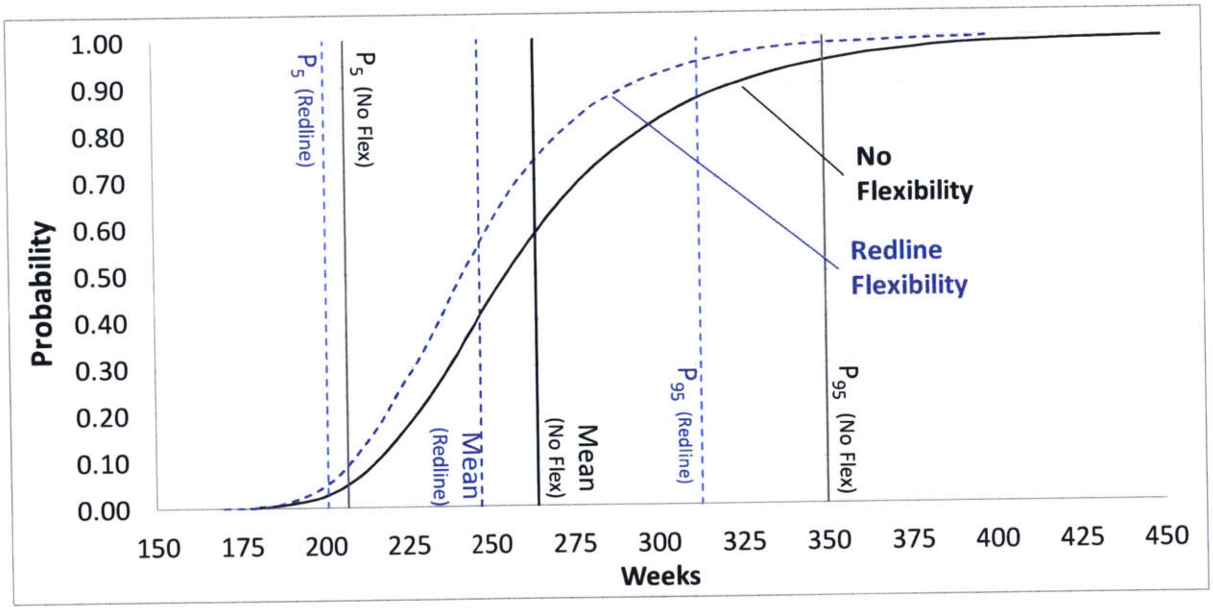


Figure 30: CDF of Project Duration

Based on this analysis, it would be recommended to incorporate the redline process, as there are no detrimental effects over the range of possibilities, and it is expected to provide a benefit of over 4.6% of the project budget. Furthermore, it would be recommended to re-evaluate the value of this flexibility on a periodic basis to ensure the flexibility is still worth maintaining for this project. It is possible unknown unknowns can arise that may need to be factored in down the road.

4.9 Assessment of Valuation Framework

The valuation approach provided a better insight into the amount of value of flexibility hidden when only considering deterministic conditions. This approach helped to better understand the dynamics of interrelationships within the process, as well as the uncertain environment in which the process is used. The redline process would likely have been rejected when initially considering waste within the design process. This approach also provided a means to play around with potential rules or policies in order to optimize the usefulness of the flexibility.

It makes sense to consider the full realm of uncertainties imaginable that could impact processes. Some uncertainties may be easier to quantify than others. But when forecasting how the process will behave in the future, we must assume some expected value regardless of the valuation method. This framework does require more thought from those assessing the process in terms of defining probability distributions for uncertainties. This step should be carefully considered, as the value of the flexibility is dependent upon the definition of this uncertain environment

Although the behavior and full worth of the flexibility was better understood with this framework, the practicality is limited to those who are experienced with developing and managing system dynamics models. Those who utilize the process should be involved in developing the system dynamics models to ensure behaviors are accurately represented. A significant amount of experience and training is required to develop a system dynamics model that accurately depicts the behavior of the system and all pertinent interrelationships while avoiding overly complex detail that includes every step along the process flow map. It is easy to fall into the mindset of wanting to model a very detailed flow. This, however results in an unnecessary amount of excessive time and effort with little value to be gained. This skill requirement is likely to hinder the adoption of this framework as a common practice.

The other aspect that may hinder adoption of this valuation approach is the lack of demonstrated metrics. By implementing the redline flexibility process into a $10M product development project, I cannot obtain measurement data indicating a gain of $450K due to the incorporation of the flexibility. This is a theoretical value which cannot be substantiated based on demonstrated performance. This value may be different on other projects and may be different 5 years from now on the same project. All I can say is that this is the full value of the redline flexibility for this project within the full range of probabilities that we know of today. Although very powerful, Monte Carlo simulations only present potential outcomes. At the end of every completed project, there will only be one outcome. The full power of certain flexibilities and the extent of their value may not be thoroughly appreciated by everyone, especially those who place value based on demonstrated metrics.

5 Conclusion

The framework of valuating flexibilities within processes combined benefits from conventional approaches, as well as methods used in real options. It is certainly useful to eliminate waste wherever possible for the sake of developing an efficient product development process. However, it is also valuable to re-consider non-value added activities or enabling activities in a restructured manner which incorporates flexibility.

When utilizing this framework to assess value, one must acknowledge the many uncertainties that could impact the performance of a process, consider the holistic nature of interfacing processes, and overcome the urge to substantiate value based on actual measurements. It often seems reasonable to use past experience and historical data to set forecasts for future operating conditions. This may be a good place to begin, but it must not constrain the full range of possibilities that may occur in the future which may present both opportunities and risk. It may not be sufficient to consider that the upcoming development project may have a 10% design scope increase over its duration based on experience with similar projects in the past. The desires of the customer may change significantly more during the upcoming development, or perhaps needs will be altered due to the introduction of new game-changing technologies. Furthermore, the holistic behavior of parameters affecting processes must be understood. Processes are often scrutinized very closely to eliminate waste. If an attribute within a process does not add value to that specific process it may be considered a waste. A drawing release process may include a risk mitigation attribute to circumvent standard procedures in order to expedite required input to downstream development processes. This attribute may expend more resources and ultimately increase the costs within the drawing release process. If the process is evaluated in isolation, the risk mitigation option may be considered a waste which adds costs and potentially masks underlying issues of needing to reduce delays associated with the standard drawing release process. However, if evaluated with respect to other key interrelated processes, a net benefit could be realized for the entire company due to resulting behaviors of downstream impacts. Lastly, it is natural to desire substantiation of an investment's value by obtaining data measured during actual events. This is perhaps the most difficult challenge to overcome. If the flexible option is exercised due to certain conditions, the value may seem high. If the option is never exercised due to other conditions, the value may appear worthless. Neither of the scenarios may truly demonstrate the full worth of the flexibility. Rather, a consideration of many possible conditions should be considered.

5.1 Recommendations for Future Research

The framework discussed within this research was evaluated using a simple process within product development. In addition, the process was evaluated with a development project only lasting several years. It is recommended to determine the usefulness of the valuation approach in more complex processes and with even longer development projects within product development, and which span many more organizations. It is not yet clear how the complexity of the valuation approach scales with the size of the process being analyzed. Even with simple processes, the system dynamics modeling can be difficult to develop.

5.2 Concluding Thoughts

The small company described in the introduction experienced tremendous growth and decay up within a decade of becoming a subsidiary to a large corporation, up until its closure. A significant amount of additional talent, experience, and resources became available during that time along with many new business opportunities and product development challenges. Capabilities, organizational structures, and operating processes and procedures rapidly changed. At the time the privately owned company was purchased, the amount of change that would occur over the next ten years was unimaginable to most, if not all. During that time, an unmanned helicopter was being developed while the organization underwent a major transformation with shifts in capabilities and operating procedures. Mission requirements changed considerably as unmanned technology had entered the industry and grew with tremendous uncertainty. There were many risks and many opportunities.

Within two years of transferring five legacy programs into the larger organization, only two remained. Two development programs were cancelled, and the other was divested. The legacy programs were much smaller in scale than most of the programs within the larger organization. The program which was divested was once profitable for the smaller subsidiary, however became a burden to the larger organization which was unable to generate profits within operating constraints. A shortfall of knowledge transfer and demand from competing programs for critical resources only added to the burden. Ten years ago, forecasts of knowledge retention, in-house manufacturing capabilities, overhead costs, and technical support response rates would have fallen pretty far from reality.

Within product development there are, of course, many uncertainties that may influence its success or demise. The impact of uncertainties increases as projects increase in scale, complexity, and duration. Flexibilities within product development processes may provide a means to avoid significant risks or to grasp unforeseeable opportunities. The full worth of such flexibilities can easily be obscured by manners in which they are measured. A flexible option within an organization's business processes might not ever be exercised, and yet still carry significant value.

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APPENDIX A

This section defines variables used in the system dynamics model presented within this thesis.

VARIABLE	UNIT	EQUALS	COMMENTS
% Complete Mfg	Dimensionless	Total Completed Mfg / Total Mfg	This value indicates the actual amount of build completed with respect to amount of manufacturing identified to be completed.
Added Mfg Scope Rate	Build % / Week	Added Scope Rate	This flow adds manufacturing to be completed based on increases to design work.
Added Scope Rate	Design% / Week	(Scope Increase per Year / 52) / TIME STEP	This indicates the rate as to which design scope is added to the project.
Avail Dsn Resources for RL Incorp	FTEs	Min(Req'd Dsn Staff for RL Incorp , Design Staff - (Avail Dsn Staff for Initial Design + Avail Dsn Staff for Redlines + Avail Dsn Staff for Full Rev))	This indicates how many full time equivalents are available to work on incorporating redlines thru full design revisions.
Avail Dsn Staff for Full Rev	FTEs	Min(Req'd Dsn Staff for Full Revs , Design Staff - Avail Dsn Staff for Redlines)	This indicates how many full time equivalents are available to work on completing full drawing revisions.
Avail Dsn Staff for Initial Design	FTEs	Min(Design Staff - Avail Dsn Staff for Redlines - Avail Dsn Staff for Full Rev , Req'd Dsn Staff for Initial Design)	This indicates how many full time equivalents are available to work on completing initial drawings.
Avail Dsn Staff for Redlines	FTEs	Min(Req'd Dsn Staff for Redlines , Design Staff)	This indicates how many full time equivalents are available to work on releasing redlines to the floor.
Avg Full Rev Effort	Weeks / FTE	16 (Deterministic Valuation) Normal Distribution ($\mu = 16$, $\sigma = 2$, 12 Min, 20 Max)	Refer to Section 4.7.
Avg Revision Duration	Weeks	Normal Distribution ($\mu = 4$, $\sigma = 0.2$, 1 Min, 10 Max)	This indicates the average duration for revising drawings.
Avg RL Effort % (of Full Rev)	Dimensionless	4	This represents the average benefit that redlines have over full dwg revisions.
Build Completion Pressure	Dimensionless	IF THEN ELSE(Estimated Time Until Completion > 0 :AND: Project Complete = 0 , Req'd Dsn Effort for Full Rev / Estimated Time Until Completion , 10)	This indicates pressure for incorporating full drawing revisions instead of redlines as the estimated completion approaches.
Build Efficiency	Build % / Week	0.75 (Deterministic Valuation) Normal Distr ($\mu = 0.75$, $\sigma = 0.05$, 0.60 Min, 0.85 Max)	Refer to Section 4.7.

VARIABLE	UNIT	EQUALS	COMMENTS
Build Rate	Build % / Week	IF THEN ELSE (Mfg WIP > 0, Min(On Hold Factor(On Hold %) * Build Efficiency , Build Efficiency / TIME STEP) , 0)	Rate as to which the build of the initial product is completed.
Build Start	Dimensionless	INTEG (Schedule Pressure , 0)	Indicator for when the build can be started.
Completion Threshold	Dimensionless	0.95	The project is considered complete after 95% of the known design and manufacturing work is complete.
Demand Factor	Dimensionless	Lookup Graph [(0,0)-(500,10)],(0,1),(2,1),(10,0.5),(25,0.05),(500,0.05))	Staffing capacity constraints (limits how much staff can be hired within a certain amount of time).
Design % Complete	Dimensionless	Total Completed Design / Total Design	Amount of design work completed to date.
Design Quality	Dimensionless	0.18 (Deterministic Valuation) Normal Distr ($\mu = 0.18$, $\sigma = 0.15$, 0.00 Min, 0.36 Max)	Refer to Section 4.7.
Design Resource Cost	% Budget	INTEG (IF THEN ELSE(Project Complete = 0, Resource Spending Rate , 0), 0)	Total costs due to design staff labor.
Design Resource Rate	$ / FTE	40 * <Hourly Rate>	Weekly rate of labor wages.
Design Staff	FTEs	INTEG (Staffing Rate - Staff Dismissal Rate, 0)	Total amount of full time equivalent design staff.
Designer Capacity	Design % / FTE	2.5 (Deterministic Valuation) Normal Distr ($\mu = 2.5$, $\sigma = 0.3$, 2.0 Min, 2.8 Max)	Refer to Section 4.7.
Dsn Discovery	Design % / Week	Dsn Error Discovery Rate + Added Scope Rate	Rate as to which addition design work is discovered (adds to initial estimate).
Dsn Error Discovery Rate	Design % / Week	Mfg Issue Discovery Rate	Rate as to which design efforts are detected and reported.
Dsn Staff Efficiency	Week * FTE / Design %	20 (Deterministic Valuation) Normal Distr ($\mu = 20$, $\sigma = 2$, 15 Min, 25 Max)	Refer to Section 4.7.
Estimated Time Until Completion	Dimensionless	IF THEN ELSE(% Complete Mfg < 1 , (100 - (% Complete Mfg * 100)) / Build Efficiency , 10)	Remaining time estimated until project is completed
Full Rev Resolution	Build % / Week	IF THEN ELSE(Mfg On Hold > 0 , IF THEN ELSE(Mfg On Hold > 0.01 , Revision Rate , Mfg On Hold / TIME STEP) , 0)	Rate at which Mfg WIP is resolved and ready to build based on full design revision responses.
Full Revision Allocation Rate	Design % / Week	IF THEN ELSE(To be Corrected > 0 , max(0 , (To be Corrected / TIME STEP) -Redline Allocation Rate), 0)	This variable simply dumps designs to be corrected into full revision work, depending on redline policy factors.
Hidden Design Factor	Dimensionless	Lookup Graph [(0,0)-(100,10)],(0,1),(10,1.05),(20,1.1),(30,1.2),(40,1.35),(50,1.55),(60,1.8),(70,2.1),(80,2.5),(90,3),(100,4))	Impact that hidden design due to open redlines has on design quality (design errors)

VARIABLE	UNIT	EQUALS	COMMENTS
Hiring / Transfer Duration	Weeks	8 (Deterministic Valuation) Normal Distr ($\mu = 8$, $\sigma = 1$, 4 Min, 16 Max)	Refer to Section 4.7.
Initial Design Estimate	Design %	100	Set as 100%.
Initial Dsn Completion Rate	Design % / Week	IF THEN ELSE (To be Designed > 0, Avail Dsn Staff for Initial Design / Dsn Staff Efficiency , 0)	Rate as to which the initial design work is completed and released.
Max Design Staff	FTEs	30 (Deterministic Valuation) Normal Distr ($\mu = 30$, $\sigma = 10$, 20 Min, 40 Max)	Refer to Section 4.7.
Mfg Complete	Build %	INTEG (Build Rate , 0)	Amount of build actually completed.
Mfg Discovery	Build % / Week	Added Mfg Scope Rate	Rate of discovering additional work to be built (based in new design work).
Mfg Issue Discovery Rate	Build % / Week	IF THEN ELSE(Mfg Queue > 0 , max(Open RL Impact on Quality (Hidden Design) * Design Quality * Mfg Queue / TIME STEP , 0) , 0)	Rate as to which design errors are discovered during the initial build.
Mfg On Hold	Build %	INTEG (Mfg Issue Discovery Rate - Full Rev Resolution - Redline Resolution, 0)	Amount of build on hold due to discovered manufacturing issues associated with design errors.
Mfg Prep Duration	Weeks	20 (Deterministic Valuation) Normal Distr ($\mu = 20$, $\sigma = 2$, 18 Min, 22 Max)	Refer to Section 4.7.
Mfg Queue	Build %	INTEG (Mfg Work Readiness Rate - Mfg Start Rate - Mfg Issue Discovery Rate , 0)	Amount of build ready to be built or which may have design errors.
Mfg Start Rate	Build % / Week	(Mfg Queue / TIME STEP) - Mfg Issue Discovery Rate	Rate as to which manufacturing work becomes available to start building.
Mfg WIP	Build %	INTEG (Full Rev Resolution + Mfg Start Rate + Redline Resolution - Build Rate, 0)	Amount of product to be built (workable work).
Mfg Work Readiness Rate	Build % / Week	IF THEN ELSE(Released Initial Design > Total Mfg Queued :AND: To be Manufactured > 0 , Min(Min (Workable Mfg % (Mfg Complete) * To be Manufactured / Mfg Prep Duration , To be Manufactured / TIME STEP) , (Released Initial Design - Total Mfg Queued) / TIME STEP), 0)	Rate as to which build packages become available to manufacturing to start building.
On Hold %	Dimensionless	IF THEN ELSE(Mfg WIP > 0 :AND: Mfg On Hold > 0.1 , Mfg On Hold / (Mfg On Hold + Mfg WIP),0)	Ratio of Mfg On Hold to Mfg in work.
On Hold Factor	Dimensionless	Lookup Graph [(0,0)-(1,1)],(0,1),(1,0))	Linear graph used to represent impact of MFG On Hold on build efficiency.

VARIABLE	UNIT	EQUALS	COMMENTS
Hiring / Transfer Duration	Weeks	8 (Deterministic Valuation) Normal Distr ($\mu = 8$, $\sigma = 1$, 4 Min, 16 Max)	Refer to Section 4.7.
Initial Design Estimate	Design %	100	Set as 100%.
Hiring / Transfer Duration	Weeks	8 (Deterministic Valuation) Normal Distr ($\mu = 8$, $\sigma = 1$, 4 Min, 16 Max)	Refer to Section 4.7.
Initial Design Estimate	Design %	100	Set as 100%.
Project Complete	Dimensionless	IF THEN ELSE(Design % Complete >= Completion Threshold :AND: % Complete Mfg >= Completion Threshold , 1 , 0)	Signals when the project is complete based on the Completion threshold.
Project Deadline	Weeks	<Budgeted Project Duration>	Number of weeks budgeted to complete the project.
Project Duration	Weeks	INTEG (IF THEN ELSE(Project Complete = 0 , Project Rate , 0), 0)	Sum of weeks spent on the project, up until completion.
Project Rate	Weeks	TIME STEP	Time tracker used for project duration
Queue Rate	Build % / Week	Mfg Work Readiness Rate	Rate as to which manufacturing build is queued up and ready to be built.
Redline Allocation Rate	Design % / Week	IF THEN ELSE(To be Corrected > 0 :AND: Build Completion Pressure < RL Threshold for Build Completion Pressure :AND: RL Response Rate Benefit > RL Threshold for Response Rate Benefit, max(0, To be Corrected / TIME STEP) , 0)	This variable simply dumps designs to be corrected into redline work, depending on redline policy factors.
Redline Completion Rate	Design % / Week	IF THEN ELSE(To be Redlined > 0, Avail Dsn Staff for Redlines / Req'd Dsn Effort for Redlines ,0)	Rate as to which redlines are released.
Redline Incorporation Rate	Design % / Week	IF THEN ELSE(RL to be Incorp > 0 , Avail Dsn Resources for RL Incorp / Req'd Dsn Effort for Full Rev , 0)	Rate as to which redlines are incorporated thru full design revisions.
Redline Resolution	Build % / Week	IF THEN ELSE(Mfg On Hold > 0, IF THEN ELSE(Mfg On Hold > 0.01, Redline Completion Rate , Mfg On Hold / TIME STEP) , 0)	Rate at which Mfg WIP is resolved and ready to build based on redline responses.
Released Initial Design	Design %	INTEG (Initial Dsn Completion Rate , 0)	Amount of initial design released and ready for manufacturing.
Req'd Dsn Effort for Full Rev	Week * FTE / Design %	SMOOTH(RANDOM NORMAL(Avg Full Rev Effort - 2, Avg Full Rev Effort + 2 , Avg Full Rev Effort , 0.5 , 1) , 5)	Amount of effort required to fully revise drawings.
Req'd Dsn Effort for Redlines	Week * FTE / Design %	Req'd Dsn Effort for Full Rev / RL Effort % (of Full Rev)	Amount of effort required to complete redlines.

VARIABLE	UNIT	EQUALS	COMMENTS
Req'd Dsn Staff for Full Revs	FTEs	To be Revised / Designer Capacity	Amount of design staff required to conduct full drawing revisions.
Req'd Dsn Staff for Initial Design	FTEs	To be Designed / Designer Capacity	Amount of resources required to complete the initial design work.
Req'd Dsn Staff for Redlines	FTEs	To be Redlined / Designer Capacity	Amount of resources required to release redlines to the manufacturing floor.
Req'd Dsn Staff for RL Incorp	FTEs	RL to be Incorp / Designer Capacity	Amount of resources required to incorporate redlines into full design revisions.
Resource Gap	FTEs	Min(max(Resource Need - Design Staff , 0) , (Staffing Cap Increase (Full Funding) + Staffing Cap (Advanced Start)) - Design Staff)	Difference between staffed resources and required resources.
Resource Need	FTEs	SMOOTH(Req'd Dsn Staff for Initial Design + Req'd Dsn Staff for Full Revs + Req'd Dsn Staff for Redlines + Req'd Dsn Staff for RL Incorp ,4)	Amount of full time equivalent resources required to address all required design work in progress.
Resource Spending Rate	% Budget / Week	((Design Staff * Design Resource Rate) / Project Budget) / TIME STEP	Rate at which labor costs are accumulated due to design effort.
Revised Design	Design %	INTEG (Redline Incorporation Rate + Revision Rate, 0)	Amount of design corrections which have been fully revised.
Revision Rate	Design % / Week	IF THEN ELSE(To be Revised > 0 , Avail Dsn Staff for Full Rev / Req'd Dsn Effort for Full Rev , 0)	Rate at which design can be fully revised.
Reward	% Budget	IF THEN ELSE(Project Complete = 1 :AND: Project Duration < Project Deadline , Reward per week ahead *(Project Deadline - Project Duration) , 0)	Sum of schedule rewards for the project.
Reward per week ahead	% Budget / Week	<Reward Value> / Project Budget	Value assigned to schedule performance based on beating schedule deadlines.
RL Effort % (of Full Rev)	Dimensionless	SMOOTH(RANDOM NORMAL(0.5, Avg RL Effort % (of Full Rev) + (Avg RL Effort % (of Full Rev) - 0.5) , Avg RL Effort % (of Full Rev) , 2 , 1), 4)	Redline effort as a percentage of full design revision efforts.
RL Response Rate Benefit	Dimensionless	Req'd Dsn Effort for Full Rev / Req'd Dsn Effort for Redlines	A ratio of efforts indicating overall benefit for the redline usage.
RL Threshold for Build Completion Pressure	Dimensionless	1 (Initial Value) 1.1 (Optimized Value)	This represents the redline policy for determining if redlines can be utilized based remaining time until the build is completed (see Section 4.2)

VARIABLE	UNIT	EQUALS	COMMENTS
RL Threshold for Response Rate Benefit	Dimensionless	1 (Initial Value) 3.25 (Optimized Value)	This represents the redline policy for determining if redlines can be utilized based on current benefit (see Section 4.2)
RL to be Incorp	Design %	INTEG (Redline Completion Rate - Redline Incorporation Rate , 0)	Amount of open design work needing to be revised due to previously released redlines.
Schedule Cost	% Budget	Penalty + Reward	Sum of project penalty costs and rewards (negative value in terms of cost).
Scope Increase per Year	Design %	2.5 (Deterministic Valuation) Uniform Distribution (0 Min, 5 Max)	Refer to Section 4.7.
Staff Dismissal Rate	FTEs / Week	IF THEN ELSE(Design Staff > Resource Need , (Design Staff - Resource Need) / Staff Reduction Delay , 0)	Rate at which full time equivalents can be transfer off of the project and be absorbed onto other work.
Staff Reduction Delay	Weeks	2	Average amount of time needed to transfer staff off of the project and be absorbed onto other work.
Staffing Cap (Advanced Start)	FTEs	3	Max capacity of design resources permitted to begin design work in advance of official project start.
Staffing Cap Increase (Full Funding)	FTEs	STEP(Max Design Staff - Staffing Cap (Advanced Start) , 26)	Max capacity of design resources after full project funding has been provided.
Staffing Need	FTEs / Week	IF THEN ELSE(Resource Gap > 0 , Resource Gap / 8, 0)	The amount of full time equivalent resources that are required to support all design work currently identified
Staffing Rate	FTEs / Week	IF THEN ELSE(To be Staffed > 0 :AND: Resource Gap > 0 , Min(Demand Factor(To be Staffed) * To be Staffed / Hiring / Transfer Duration , To be Staffed / TIME STEP), 0)	Rate at which full time equivalents are hired or transferred onto the project.
TIME STEP	Week	1	The time step for the simulation
To be Corrected	Design %	INTEG (Dsn Error Discovery Rate - Redline Allocation Rate - Full Revision Allocation Rate , 0)	Amount of design work identified to be corrected, based on issues reported from manufacturing.
To be Designed	Design %	INTEG (Added Scope Rate - Initial Dsn Completion Rate , Initial Design Estimate)	Amount of design work remaining to be completed (initial design)
To be Manufactured	Build %	INTEG (Added Mfg Scope Rate - Mfg Work Readiness Rate , 100)	Amount of manufacturing work identified to be built.
To be Redlined	Design %	INTEG (Redline Allocation Rate - Redline Completion Rate, 0)	Amount of open design corrections to be redlined to support the floor.
To be Revised	Design %	INTEG (Full Revision Allocation Rate - Revision Rate , 0)	Amount of open design corrections to be revised thru full drawing revisions.

VARIABLE	UNIT	EQUALS	COMMENTS
To be Staffed	**FTEs**	**INTEG (Staffing Need - Staffing Rate , 1)**	**Amount of remaining full time equivalents that need to be hired or transferred onto the project.**
Total Completed Design	Design %	Released Initial Design + Revised Design	Amount of total design work completed.
Total Completed Mfg	**Build %**	**Mfg Complete**	**Amount of manufacturing build completed.**
Total Costs	% Budget	Design Resource Cost + Schedule Cost	Sums up all project costs.
Total Design	**Design %**	**INTEG (Dsn Discovery , Initial Design Estimate)**	**Sums up all design requirements to date.**
Total Mfg	Build %	INTEG (Mfg Discovery , 100)	Sums up all manufacturing requirements to date.
Total Mfg Queued	**Build %**	**INTEG (Queue Rate, 0)**	**Indicates how much manufacturing has been queued up to build to date.**
Workable Mfg %	Dimensionless	Lookup Graph ([(0,0)-(200,1)],(0,0.05),(95,1),(200, 1))	Lookup chart for assessing how much build can be started based on what has already been built.