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Mitigating Space Industry Supply Chain Risk Thru Risk-Based Analysis

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To the Graduate Council:

I am submitting herewith a dissertation written by Jennifer S. Cooper entitled "Mitigating Space Industry Supply Chain Risk Thru Risk-Based Analysis." I have examined the final electronic copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Industrial Engineering.

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Mitigating Space Industry Supply Chain Risk Thru Risk-Based Analysis

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Dedicated to Sahara

ad astra

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ABSTRACT

Using risk-based analysis to consider supply chain disruptions and uncertainty along with potential mitigation strategies in the early stages of space industry projects can be used avoid schedule delays, cost overruns, and lead to successful project outcomes.

Space industry projects, especially launch vehicles, are complicated assemblies of high-technology and specialized components. Components are engineered, procured, manufactured, and assembled for specific missions or projects, unlike make-to-stock manufacturing where assemblies are produced at a mass production rate for customers to choose off the shelf or lot, like automobiles.

The supply chain for a space industry project is a large, complicated web where one disruption, especially for sole-sourced components, could ripple through the project causing delays at multiple project milestones. This ripple effect can even cause the delay or cancelation of the entire project unless project managers develop and employ risk mitigations strategies against supply chain disruption and uncertainty. The unpredictability of when delays and disruptions may occur makes managing these projects extremely difficult.

By using risk-based analysis, project managers can better plan for and mitigate supply chain risk and uncertainty for space industry projects to better manage project success.

Space industry project supply chain risk and uncertainty can be evaluated through risk assessments at major project milestones and during the procurement process. Mitigations for identified risks can be evaluated and implemented to better manage project success. One mitigation strategy to supply chain risk and uncertainty is implementing a dual or multi-supplier sourcing procurement strategy.

This research explores using a risk-based analysis to identify where this mitigation strategy can be beneficial for space industry projects and how its implementation affects project success. First a supply chain risk assessment and mitigation decision tool will be used at major project milestones to show where a multi-sourcing strategy may be beneficial. Next, updated supplier quote evaluation tools will confirm the usage of multiple suppliers for procurement. Modeling and simulation are then used to show the impact of that strategy on the project success metrics of cost and schedule.

PREFACE

This research does not contain classified or proprietary information.

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CHAPTER 1 INTRODUCTION

The space industry consists of spacecrafts, ground support, and launch sectors through a combination of public and private projects. The industry was valued at approximately $6 Billion USD in 2020. The industry is expected to double by 2025 and become a multi-trillion industry within the next decade with the continued growth of commercial projects and products.[1]

Space industry products, especially launch vehicles, are complicated assemblies of high-technology and specialized components. Unlike make-to-stock manufacturing where assemblies are produced at a mass production rate for customers to choose off the shelf or lot, like automobiles, space industry components are often products are that are procured, manufactured, and assembled for specific missions or projects or made/engineered-to-order.

Complex space industry projects require rigorous project management, scheduling, supply chain management, and procurement to meet project objectives, schedules, and costs.

As the space industry continues to grow and becomes more competitive, supply chain disruptions and uncertainty will increasingly affect project management and execution.

The purpose of this research is to develop a risk-based procurement process to understand and mitigate supply chain disruptions and uncertainty to better manage space industry projects to successful completions.

1.1 Space Industry Project Development Milestones

The NASA Systems Engineering Handbook details the systems engineering and project management processes required for the space agency as summarized in Figure 1.1. Although projects may not follow all aspects of this process, this paper will consider the NASA process as the basis for all space industry projects.

A series of project milestones define the project life cycle from concept to closure. More than 50 precent of project costs are committed to post Critical Design Review (CDR) activities such as production, testing, and operations as shown in Figure 1.2.

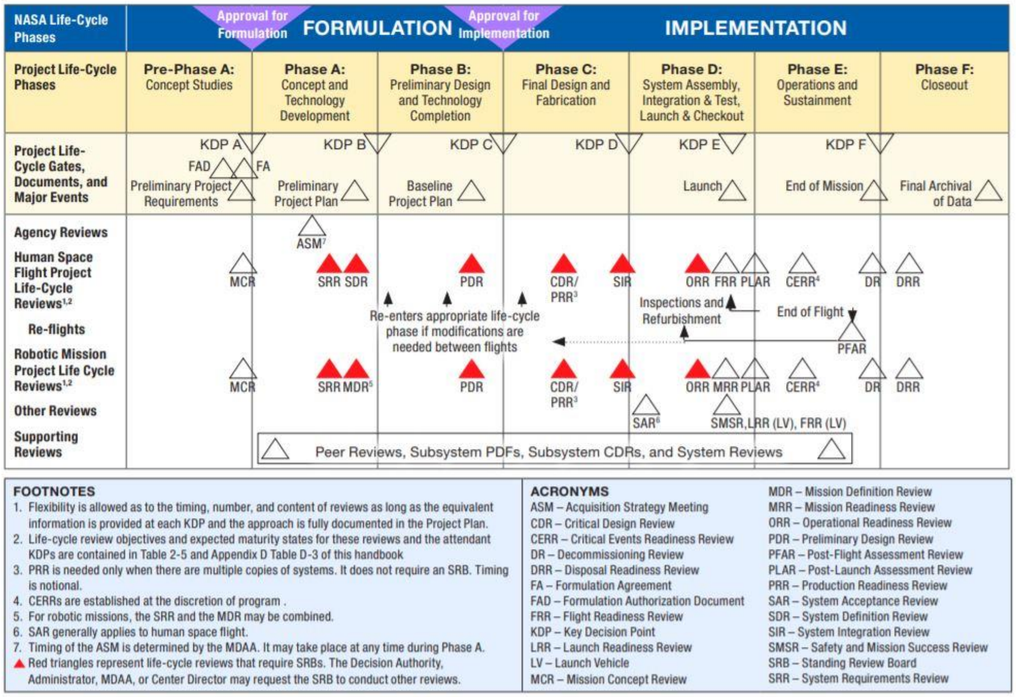
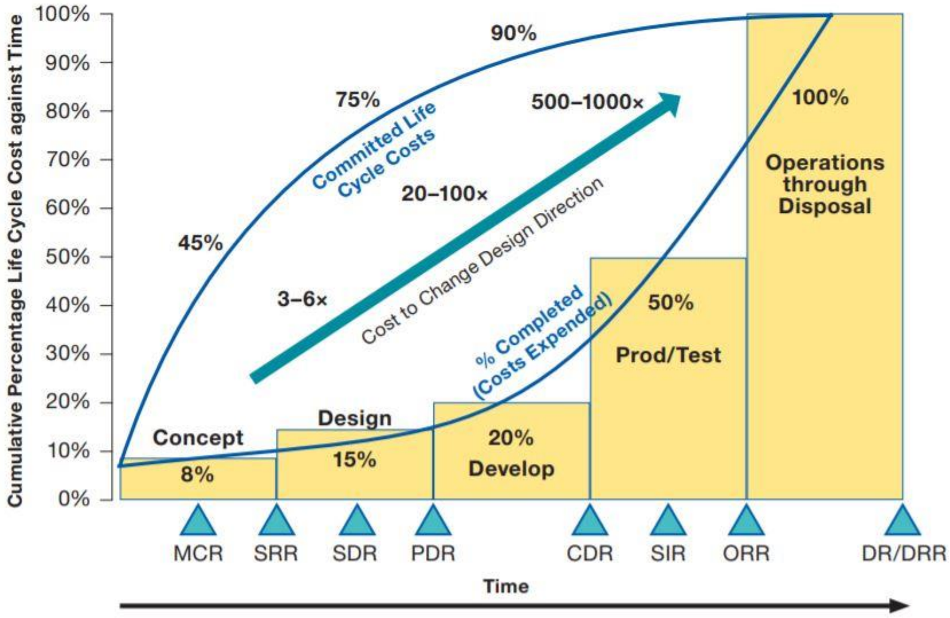


Figure 1.1. NASA Project Phases



MCR	Mission Concept Review	**CDR**	Critical Design Review
SRR	System Requirements Review	**SIR**	System Integration Review
SDR	System Definition Review	**ORR**	Operational Readiness Review
PDR	Preliminary Design Review	**DR/DRR**	Decommissioning/Disposal Readiness Review

Adapted from INCOSE-TP-2003-002-04, 2015

Figure 1.2. Project Costs by Project Phase

After CDR, a project moves to the production, testing, and operation phases. Project production and testing brings together components into section assemblies which are joined together and tested to form the final deliverable product for the project as illustrated in a simplified example in Figure 1.3.

1.2 Space Industry Project Management and Success

A disruption anywhere along the project procurement chain can create a ripple effect, delaying later stages of the project production and testing. Delays can be costly, leading to rework and reprioritization or redeployment of manufacturing resources. This ripple effect can cause delays to the entire project completion or mission and in some cases a significant delay can lead to the cancellation of the project.

Project managers focus on maintaining their baseline project schedule and costs. When a disruption is experienced in their project, a significant amount of the project manager's time is spent developing recovery plans or mitigation strategies to try to continue to meet the overall project budget and schedule.

1.3 Project Baselines

A project baseline is the project plan that allows a project manager to assess the progress over time. Without the baseline plan, project managers would be unable to measure project progress and success. Cost, schedule, scope, and milestones can all make up a project baseline.

With a space industry project, there are several detailed and complex components and subassemblies that make up a section such as a variety of avionics components for power and/or navigation. Components may be produced by a variety of suppliers. Components are also made from subassemblies and piece parts from an even wider variety of suppliers. Parts, components, subassemblies, and sections all have individual lead-times and costs that contribute to the project baseline.

"A quantifiable deviation, departure, or divergence away from a known baseline or expected value," is simply described as a variance in industry and as defined in the Project Management Body of Knowledge (PMBOK).[2] Due to the academic nature of this dissertation, a variance of any of the project baselines will simply be called a deviation.

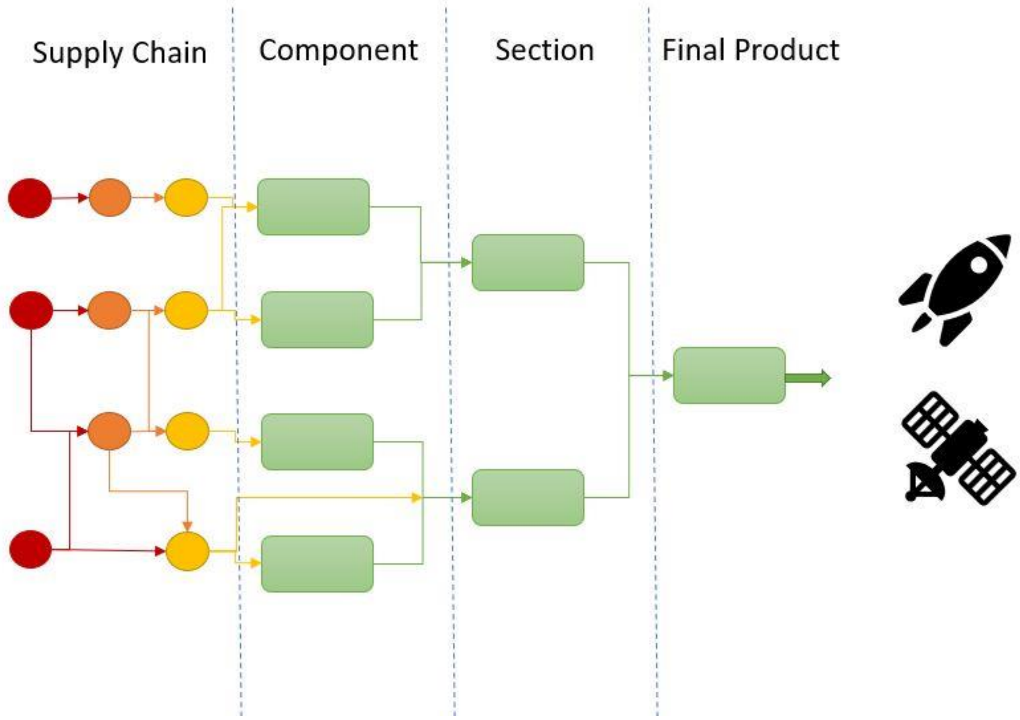


Figure 1.3. Example Project Build

1.4 Project Success Metrics

Since the 1970s, project managers have used the Project Management Triangle as a representation for the basic project performance measures, also known as the Iron Triangle or Triple Constraint. Time and Cost make up two of the sides of the triangle and are the two that will be the metrics focused on in this research.

The third side usually represents quality, performance, or scope, depending on the research focus. Quality and performance will be indirectly represented in the review of the time metric as quality or performance issues at suppliers may cause schedule delays, illustrating the concept that failures or issues in one side of the triangle affects the other two sides.

The Project Management Triangle and the metrics used to assess projects have evolved since the 1970s. Project managers may use a variety of metrics to measure project performance and success. [3]

1.5 Structure

This Chapter introduces the dissertation by introducing the current state of the space industry and its forecasted growth.

Chapter 2 reviews the literature in project scheduling, manufacturing strategies, and supply chain risk and uncertainty.

Chapter 3 discusses an overview of the dissertation problem, case study, baseline scenario, and research methods.

Chapter 4 details a supply chain risk assessment model to determine when a multiple supplier strategy would be beneficial for supply chain risk and uncertainty.

Chapter 5 contains procurement evaluation utilizing a supplier scorecard for determine when to place an order with multiple suppliers.

Chapter 6 contains the mathematical model and simulations to optimize the order split among suppliers when using a multi-supplier sourcing strategy.

Chapter 7 contains the conclusion and recommendations for future work.

CHAPTER 2 LITERATURE REVIEW

This literature review will discuss several relevant topics to this research to better understand the existing literature and its gaps.

- Section 2.1 reviews a variety of project scheduling techniques.
- Section 2.2 will discuss schedule recovery.
- Section 2.3 compares manufacturing strategies. The space industry relies heavily on make-to-order or engineer-to-order products.
- Section 2.4 discusses supply chain risk and uncertainty.
- Section 2.5 reviews mitigations strategies such sourcing strategies, inventory controls, and supplier selection are also discussed.
- Section 2.6 will summarize the gaps in existing research that this paper will contribute towards.

2.1 Discussion of Project Scheduling Techniques

As a project is started management develops a baseline project schedule for the overall project completion. These project schedules often include buffers in each project phase, milestone, assembly, or component delivery to account for unforeseen events and still meet delivery needs. Should the buffer time not be used or not be completely used the project or project phase will finish early; however, if unforeseen delays exceed the buffer, the project phase or project will be delayed and not meet delivery needs.

2.1.1 Project Scheduling Techniques

The following is a discussion of various scheduling and buffer techniques to develop a baseline schedule.

2.1.1.1 Forwards and Backwards Scheduling

Forward Scheduling is completing production and/or delivery as soon as possible. Forward scheduling minimizes slack time and maximizes labor utilization. This technique can lead to bottlenecks in production and increase lead-time. As products are produced before need, additional holding costs may result. Satellite launches, space station/port build, space tourism, and missions to the moon may utilize a forward scheduling production approach based on component availability and completion. Schedule and supply chain uncertainty would need to be accounted for within the project, but unrealized risks could accelerate the project and reduce costs.

Backwards scheduling is waiting to produce at the last possible date to meet delivery or ship just-in-time. Backwards scheduling can result in lower inventory costs; however, without a buffer or safety stock products can be delayed with material or equipment issues. A launch vehicle for a Mars mission, where there is a specific window for launch and landing due to a required alignment between the Earth and Mars for mission success, is an example of a space industry product requiring organization and backwards scheduling from the alignment dates. As such, risk and uncertainty must be scheduled into the project or the project will be severely delayed, overrun, and possibly cancelled.

2.1.1.2 Work Breakdown Structure (WBS) and Gantt Charts

As defined in the PMBOK® Guide—Third Edition, WBS is "a deliverable-oriented hierarchical decomposition of the work to be executed by the project team to accomplish the project objectives and create the required deliverables. It organizes and defines the total scope of the project. Each descending level represents an increasingly detailed definition of the project work. The WBS is decomposed into work packages. The deliverable orientation of the hierarchy includes both internal and external deliverables."

2.1.1.3 Program Evaluation Review Technique (PERT)/Critical Path Method (CPM)

Program Evaluation Review Technique (PERT) and Critical Path Method (CPM) are often used interchangeably but differ in calculating tasks times. PERT provides a visual representation of a project's activities and activity completion uncertainty by sequencing them in a network diagram. The expected completion time for activities can be calculated using a weighted average of the activity's Optimistic time, shortest time completed; Most likely time, highest probable completion time; and Pessimistic time, longest time.

weighted average:
Expected Time = (Optimistic + 4 x Most Likely + Pessimistic) / 6

From the network diagram the critical path can be determined. This path is the longest as determined by adding activity times for each path. Non-critical path activity slack time or float time can be calculated by working forwards and backward through the network. Earliest Start (ES) and Earliest Finish (EF) activity times are determined by working forward through the network; Latest Start (LS) and Latest Finish (LF). The difference in LF and EF of each activity is the activity slack. The critical path has no slack.

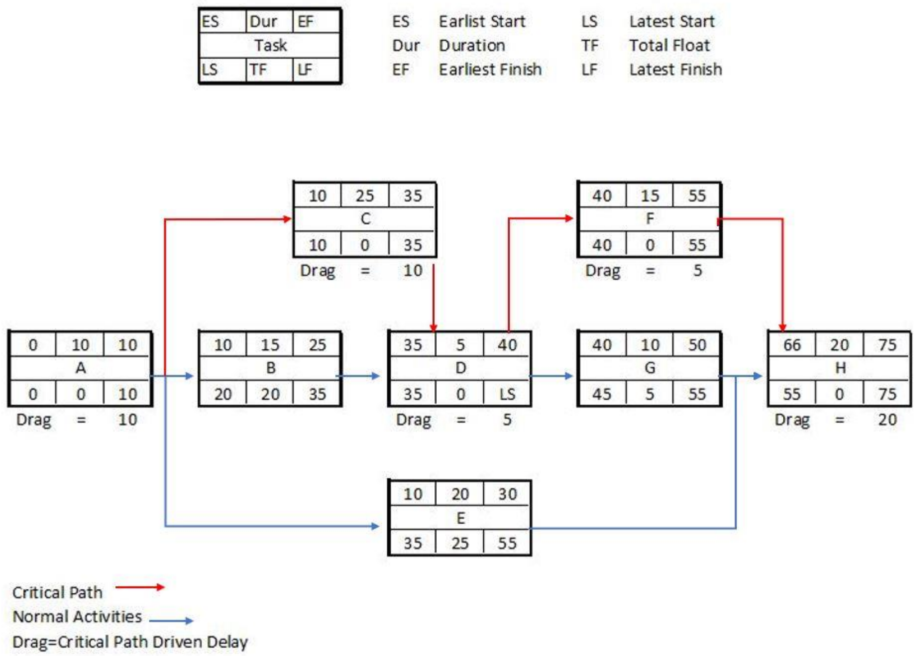


Figure 2.1 PERT/CPM Example

PERT and CPM allow project managers to see and evaluate time and resources of a project but rely heavily on subjective experience or historical project data. In new development projects such as those for the space industry, unreliable or incomplete data can lead to bad estimations for activity durations causing schedule delays and increased costs.

2.1.1.4 Resource Constrained Project Scheduling Problem (RCPSP)

RSPSP is an often-studied extension of PERT/CMP. This type of optimization problem considers the limitation of resources such as equipment, material, and labor in minimizing the project make span. With more complex projects and resource constraints, numerical methods for analyzing.

2.1.1.4.1 A simple RCPSP example

A simple, visual example of a Resource Constrained Project Scheduling problem for four tasks and three resource types is described in Table 2.1.The order of tasks and resource type needs is shown in shown in

Figure 2.2.

This visually shows each task start follows its predecessor and resource histograms to determine how many of each resource type is needed to complete the shortest schedule duration. In the shortest schedule, two of resource type two are needed during Week 3; however, if only one is available this type of resource becomes a constraint and the tasks that utilize this resource must be scheduled sequentially rather than concurrently. Figure 2.3 shows two different schedule examples with resource two constrained.

2.1.1.5 Critical Chain Project Management

CCPM was first introduced in 1997 by Eliyah Goldratt as the business novel, “Critical Chain.” [4] Since the novel’s publication additional academic studies have been conducted on CCPMs methodology and implementation. Until Goldratt’s novel, project scheduling methods had been unchanged since the 1950s.

Critical Chain Project Management (CCPM) is a newer methodology of scheduling based on theory of constraints (TOC). Unlike PERT and CPM, CCPM is less focused on task and task order and more on resource availability and flexibility. Unlike traditional project scheduling where each task may have a buffer, and the next task does not start until the previous task, including buffer ends, CCPM accumulates all task buffers at the end of the chain of tasks as an overall project buffer.

Table 2.1 RCPSP Example

Activity	Predecessor	Duration (week)	Resource Type
Task 1	None	2	R1
Task 2	Task 1	1	R2
Task 3	Task 1	2	R2
Task 4	Task2, Task 3	2	R3, R2

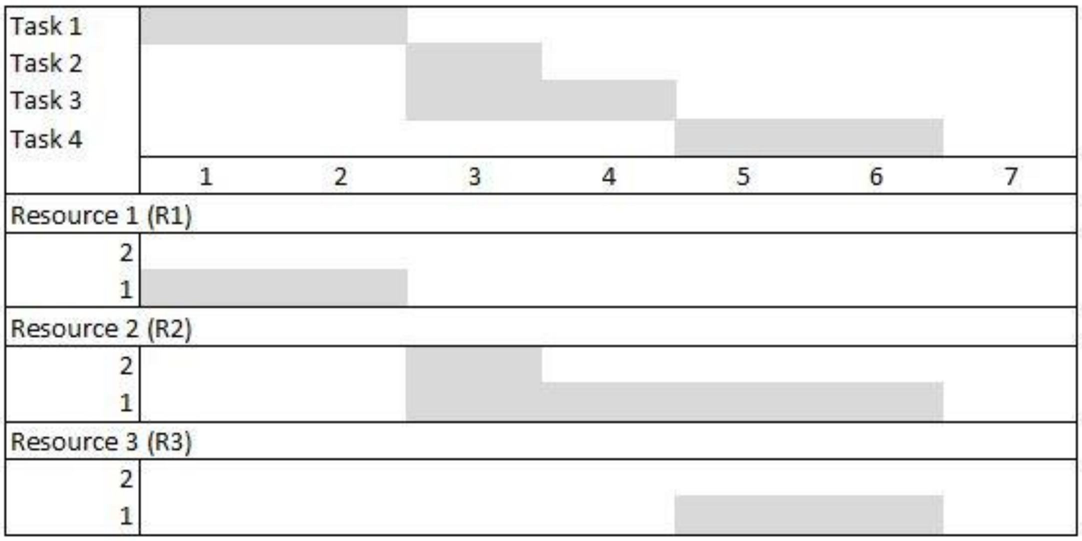


Figure 2.2 RCPSP Example Resource Needs

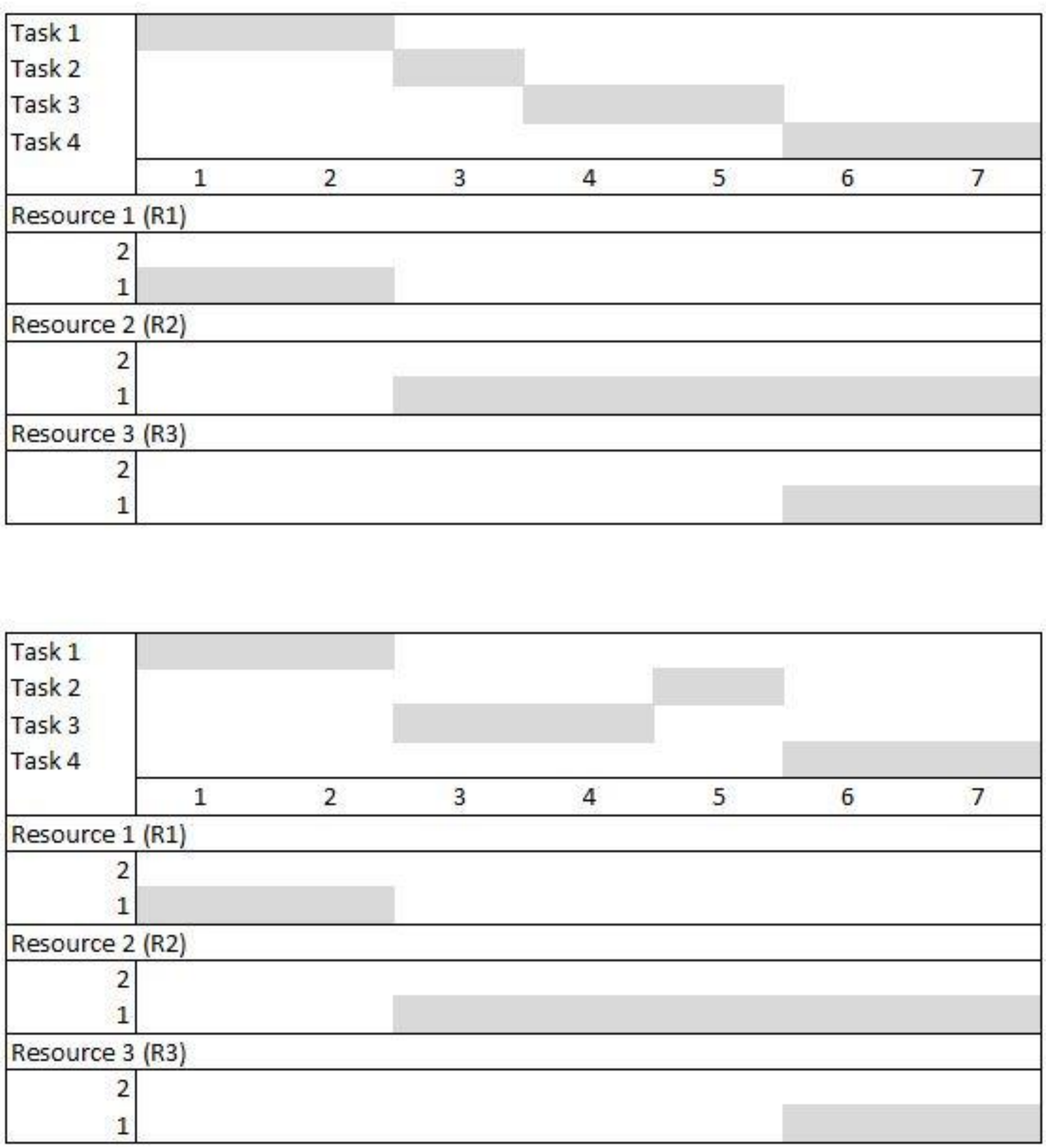


Figure 2.3 RCPSP Example Schedules with R2 Constrained

Figure 2.4 shows a simplified example of a project's critical path scheduled with uncertainty buffered at the end of each part, component, etc. verses the project scheduled using Critical Chain Project Management (CCPM), with the critical path buffers accumulated at the end.

Initial research focused on the principles and fundamentals of CCPM. [5] [6] [7],[8] Leach's book contains a comprehensive study of the principles and application of CCPM.[9] Anytime something new is introduced, it triggers critical studies and examinations that closer examination the new methodology and lead to improvements. [10], [11], [12], [13], [14]

One area of contention in initial research was the 50% buffer. A significant amount of research in CCPM has been in buffer sizing improvements.

Of the few industry case studies in research, engineering and construction projects dominate the research. [11], [13], [15], [16], [17], [18], [19], [20] Even fewer studies examine CCPM in relation to project costs. [21], [22]
A make-to-order or engineer-to-order product, such a space vehicle is like a construction project in its scheduling and project development.

Buffer sizing techniques are one of the most studied topics of CCPM. Initially a buffer size was set at 50% of the activity's duration. This led future researchers to study developing more scientific mathematical models to calculate buffer size. Root Square Error Method (RSEM) and its derivatives are the most widely studied buffer method. Buffer size continues to be an area of research interest especially in other methodologies such as fuzzy logic. [23]–[25]

2.1.2 Project Scheduling Tools

There are several public and proprietary project management tools that a project manager may use for project scheduling. Two of the most widely used software tools are Microsoft Project and Open Plan. Microsoft Project is available in many versions for commercial and personal use, including a web-based platform. Open Plan is a commercial, Windows-based project planning tool. Both tools contain a variety of the same project planning resources including, but not limited to, Gantt charts, PERT charts, Baselines, Cost tracking, Earned Value Management, and Risk Management. Although this research is not focused on the software tools available for scheduling, a successful project manager should be familiar with the scheduling tools used for project management.

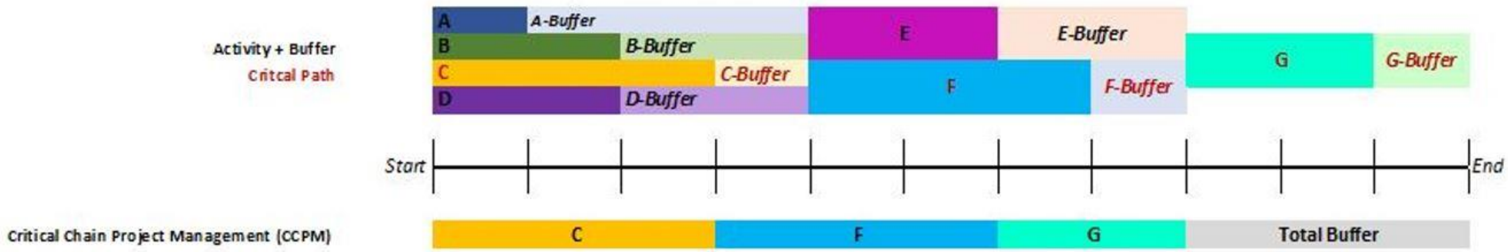


Figure 2.4 Graphical Example Project Schedules with Schedule Buffers

2.2 Project Schedule Recovery

Once a project schedule is developed it needs to be maintained and updated. Project managers need to be able to forecast if the project will be completed on time, how much work is still left on the project, and if there will be delays or overages. Project managers will need to determine if the project schedule is recoverable or if a new project schedule needs to be developed or re-baselined.

2.2.1 Recovery Decision Models

There is little research on recovery decision models. Projects funded by the United States' Government utilize Earned Value Management as a method for project management and forecasting. Many space industry projects are government funded, so it is important to understand the benefits and limitations of earned value management.

2.2.1.1 Earned Value Management

The project management technique of Earned Value Management (EVM) dates to 1966 implementation on projects by the United States Air Force. Its main objectives are to measure the performance and progress of a project and forecast the outcome of the project. Since it has become a technique used worldwide by programs, companies, and government agencies to provide management with visibility into cost and schedule issues. The Project Management Institute's "Standard for Earned Value Management" provides a comprehensive understanding of EVM and its applications. [26]

"The traditional EVM performs well in forecasting… cost metrics. However, in terms of schedule performance, the accuracy of the forecasted schedule metrics through the traditional EVM approach are always questionable."[27]

Using cost metrics to forecast schedule impacts may be misleading to understanding the reality of schedule delays. Lipke's earned schedule extension to EVM offers a better forecasting method, but still uses cost metrics. [28] Sackey et al. 2020's DEAC model and Kim et al. 2014's KEVM models offer additional extensions of EVM and ES for better accuracy; however, what these studies and EVM in general fail to account for is uncertainty.[27], [29]

2.3 Manufacturing Strategy

The manufacturing strategy of the overall project and the components that make up the project's supply chain are important to understanding how flexible the project and the supply chain are when disruption is experienced. With complex supply chains and multi-phased projects understanding there may be many different combinations of manufacturing strategies.

2.3.1 Make-to-Stock (MTS)

Make-to-Stock or Made-to-Stock is a manufacturing strategy where a product is produced based on a demand forecast to fulfill orders. An example of an MTS manufacturing strategy are gaming systems which are found in stock for purchase at several department stores or online. The manufacturer may ramp up production to meet higher demands during the holiday purchasing season or the initial release from preorders.

This strategy is advantageous for economies of scale and lower cost items. Unpredictable buying trends and inaccurate forecasts can be detrimental to using this strategy resulting in unused inventory and waste.
This strategy is also known as Built-to-Stock or Build-to-Stock (BTS).

2.3.2 Make-to-Order (MTO)

Make-to-Order or Made-to-Order is a manufacturing strategy where a standardized product is produced only after it is ordered. This strategy allows for customization and reduced waste. An example of a MTO manufacturing strategy is airplane production. The airplane manufacturer produces the aircraft after receiving an order from the airline with specific specifications on capacity, luxury, and aesthetics. MTO is also known as Built-to-Order or Build-to-Order (BTO).

Similarly, Engineer-to-Order (ETO) to order products are products that are also designed or engineered as well as produced after an order has been placed. Developmental space industry projects are an example of an engineered-to-order product. The product is designed to meet mission objectives once placed on contract or order.

Space industry projects that move from a development phase to multiple orders of the same design become MTS or BTO products.

In Tang’s review postponement models in studies are either MTO or MTS and forecast updating or not. At the time of his study there were no known MTO postponement models with forecasting. [30]

2.4 Supply Chain Risk and Uncertainty

Many space products must come from qualified vendors who meet specific quality and testing requirements. Once a demand is generated for a piece part or component, a request for quote to qualified vendors is sent. Each contractor or manufacturer has their own set of criteria for selecting a vendor to place an order with, but often the order is placed with a single vendor who either has the lowest cost or shortest lead-time. If the vendor experiences a disruption it could ripple throughout the entire project and cause a project delay if the vendor is on the critical path. The main project contractor could qualify multiple vendors for parts using a multi-sourcing strategy to minimize schedule risks and supply chain uncertainty.

Supply Risk and Uncertainty is a growing area of research. This section will summarize the literature for supply chain risk and uncertainty as well as discuss risk mitigation strategies.

2.4.1 Risk

There are four major categories of risks to supply chains—economic, ethical, environmental, and political. Some economic risk examples are bankruptcies, worker shortages, and recession. Ethical risks are when a company's suppliers do not share the same values or break the law. Natural disasters such as hurricanes, tornados, and wildfires are all examples of environmental risks to the supply chain. Political risk examples are war and restrictive trade policies.

Heckman reviewed the definition, measurement, and modelling of supply chain risk. In addition to the challenge of not having a consistent definition across the studies reviewed, researchers are challenged with the quantification and modeling of supply risk. Most studies use cost, waste objectives, and evaluate the system in retrospect but miss studying operational effectiveness.

Sodhi et al. 2012's study reviews various quantitative models for supply chain risk management. Again, it is noted that most research objectives are based on cost and profit. Studies that consider uncertain lead-times use S-Q make-to-stock modes or stochastic lead-times with deterministic demand. [31]
demand.

Rajagopal et al. 2017's review of decision-making models for Supply Chain risk mitigation showed that studies mostly use Stochastic programming, multi-integer, and game theory while probabilistic, dynamic, and Bayesian models were limited. Rajagopal et al. 2017's review noted that models deal with two or three tiers of supply chain and that modeling of supply network interdependencies and ripple effect was an area of research that is needed.[32]

2.4.2 Uncertainty

Supply chain uncertainty is when risks are unknown, or a likelihood of a discrete disruption is unknown. Sreedevi et al. 2017 study shows that uncertainty in the supply chain leads to greater supply chain risk. With environmental uncertainty, manufacturing and supply flexibility can be used to mitigate risks. [33]

Capacity and demand uncertainty are two types of supply chain uncertainty. Capacity uncertainty is not knowing if suppliers have enough throughput to meet demand in time. Demand uncertainty is a fluctuation in order quantity or size. Fattahi et al. 2017 study models design supply network under uncertainty where demands affect lead-time.[34] Mahnam et al. 2009 uses fuzzy sets to model customer demand uncertainty and unreliability of suppliers. This model uses deterministic lead-time and unlimited capacity for a make-to-stock system. [35]

2.4.3 Supply Chain Disruption and Ripple Effects

When these risks affect the supply chain, disruptions occur. Supply chain disruptions can be caused by one or more of these risk areas. These are often considered as discrete events with a probability or likelihood of occurrence. When a disruption happens, it can cause additional delays to other supplier-tiers and the manufacturer, this is known as a ripple effect.

Ivanov et al. 2017 surveyed supply chain design with description and recovery considerations studies and noted simulation to be a suitable tool for ripple effect. The survey noted a gap in integrating operability and dynamic behavior.[36]

2.5 Supply Chain Risk Mitigations Strategies

Understanding the manufacturing strategies, supply chain relationships, risk and uncertainty, and the ripple effects of disruption for a project lead to investigating and implementing risk mitigation strategies to minimize impact and recover the project’s schedule.

2.5.1 Concurrent, Dual, Multi-supplier, and Contingent Sourcing Strategies

A variety of sourcing strategies can be employed to mitigate the risk and uncertainty of supplier disruption. Concurrent sourcing is where a manufacturer both procures and makes an item. Dual sourcing is where two vendors supply the same part to a manufacturer; multi-sourcing is the same with more than two vendors. Contingent sourcing is dual sourcing but where the second vendor is an emergency back-up usually at extra cost.

Several studies evaluate aspects of dual sourcing in comparison to single sourcing in make-to-stock systems. Yu et al. 2009 and Gupta et al. 2015 both evaluate supply disruption impacts of dual sourcing compared to single sourcing for make-to-stock systems. [37] [38] While Zhu compares dual sourcing between local and overseas suppliers who both experience disruption and their impact on cost performance. [39]

Additional studies for make-to-order systems consider the second supplier as an emergency back-up to use only when the primary supplier experiences a disruption. Chen et al. 2014 supplement demand with an emergency back supplier to makeup shortages from the primary supplier.[40] Wang et al. 2020 compares pricing in a contingent sourcing strategy to a dual sourcing strategy.[41] He et al. 2020 models dynamic contingent strategies in the make-to-order system. [42]

Few sourcing strategy studies consider the make-to-order system. Li et al. 2021 studies a make-to-order system for a single supplier and manufacturer who mitigates disruption through safety stock or a contingent supplier to minimize the cost of the disruption.[43] Safety stock is not widely practiced in the manufacturing of the space industry project due to the low demand quantities. It is not economical to carry safety stock for low demand products, although a spare for critical components may be placed on the contract as back-up.

This research fills a study gap of sourcing strategies for make-to-order and engineer-to-order systems. This research does not consider the additional sourcing as a contingent only basis due to the low demand often associated with projects.

Concurrent sourcing for space industry products is usually not economically feasible for these types of projects. Mols reviews the economic reasons for concurrent sourcing, butt this research will focus on dual and multi-supplier sourcing.[44]

When to select multiple suppliers, especially in an MTO or ETO industry, is not a widely researched area. This research will propose an adaptable decision methodology that can be used to determine when selecting multiple suppliers is a beneficial supply chain risk mitigation strategy.

2.5.1.1 *Supplier Selection*

In addition to choosing a supply strategy, a project must determine how suppliers will be selected. It is important to understand when using dual or multi-sourcing strategies that there are many decision-making applications each with differing selection benefits. For the purposes of this research supplier selection will mainly refer to identifying and selecting qualified suppliers to send requests for order quotes.

In addition to choosing a supply strategy, a project must determine how suppliers will be selected. Sodhi et al. 2012 reviewed many studies on supplier selection, especially in the automotive industry. Ho et al. 2010 also provided a review on sourcing decision making. From these reviews, selection is often based on a linear weighted mode, total cost of ownership, mathematical model, or simulation. The most used multi-criteria decision making (MCDM) techniques are analytic hierarchy process (AHP), technique for order performance by similarity to ideal solution (TOPSIS), multi-objective programming (MOP), and Vlse Kriterijumska Optimizacija I Kompromisno Resenje (VIKOR). [31], [45]

AHP is a decision-making application based on mathematics and psychology. It is flexible and can provide a simple solution to complex decision-making problems such as supplier selection. This application, however, struggles to manage uncertainty unless combined with Fuzzy Set Theory (FST). Analytic network process (ANP) is a more general form of AHP that structures the decision in a network instead of hierarchy.

TOPSIS is another mathematical decision-making technique where the most favorable decision should have the shortest geometric distance and conversely the least favorable the longest geometric distance.

MOP which is also known as multi-objective optimization, vector optimization, multicriteria optimization, and other descriptors is another mathematical decision-making application where more than one objective function is optimized at the same time, for example, minimizing supplier lead-time and costs.
VIKOR ranks alternatives with conflicting criteria; this application is also often paired with FST.

Other applications used for supplier selection include Quality Function Deployment (QFD), Balanced Score Card (BSC), Grey Relational Analysis (GRA), and others. Supplier selection applications are often combined with FST or another application in research to form a hybrid application utilizing the best features of each application. [46]

2.5.1.1.1 Order Splitting

When selecting multiple suppliers in a mutli- or dual sourcing strategy, the next step is to decide how to optimally split the order among selected suppliers. The existing research considers make-to-stock manufacturing strategies in relation to inventory needs and demand, not make-to-order or engineer-to-order.

Hong et al. 2018 paper summarizes strategies for mitigating procurement uncertainty, including back up suppliers, but for uncertain demand like those in a make-to-stock industry. [47] Guo et al. 2014 investigate supplier selection in multi-echelon, make-to-stock system with a mixed-integer model based on the order quantity and reorder point (Q,R), but this research does not include order splitting. [48] Sun et al. 2022 expands a similar Q-R model and consider order splitting to find the optimal inventory policy to maximize profit. [49] Luo et al. 2001 studies an optimal ordering policy in two-supplier (s, S) single-product inventory system. [46] While Sazvar et al. 2014 looks at a strategy of pooling lead time risks by splitting replenishment orders in a stochastic (s,Q) system. [50]

Cheng et al. 2011 looks at splitting orders among parallel suppliers with two different objectives, cost and production load balance. [51]

2.5.1.2 Inventory Strategy

The Yoon et al. 2018 study showed that increasing inventory capacity provided better risk mitigation for a make-to-stock manufacturing strategy than redundant suppliers.[52]

Inventory strategies can also be employed to mitigate supply chain disruptions and uncertainty. The three types of inventory systems are push (forecasted demand), pull (known demand), and just-in-time (scheduled demand). All these systems can be set up in a Material Requirements Planning (MRP) system for automation, control, and feedback.

Some of the strategies to avoid disruptions and stockouts include safety lead-time and safety stock. Safety lead-time uses the S-Q reorder point, setting a buffer to place the next order before the current inventory runs out. Safety stock is an extra inventory that is not needed to meet current demands but is maintained as a buffer inventory in case there is an increase in demand. In research these systems are often modeled using queueing theory and Monte Carlo simulations.

While these strategies work well for make-to-stock systems, they are not always applicable to make-to-order and engineer-to-order projects where there is maintaining high levels of safety stock is not practical and low demand may not allow a safety lead-time to be utilized.

2.5.2 Supply Chain Probability Risk Modelling

Project managers can consider their supply chains and project phases as Markov Chains or Bayesian Networks, simply asking what is the probability that the project will be delayed if a supplier is disrupted. However, the reliability of suppliers and the probability of project is often determined from historical experience or knowledge and becomes difficult to determine project success in complex, multi-phased projects.

2.5.2.1 Markov Chains

A stochastic model to describe a sequence of possible events where the probability of each event depends on the previous is known as a Markov Chain or Markov Process. This can be used to study supply chain and manufacturing disruptions where each stage of the supply chain or manufacturing process has a probability of disruption.

2.5.2.2 Bayesian Networks

Hosseini et al. 2020 provide a literature review of Bayesian networks for supply chain risk, resilience, and ripple effect analysis. [53] The literature review is a recent compilation of the usage of Bayesian networks in supply chain risk research. The review considers the top ten cited journals, maps key terms, and provides a mathematical overview of Bayesian networks. Bayesian networks are rooted in probability and statistics, making this method well suited for modeling risks associated with supply chains. Additionally, the technique has been used to model supply chain resiliency and conversely study the rippling effect of supply chain disruption. The review notes that many networks developed in research are unique to an industry, project, or case study. Although research using Bayesian networks is increasing, their use in Supply Chain risk, resilience, and the ripple effect is an area where research is lacking.

Looking at a few studies where Bayesian networks are used in supply chain risk management, Lockamy et al. 2012 is an often-quoted paper using Bayesian networks to model supplier risk. The paper studies multiple suppliers to an Automotive manufacturer and uses Bayesian networks to model the probability of supplier disruption. [54] Risk and probabilities are gathered from actual suppliers. Supplier risk is minimized by minimizing the costs to the manufacturer for supply disruption from twelve factors divided into three categories. This model allows managers of the manufacturer to understand which supplier(s) could have the greatest impact on cost and develop mitigation strategies. Although this is an often-referenced study for supplier risk modeling, the model produced is specific to a specific industry and type of part for the studied manufacturer.

Sharma et al. 2016 offer another study of Bayesian networks to model supplier risk, again in the automotive industry, but focusing uniquely on information risk such as hackers, spyware, data backups and more. [55] This study uses Bayesian networks like as the Lockamy et al. 2012 study to minimize costs impacts; however, identified risks and risk categories are unique and a sensitivity analysis is performed. These studies show the adaptability of the usage of Bayesian Networks for modeling supplier risks. Considering these two studies, one may start to formulate ideas to adopt Bayesian Networks for their specific supply chain risk research.

Liu et al. 2021 consider a dynamic Bayesian Network by building on a previous study from Hosseini et al. 2020 which considers a two supplier-manufacturer relationship over three time periods. [56] The Liu et al. 2021considers a three supplier-manufacturer relationship over three time periods. [57] The study expands on the previous study's precise probability distributions by allowing probability intervals through Markov transition matrices. The Liu et al. 2021 study considers a case study comparison between the two papers, between two and three suppliers.

Ojha et al. 2018 expands beyond the two-echelon models of supplier-manufacturer. This paper considers resiliency and ripple effects by modeling four-echelons. [58] Again, this study is within the automotive industry but considers the supply chain resiliency and rippling from supplier to manufacturer to distributor to retailer. The ripple effect is when a risk realized or originating in one node generates additional risks throughout. The study looks holistically for all nodes the fragility of each node, lost sales, service level, and total inventory and backup costs. The study examines the supplier to distributor by examining a Risk Exposure Index, gathered from fragility and lost sales, and a Resiliency Index over time. The Resiliency Index allows for the study of assessing the impact of single node disruption on the entire network.

2.5.2.3 Probability of Project Delay Markov Chain / Bayesian Network Example

Considering the general case of a supplier and alternate supplier as shown in Figure 2.5 the question of if the primary supplier is disrupted can the project recover by the end of Phase-2 can be examined through the probabilities of a Markov chain solved through a Bayesian Network. Once a baseline schedule for the project has been determined utilizing the methods discussed in chapter two, the probabilities can be examined as meeting or exceeding the baseline schedule.

Examining the probability that the first project phase would complete on time because parts are delivered and available from the suppliers through a Bayesian Network would look something like the following table. If the primary supplier is disrupted and does not deliver as expected *p(-s)* then we can consider the probability that the project phase-1 will complete on time with the multi supplier arriving before the primary supplier, *p(q)*, or after *p(-q).*

The probability that Project Phase 1 will complete on time if the primary supplier does not deliver on time and the alternate supplier's order arrives before the delayed order is described by the probability, *p (P1*|*-s, q).* A high probability of this occurrence may make an alternate supply strategy advantageous to project managers looking to reduce supplier and schedule risk.

2.6 Gaps This Research Addresses

Project managers can utilize a variety of software tools for scheduling a project, forecasting, and project management; however, these tools are only as accurate as the input information. Not having a sound understanding of scheduling techniques and the effects of supply chain disruption can lead to incorrect. information, bad forecasting, and project failure. Understanding strategies for manufacturing, supplier sourcing, supplier selection, and mitigations are key to determining the and the impact of supply chain uncertainty and disruption on a multi-tier supply and phased project.

Many topics discussed in this literature review are individually studied. This research is unique in combining project scheduling with supply chain risk and uncertainty. Additionally, this project studies MTO or ETO projects throughout the project's design phases unlike the great volumes of research in MTS industries like automotive and other goods.

The next chapters will demonstrate how to select risk mitigation strategies throughout the project's design phases and how the risk mitigation strategy of multi-supplier sourcing affects a space industry's project schedule.

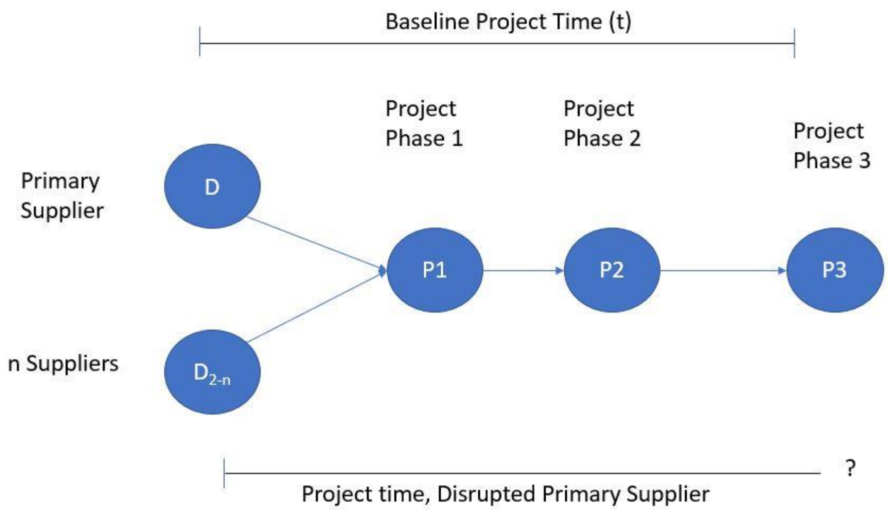


Figure 2.5. Probability of Project Delay Markov Chain

Table 2.2 Probability of Project Delay Bayesian Network

<table>
<tr><td colspan="2">Primary Supplier On Time</td><td rowspan="6"></td><td colspan="5" rowspan="2">Project Phase 1 Completes on time because parts are available from suppliers</td></tr>
<tr><td>s</td><td>-s</td></tr>
<tr><td colspan="2"></td><td rowspan="2"></td><td colspan="2">s</td><td colspan="2">-s</td></tr>
<tr><td colspan="2" rowspan="2">Alternate Supplier Order Arrives Before Primary Supplier</td><td>q</td><td>-q</td><td>q</td><td>-q</td></tr>
<tr><td>P1</td><td>p (P1|s, q)</td><td>p (P1|s, -q)</td><td>p (P1|-s, q)</td><td>p (P1|-s, -q)</td></tr>
<tr><td>q</td><td>-q</td><td>-P1</td><td>p (-P1|s, q)</td><td>p (-P1|s, -q)</td><td>p (-P1|-s, q)</td><td>p (-P1|-s, -q)</td></tr>
</table>

CHAPTER 3 PROBLEM DISCRIPTION

As previously discussed, space industry products, especially launch vehicles, are complicated assemblies of high-technology and specialized components. Hundreds of thousands of parts may make up a single section in an integrated bill of materials. A single component or piece of hardware may contain hundreds of parts in its bill of material.

Unlike the automobile industry or other make-to-stock products, space industry components are often products that are engineered, manufactured, assembled, and tested for specific missions. While commercial off the shelf components may be used in some instances, made/engineered-to-order components currently make up most of the bill of materials for a project.

For the main contractor, sourcing various materials and parts can be a complicated process of requests-for-quotes, bidding, and evaluation before vendors and suppliers are placed on contract. There are various methods for determining and selecting a vendor or supplier from the bidding process. The components must also meet rigorous testing, production, environmental, and material requirements or qualifications. Vendors may supply multiple components. They may have multiple sub-tier suppliers themselves who may also supply multiple components and projects within the same industry or others.

The entirety of the supply chain for the project becomes a complicated web like that shown in Figure 3.1 for a project manager to navigate and understand how an issue with one strand of the web can affect the entire project. While the figure below shows differentiating references for suppliers for project phases one and two (P1, P2), these suppliers may be the same and overlapping across project phases. With many combinations of suppliers, the uncertainty of supply chain web is difficult to plan for within the project schedule.

In an ideal situation the baseline project schedule will be developed from extensive knowledge and experience of design, supply, manufacturing, and testing to include enough margin for any delays that may be experienced. However, the rapid pace of innovation combined with supply chain issues leave a lot of uncertainty for project managers developing baseline schedules. Most of the time only a single vendor is selected for procurement of a component based on either lead-time or lowest cost, depending on the project constraints.

Should a sole sourced component be on the project’s critical path and the supplier experience a disruption or delay, that delay can ripple through the rest of the project causing delays at multiple project milestones.

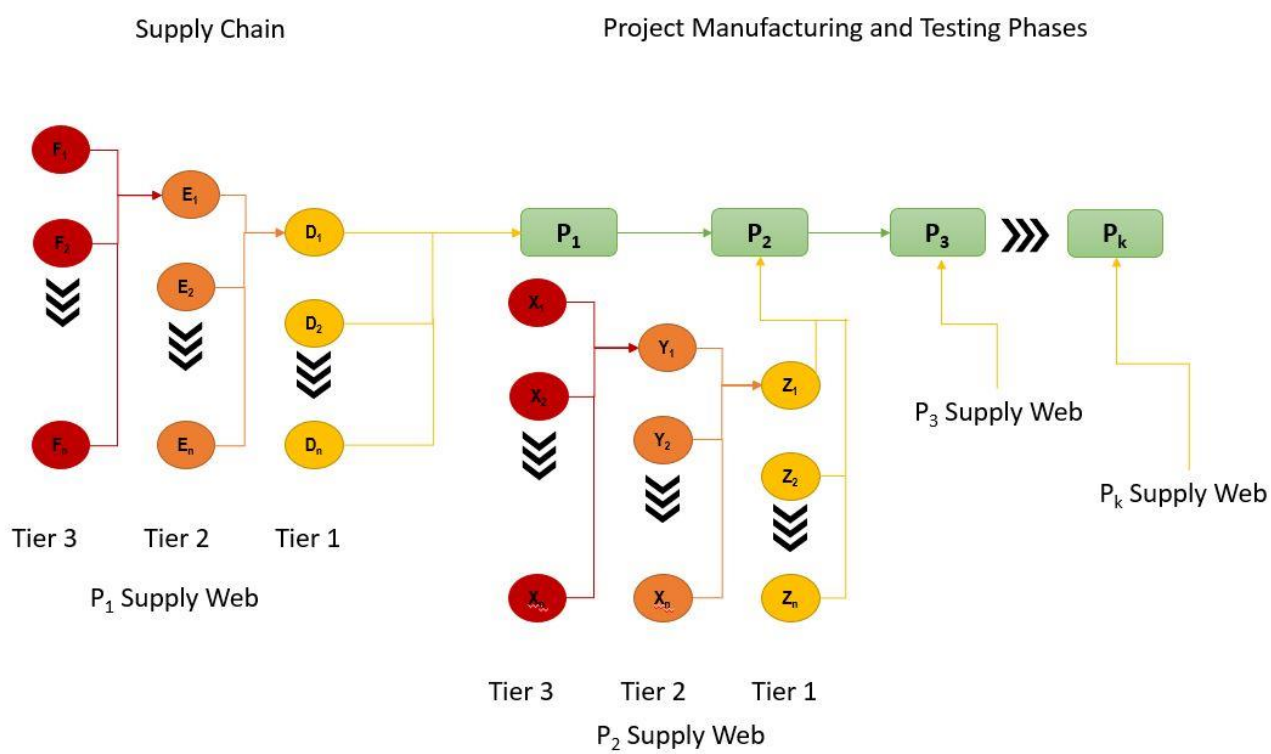


Figure 3.1 Supply Chain Web

This ripple effect can even cause the delay or cancelation of the entire project unless project managers develop and employ risk mitigations.

Delays and cancellations are costly not only in terms of an unsuccessful project but to the contractor's reputation and future business prospects. When delays are not mitigated a project can drag on decades past its original planned schedule or be canceled or be cancelled. While the recently launched James Webb Telescope was not cancelled, it was $8 Million USD over budget and 14 years beyond its originally planned launch date. The project suffered a variety of delays not limited to supplier or contractor disruptions.[59]

The unpredictability of when delays and disruptions such as material shortages, market demand increases, political disruptions, weather, and other issues may occur makes scheduling complex projects extremely difficult.

Schedules are based on known data points without considering supply chain uncertainty except for generalized buffers. As disruptions exceed the existing schedule buffers, the project becomes increasingly delayed. A recent example of the unpredictability of supply chain disruptions causing significant project delays is the supply chain issues caused by Covid-19. Government and corporations implemented shutdowns and travel restrictions that slowed manufacturing or in some cases shutting it down altogether. As many industries experienced supplier delays due to Covid-19 shutdowns, so did the space industry. The 2021 United States Government Accountability Office (GAO) report on major NASA project highlights these delays for NASA projects. For example, the report notes that Nancy Grace Roman Space Telescope project "the delivery schedule for the Wide-Field Instrument (WFI)— Roman's principal instrument—has slipped 6 months due to supply chain effects from COVID-19." [60] This project has a launch baseline of October 2026 so there is still an opportunity to mitigate these delays through other mitigation strategies and forecast project recovery.

Utilizing multiple suppliers for the procurement of the same component or system can be utilized to mitigate schedule risks caused by supply chain uncertainty for space industry projects. Not all parts need alternative sourcing strategies applied, but where the risk to delay outweighs any additional costs that may be incurred, utilizing this strategy allows project managers to better forecast project recovery or plan alternative mitigations for critical parts of the project.

To solve the problem of critical path supplier disruptions delaying an entire project, this research will develop an understanding how to apply supplier selection and sourcing strategies to a complicated project like those of the space industry, to mitigate the risks of supply chain uncertainty.

3.1 Baseline Scenario

Consider the scenario of a project manager for an avionics component that just completed its critical design review. The component is comprised of several circuit card assemblies (CCAs) which are made from printed wiring boards (PWBs) loaded with resistors, diodes, and other electrical components. The printed wiring boards are engineered to the specific functionality of the component. Several are needed for the entirety of the project and are a critical path to the component assembly and testing as well as the overall project schedule.

Following the typical procurement process summarized in Figure 3.2, a request for quotes is sent to a pool of pre-qualified suppliers. Quotes are returned from a few suppliers with a range of costs and lead-times.

3.1.1 Supplier Quotes

For this scenario, the total demand quantity is 50 parts with a baseline schedule of 10 weeks. Four suppliers return quotes as described in Table 3.1 Supplier Quotes. A summary of supplier quote characteristics is:

- **Supplier 1:** Lowest total cost, shortest lead-time, no minimum order quantity, little to no historical information on past performance
- **Supplier 2:** Mid-range cost and lead-time, requires a minimum order, little to no historical information on past performance, request for quote is incomplete and qualifications are expired.
- **Supplier 3:** Highest total cost, longest lead-time, requires a minimum order quantity, has a history of quality issues and delays.
- **Supplier 4:** Mid-range cost and lead-time, no minimum order quantity, historically somewhat reliable with some quality issues

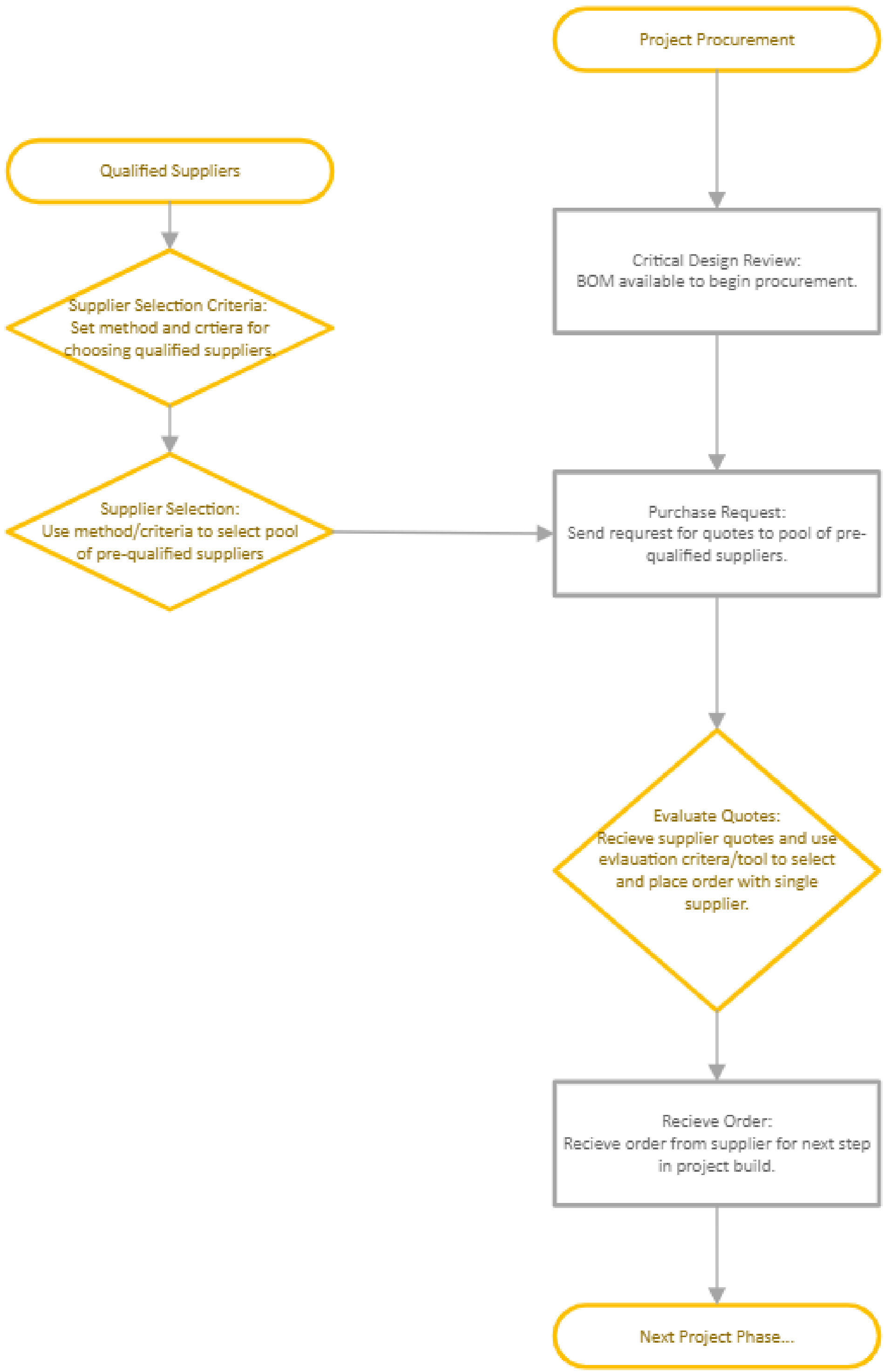


Figure 3.2 Baseline Project Procurement Process

Table 3.1 Supplier Quotes

	Supplier 1	Supplier 2	Supplier 3	Supplier 4	
Price per Part	$ 500	$ 700	$ 800	$ 650	
Leadtime	8	12	16	14	In Weeks
Costs	$ 25,000	$ 35,000	$ 40,000	$ 32,500	Cost per total qty
	$ 7,000	$ 2,500	$ -	$ -	Additional Fees
	$ 32,000	$ 37,500	$ 40,000	$ 32,500	Total PO

3.1.2 Supplier Quote Evaluations

The quotes are evaluated using a weighted scorecard. The score card covers seven categories.

1. Adherence to RFP/RFQ Instructions
2. Company Information
3. Terms & Conditions
4. Requirements
5. Quality
6. Delivery
7. Financial

Every category contains evaluation criteria where each supplier is ranked from 1-5, worst to best. The scores in each category are averaged and multiplied by a weighting factor.

The order is placed with Supplier 1 who receives the best weighted score on the evaluation scorecard. Table 3.2 contains the scorecard weighting criteria for this baseline scenario. A summary of the weighted scores is shown in Table 3.3 and a full score card is included in the dissertation attachments.

Now the project manager is waiting for the order to arrive to complete the building of the avionics components.

3.1.3 Supplier Delays

Later, the supplier lets the project manager know that they will need to double the lead-time to a total of 16 weeks due to technical difficulties. The delay to this critical component is too large to completely mitigate. This delays not only the production of the avionics component, but downstream steps of the project.

1. Worst case day for day slip in schedule: $8000, 8-week delay

The project team re-sequences some project steps to mitigate two weeks in the delay. This saves $2000 off the day for day slip costs, but costs $1000 to implement.

2. Total Mitigated Delay: $7000, 6-week delay

Table 3.2 Supplier Evaluation Criteria Weighting

CRITERIA SCORES (AVG)	WEIGHT
1. Adherence to RFP Instructions	0.05
2. Company Information	0.05
3. Terms & Conditions	0.10
4. Requirements	0.25
5. Quality	0.25
6. Delivery	0.15
7. Financial	0.15
Total Score	1.00

Table 3.3 Supplier Evaluation Scores Baseline Scenario

CRITERIA SCORES (AVG)	Supplier 1 WEIGHTED SCORE	Supplier 2 WEIGHTED SCORE	Supplier 3 WEIGHTED SCORE	Supplier 4 WEIGHTED SCORE
1. Adherence to RFP Instructions	0.20	0.10	0.15	0.20
2. Company Information	0.18	0.12	0.20	0.20
3. Terms & Conditions	0.43	0.10	0.23	0.37
4. Requirements	1.15	0.45	0.95	1.15
5. Quality	0.92	0.58	0.75	0.83
6. Delivery	0.35	0.30	0.50	0.35
7. Financial	0.45	0.30	0.35	0.55
Total Score	3.68	1.95	3.13	3.65

3.2 Research Steps

Could this delay have been mitigated if the project manager had used a risk-based analysis and procurement process, implementing mitigation strategies for critical components?

The following research steps for risk-based analysis and procurement of MTO/ETO products seeks to answer this question through the following steps:

1. The first step in this research is to develop a Supply Chain Risk Assessment Model that could be utilized to determine supply chain risks and weigh mitigation strategies, including that of a multi-sourcing strategy.

2. The next step implements a scoring threshold in the quote evaluation scorecard to help determine if one supplier can meet the project demands and requirements or if multiple suppliers should be used.

3. Upon deciding to implement a multi-sourcing strategy, optimization of the order quantities split among the suppliers is determined through modeling and simulation.

This research follows the risk-based procurement process described in the next figure; however, selecting the pool of qualified suppliers is not part of the scope of this research.

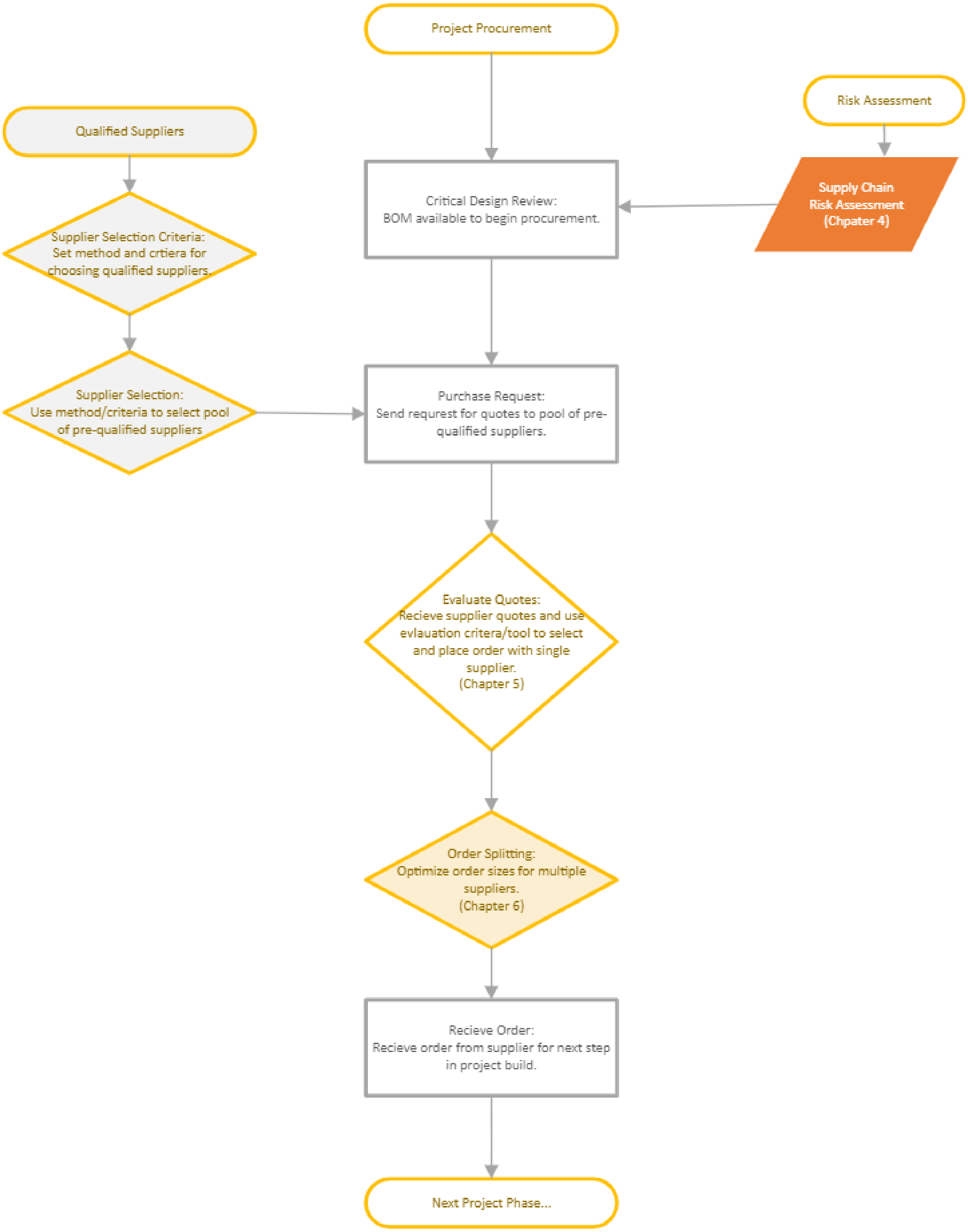


Figure 3.3 Risk-based Procurement Process

CHAPTER 4 SUPPLY CHAIN RISK ASSESENT AND MITIGATION DECISION MODEL

Understanding supply chain risks and strategies that may be employed to mitigate supply chain uncertainty early in the design process allows project managers to better schedule and forecast projects and mitigate supply chain disruptions. By using the House-of-Risk model throughout the design and build of a project, system, or component, project managers can evaluate changing supply risks and mitigation strategies as the design matures. This paper will examine the House-of-Risk (HOR) model applied to an engineering project and examine major project development milestones.

4.1 House of Risk

House of Risk is an adaptation of the House of Quality Model and FMEA to determine which mitigations strategies should be given priority in supply chain risk. Pujawan et al. 2009's paper provides the initial detailed step by step framework for HOR with a Case Study for supply chain risk management. [61]

The model consists of two parts. The first part, known as House-of-Risk 1 (HOR1) is where the severity and occurrence of supply chain risks are evaluated. Part 2, House-of-Risk 2 (HOR2) evaluates the impact of mitigation strategies and ease of implementation.

Additional papers and case studies have been conducted in recent years, usually with a case study on make-to-stock type industries such as material, food, or goods. These studies often use SCOR/FEMA or interviews to determine the risk events. Most of the papers on House-of-Risk use Preventative Action (PA) for HOR2; however, this paper will use Mitigation Strategies instead to maintain consistent terminology with the industry of the case study.

The House-of-Risk model is easily customizable, making it a great tool for case studies in a variety of issues. Only Perdna and Ahmad studied make-to-order industries for the application of HOR. Additional study is needed in make-to-order and engineer-to-order industries.

Table 4.1 HOR Research

Papers/Articles	MFG Strategy	Risk Event Determination	Case Study	Industry
Purnomo et al. 2021 [62]	MTS	Interview	Y	Food (Coffee)
Lestari et al. 2021 [63]	MTS	SCOR/FMEA	Y	Food (Halal)
Purwaningsih et al. 2021 [64]	MTS	Supply Chain Mapping	Y	Food (Milkfish)
Kurniawan et al. 2021 [65]	MTS	SCOR/FMEA	Y	Food (Palm Oil)
Parenreng et al. 2019 [66]	MTS	Supply Chain Mapping	Y	Food (Seaweed)
Paillin et al. 2021 [67]	MTS	SCOR/FMEA	Y	Food (Tuna)
Yustika et al. 2021 [68]	MTS	Interview	N	Goods
Ma et al. 2018 [69]	MTS	SCOR/FMEA	Y	Goods (Appliances)
Aini et al. 2019 [70]	MTS	Interview	Y	Goods (Clothing)
Rizqi et al. 2020 [71]	MTS	Interview	Y	Goods (Craft Bags)
Islamiah et al. 2020 [72]	Unknown	Categories from Reference Journals	Y	Goods (Toys)
Boonyanusith et al. 2019 [73]	MTS	Interview	Y	Material (Blood)
Raras Dewantari et al. 2020 [74]	MTS	SCOR/FMEA	Y	Material (Blood)
Perdana et al. 2020 [75]	MTO	SCOR/FMEA	Y	Material (Compressors)
Ahmad et al. 2019 [76]	M/ETO	SCOR/FMEA	Y	Material (Construction)
Pujawan et al. 2009 [61]	MTS	SCOR/FMEA	Y	Material (Fertilizer)
Immawan et al. 2018 [77]	MTS	SCOR/FMEA	Y	Material (Rubber)
Liansari et al. 2020 [78]	MTS	SCOR/FMEA	N	
Albana et al. 2022 [79]	MTS	Categories from Reference Journals	N	

4.2 House of Risk Model

This section reviews the basics of the two-part House-of-Risk Model. This basic model is then examined throughout the engineering project milestones. During Part 1 of the House-of-Risk (HOR1) model the severity of the risk events changes depending on design maturity and production readiness. During Part 2 of the House-of-Risk (HOR2) model the implementation of mitigations in relation to the changing risk and design is evaluated to determine which mitigations are best to employ at each project phase.

4.3 HOR1

HOR1 is developed through the following steps to fill in Table 4.2:

1. Identify risk events, E_i. This can be done through SCOR, FMEA, or other means. Assess the severity of these events, S_i, represented by a scale (Likert, 1-10, or other).
2. Identify risk agents, A_j, and their likelihood of occurrence, O_j, also represented by a scale (Likert, 1-10, or other).
3. Develop a relationship matrix between each risk agent and event. No correlation, low, moderate, high correlations.
4. Calculate the aggregate risk potential, ARP_j, which is the likelihood of occurrence of the risk.

$$ARP_j = O_j \sum_i S_i R_{ij}, \text{ for } i=1, 2, \ldots, I; \ j=1, 2, \ldots, J \tag{4.1}$$

5. Once calculated the risk agents can be ranked from highest to lowest by ARP_j.

A variety of methods can be used to determine which Risk Agents to carry over to HOR2. The top few can be carried over. Or a percentage of the total aggregate risk can be carried over. The individual risk agent’s *ARP* divided by the total *ARP* makes the percentage for each risk agent. For the Pareto method, sum the highest ranking to a total of ~80% of the total ARP per phase to carry over to HOR2. This calculation can also be used to assess other risk percentages such as the top 50% of risks.

Table 4.2 HOR1

E_i/A_j	A_1	A_2	A_3	A_4	A_5	S_i
E_1	R_{11}	R_{12}	R_{13}	R_{14}	R_{15}	S_1
E_2	R_{21}	R_{22}	R_{23}	R_{24}	R_{25}	S_2
E_3	R_{31}	R_{32}	R_{33}	R_{34}	R_{35}	S_3
E_4	R_{41}	R_{42}	R_{43}	R_{44}	R_{45}	S_4
E_5	R_{51}	R_{52}	R_{53}	R_{54}	R_{55}	S_5
O_j	O_1	O_2	O_3	O_4	O_5	
ARP_j	ARP_1	ARP_2	ARP_3	ARP_4	ARP_5	
%ARP						
Rank						

4.4 HOR2

To determine which mitigations should be targeted first HOR2 is developed using the following steps to fill in Table 4.3:

1. Identify preventative actions or mitigations, Mk.
2. Develop a relationship matrix between each risk agent and mitigation, Ejk. No correlation, low, moderate, high correlations.
3. Calculate the total effectiveness of each by using the following equation:

$$\mathrm{TE_k} = \sum_{\mathrm{j}} \mathrm{ARP_j E_{jk}} \textit{ for } j=1, 2, \ldots, J; k=1, 2, \ldots, K \tag{4.2}$$

4. Assess the difficulty in implementing the mitigations, represented by a scale (Likert, 1-10, or other), D_k.
5. Calculate the total effectiveness to difficulty ratio.

$$ETD_k = \frac{TE_k}{D_k} \textit{ for } k=1, 2, \ldots, K \tag{4.3}$$

Once calculated, priorities can be ranked from highest to lowest ETD_k to determine which mitigations to implement first for the most impact to the overall risk.

4.5 HOR through the Project Milestones

Incorporating supply chain risks early in the design phase can help to mitigate disruptions and project delays due to these risks. At each project milestone the event severity and agent occurrence should be reexamined for updates based on the design maturity and knowledge of supply risks. The severity of risk should reflect the design maturity and production readiness. As the design and project progress, implementation of mitigation strategies for supply chain risks may also change. Strategies that may be easy to employ early in the design process may not be as easy once production begins.

To follow the evolving supply chain risks and mitigation strategy employment throughout the project phases create a HOR1 and HOR2 model where the Severity changes in HOR1 in each project phase and Mitigation Strategy Implementation changes in each HOR2.

Table 4.3 HOR2

Aj/M_k	M_1	M_2	M_3	M_4	A_5	ARP_i
A_1	E_{11}	E_{12}	E_{13}	E_{14}	E_{15}	ARP_1
A_2	E_{21}	E_{22}	E_{23}	E_{24}	E_{25}	ARP_2
A_3	E_{31}	E_{32}	E_{33}	E_{34}	E_{35}	ARP_3
A_4	E_{41}	E_{42}	E_{43}	E_{44}	E_{45}	ARP_4
A_5	E_{51}	E_{52}	E_{53}	E_{54}	E_{55}	ARP_5
Te_k	TE_1	TE_2	TE_3	TEO_4	TE_5	
D_k	D_1	D_2	D_3	D_4	D_5	
ETD_k	ETD_1	ETD_2	ETD_3	ETD_4	ETD_5	
Rank						

For this chapter we will examine three project phases: PDR, CDR, and MRR

- PDR—At the Preliminary Design Review (PDR) the design is not finalized, requirements and design features may still experience changes as the project matures. However, some long lead parts may be ordered. There is more time to implement long-term and systematic mitigations so the risk severity may not be as high as later in the project.
- CDR—By the Critical Design Review (CDR) the design is matured enough for complete ordering of all parts. There may still be some minor changes. Development testing may occur before or after CDR to prove and set the design. With production and testing approaching severity of supply chain risks increase as time to implement mitigation strategies decreases.
- MRR—Production may begin with CDR or later when most or all parts have arrived. With a later production readiness review (PRR) or manufacturing readiness review (MRR), a project manager may already be experiencing supply chain disruptions. By this late stage in the project, supply chain risk severity is at its highest and systematic mitigation strategies are nearly impossible to implement. For this paper, we will use MRR to show a differing suffix from PDR.

The following steps describe the modifications to the basic HOR model.

1. Identify the Risk Event Severity, S_i, for HOR1 by examining how the risk event will impact the project at each project phase if the risk is realized. Table 4.4
2. Create an HOR1 for each project milestone using the applicable risk severity to determine the aggregate risk potential for each risk agent. The calculated ARPs for each phase will be ranked so that the top few will be reviewed in the HOR2 created for each phase. Table 4.5
3. When identifying preventative actions or mitigations, M_k, for HOR2 identifies the general ease of implementation based on project or company processes and procedures.
4. Then identify based on design phase the ease of implementation. By applying a weighting factor by design phase ease of implementation and use that in HOR2, wD_k. Table 4.6
5. Create an HOR2 for each project milestone using the applicable ARPs calculated for each phase's HOR1 and each phases' mitigation implementation. For example, an Easy Implementation weighting factor may be like that shown in Table 4.7.

Table 4.4 HOR1 Severity Throughout the Project Phases

A_i	PDR	CDR	MRR
A_1	S_{P1}	S_{C1}	S_{M1}
A_2	S_{P2}	S_{C2}	S_{M2}
A_3	S_{P3}	S_{C3}	S_{M3}
A_4	S_{P4}	S_{C4}	S_{M4}
A_5	S_{P5}	S_{C5}	S_{M5}

Table 4.5 HOR1 Aggregate Risk Scores Throughout the Project Phases

ARP_j	PDR	CDR	MRR
ARP_1	ARP_{P1}	ARP_{C1}	ARP_{M1}
ARP_2	ARP_{P2}	ARP_{C2}	ARP_{M2}
ARP_3	ARP_{P3}	ARP_{C3}	ARP_{M3}
ARP_4	ARP_{P4}	ARP_{C4}	ARP_{M4}
ARP_5	ARP_{P5}	$ARPS_{C5}$	ARP_{M5}

Table 4.6 HOR2 Mitigation Implementation Weighting Throughout the Project Phases

M_k	D_k Baseline	PDR	CDR	PRR/MRR
M_1	D_1	wD_1	wD_1	wD_1
M_2	D_2	wD_2	wD_2	wD_2
M_3	D_3	wD_3	wD_3	wD_3
M_4	D_4	wD_4	wD_4	wD_4
M_5	D_5	wD_5	wD_5	wD_5

Table 4.7 HOR2 Mitigation Implementation Weighting Factors

	Weighting Factor
Easy Implementation	1
Somewhat Easy Implementation	1.5
Difficult Implementation	0.5

4.6 Case Study

Let us follow the design and build of a circuit card assembly (CCA) for an avionics component from the baseline scenario in Section 3.1 through the project design phases considering supply chain risks and mitigations at each stage. The CCA is made of a Printed Wiring Board (PWB) and electrical components. The PWB is an engineer-to-order or make-to-order item with custom design traces specifically made for the board's function. This study will rely on engineering experience to determine risk events, risk agents, mitigations, relationships, and weightings.

4.7 Generating the HOR 1 for each Project Phase

1. Identify risk events, E_i. This can be done through SCOR, FMEA, or other means. Assess the severity of these events, S_i, represented by a scale (Likert, 1-10, or other). Table 4.8
2. Identify risk agents, A_j, and their likelihood of occurrence, O_j, also represented by a scale (Likert, 1-10, or other). Table 4.9
3. Develop a relationship matrix between each risk agent and event and calculate the aggregate risk potential, ARP_j. Repeat for each design phase as shown in Table 4.10, Table 4.11, and Table 4.12.
   For this example, no correlation is scored with a 0; low with a 1, moderate with a 3, high correlations with a 9. ARPs are then ranked from largest to smallest.
4. To determine which risk events to carry over to HOR2 this example will carry over the risk agents from the top five ARPs from each project phase as summarized in Table 4.13

4.8 Generating the HOR 2 for each Project Phase

Continuing to HOR2 for each project phase, consider the baseline case of mitigations based on general company/project ease of implementation applying a weighting for the specific project phases.

1. Identify mitigations/preventative actions and general ease of implementation. Table 4.14
2. Then identify based on design phase the ease of implementation. By applying a weighting factor by design phase ease of implementation and use that in HOR2, wD_k. Table 4.15

Table 4.8 Case Study Risk Events

Risk Event	Code	Severity PDR	Severity CDR	Severity MRR
Supplier Delay	E1	1	3	8
Part Defect	E2	1	3	5
Equipment Issues	E3	1	5	8
Incorrect parts	E4	3	5	8
Manufacturing delays	E5	2	6	10
Test Delay	E6	6	6	8
Planning error	E7	2	4	7
Design Change	E8	6	8	10

Table 4.9 Case Study Risk Agents

Risk Agent	Occurrence	Code
Supplier reliability	6	A1
Material shortage	4	A2
Supplier Shutdown	3	A3
Manufacturing Shutdown	3	A4
Not enough certified personnel	4	A5
uncertain/unclear requirements	1	A6
Increased industry demand	8	A7
Unclear procedures	3	A8
Flawed processes	4	A9
Manufacturing inexperience	3	A10

Table 4.10 Case Study HOR1 PDR

PDR	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	S_P
E1	9	9	9	0	1	3	9	0	3	0	1
E2	9	1	1	0	1	0	0	0	0	0	1
E3	3	0	0	0	1	3	0	9	3	3	1
E4	3	3	1	0	0	9	0	3	9	1	3
E5	9	9	9	9	3	9	9	9	9	3	2
E6	0	0	1	9	9	9	0	9	1	9	6
E7	0	3	0	3	3	9	0	9	3	1	2
E8	0	0	3	0	0	9	0	1	0	0	6
O	6	4	3	3	4	1	8	3	4	3	
ARP	288	172	165	234	276	177	216	342	252	204	2326
Rank	2	9	9	5	2	8	6	1	4	6	
%ARP	12%	7%	7%	10%	12%	8%	9%	15%	11%	9%	

Table 4.11 Case Study HOR1 CDR

CDR	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	S_C
E1	9	9	9	0	1	3	9	0	3	0	3
E2	9	1	1	0	1	0	0	0	0	0	3
E3	3	0	0	0	1	3	0	9	3	3	5
E4	3	3	1	0	0	9	0	3	9	1	5
E5	9	9	9	9	3	9	9	9	9	3	6
E6	0	0	1	9	9	9	0	9	1	9	6
E7	0	3	0	3	3	9	0	9	3	1	4
E8	0	0	3	0	0	9	0	1	0	0	8
O	6	4	3	3	4	1	8	3	4	3	0
ARP	828	444	357	360	380	285	648	636	564	288	4790
Rank	1	5	8	6	6	9	2	3	4	9	
%ARP	17%	9%	7%	8%	8%	6%	14%	13%	12%	6%	

Table 4.12 Case Study HOR1 MRR

MRR	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	S_M
E1	9	9	9	0	1	3	9	0	3	0	8
E2	9	1	1	0	1	0	0	0	0	0	5
E3	3	0	0	0	1	3	0	9	3	3	8
E4	3	3	1	0	0	9	0	3	9	1	8
E5	9	9	9	9	3	9	9	9	9	3	10
E6	0	0	1	9	9	9	0	9	1	9	8
E7	0	3	0	3	3	9	0	9	3	1	7
E8	0	0	3	0	0	9	0	1	0	0	10
O	6	4	3	3	4	1	8	3	4	3	0
ARP	1530	848	639	549	576	435	1296	993	956	423	8245
Rank	1	5	6	7	7	9	2	3	3	9	
%ARP	19%	10%	8%	7%	7%	5%	16%	12%	12%	5%	

Table 4.13 Case Study HOR1 Aggregate Risk Throughout the Project Phases

Top Ranked	PDR		CDR		MRR	
1	A8	342	A1	828	A1	1530
2	A1	288	A7	648	A7	1296
3	A5	276	A8	636	A8	993
4	A9	252	A9	564	A9	956
5	A4	234	A2	444	A2	848

Table 4.14 Case Study Mitigations

Mitigation Strategy	Ease of Implementation (general)	Code
Multi-Sourcing Strategy	3	M1
Resequencing	4	M2
Overtime	3	M3
Additional Labor	4	M4
Inventory Controls	5	M5
Partial Shipment	3	M6
Borrow Equipment	4	M7

Table 4.15 Case Study Mitigation Implementation-Weighted

Y/S/N 1.5/1/0.5	PDR	CDR	MRR
M1	1.5	1	0.5
M2	4.5	3	1.5
M3	6	6	4
M4	0	4.5	1.5
M5	6	6	2
M6	5	5	2.5
M7	4.5	6	1.5

3. Create an HOR2 at each project phase with the applicable ARPs from the HOR1s and the weighted ease of implementation to understand which mitigation strategies are indicated as priority for each project phase as shown in Table 4.16, Table 4.17, and Table 4.18.

In this case study, a multi-sourcing strategy, inventory controls, and allowing partial shipments were shown to be the most beneficial and easily implemented strategies for mitigating supply chain risk and uncertainty in the case. This model can be easily modified and applied to different components and projects to assess supply chain risk and uncertainty. Understanding how the implementation of mitigation strategies, in particular the multi-sourcing strategy, is studied in the several chapters.

Table 4.16 Case Study HOR2 PDR

PDR	M1	M2	M3	M4	M5	M6	M7	ARP
A8	0	1	3	3	0	0	0	342
A1	9	0	0	0	3	3	0	288
A5	0	0	1	3	0	0	0	276
A9	0	3	3	3	0	0	3	252
A4	3	3	1	3	1	1	3	234
TE	11070	1800	2292	3312	3690	3690	1458	
D	4.5	6	0	6	5	4.5	0	
ETD	2460	300	0	552	738	820	0	
Rank	1	5	6	4	3	2	6	

Table 4.17 Case Study HOR2 CDR

CDR	M1	M2	M3	M4	M5	M6	M7	ARP
A1	9	0	0	0	3	3	0	828
A7	3	1	0	0	9	9	0	648
A8	0	1	3	3	0	0	0	636
A9	0	0	0	0	0	0	0	564
A2	9	0	0	0	9	3	1	444
TE	13392	1284	1908	1908	12312	9648	444	
D	3	6	4.5	6	5	6	6	
ETD	4464	214	424	318	2462	1608	74	
Rank	1	6	4	5	2	3	7	

Table 4.18 Case Study HOR2 MRR

MRR	M1	M2	M3	M4	M5	M6	M7	ARP
A1	9	0	0	0	3	3	0	1530
A7	3	1	0	0	9	9	0	1296
A8	0	1	3	3	0	0	0	993
A9	0	0	0	0	0	0	0	956
A2	9	0	0	0	9	3	1	848
TE	25290	2289	2979	2979	23886	18798	848	
D	1.5	4	1.5	2	2.5	1.5	4	
ETD	16860	572	1986	1490	9554	12532	212	
Rank	1	6	4	5	3	2	7	

CHAPTER 5 SUPPLIER QUOTE EVALUATION

Unlike make-to-stock industries where multiple-supplier sourcing strategies may be used to avoid stock outs or drive competitive pricing, the decision to use a multiple-supplier sourcing strategy in the space industry comes from a need to avoid the risk of schedule delay and added costs.

This chapter updates the procurement evaluation score card approach used to evaluate supplier quotes from the baseline scenario by implementing a scoring threshold to help determine if a multi-sourcing strategy should be implemented from the quotes received.

5.1 Request for Proposal/Quote Evaluation (RFP/RFQ)

A Request for Quote (RFQ) is a document that is issued by a company to solicit quotes from suppliers for the purchase of goods or services. The RFQ typically includes a description of the products or services being requested, the quantities needed, and any other relevant information such as delivery requirements and payment terms. It may also include specifications or other requirements that the supplier must meet to be considered for the purchase such as specific testing requirements often found in space industry projects.

The RFQ process is commonly used in procurement to obtain competitive quotes from multiple suppliers to make an informed decision about which supplier to select. It is an important part of the purchasing process as it allows the company to compare quotes from different suppliers and decide based on the best value for money.

A request for proposal (RFP) is similar to a formal document that is issued by a company to solicit proposals from potential suppliers or contractors for a specific product or service. The RFP process is commonly used in procurement when an organization needs to purchase a complex product or service, or when it needs to select a vendor for a long-term contract. This may be used in a space industry project for specialized design or testing services among other aspects of a project.

The RFP typically includes a detailed description of the products or services being requested, the timeline for delivery, and any other relevant information such as technical specifications, performance requirements, and payment terms. It may also include evaluation criteria that will be used to assess the proposals and a timeline for submitting proposals.

The purpose of an RFP is to provide potential vendors with enough information to allow them to submit a detailed proposal that outlines how they can meet the organization's needs. The proposals are then evaluated based on the evaluation criteria and a vendor is selected based on the best value for money. The RFP process helps organizations to make informed decisions about which vendor to select and ensures that all vendors have a fair opportunity to compete for the business.

An analysis of Federal design-build RFP evaluation criteria following the Federal Acquisition Act (FAR) by Gransberg et al. n.d., showed that cost was the dominant factor in federal design-build procurement . The study noted that improvements would be to weigh the technical portion more for technically, complex projects, especially when an innovative design is required. [80]

5.2 Quote Evaluation

Supplier quote evaluation is the process of evaluating quotes received from suppliers in a procurement process to select the best supplier for the goods or services being purchased. The evaluation process typically involves comparing the quotes based on a set of predetermined criteria, such as price, delivery lead-time, quality of products or services, and other factors.

Thiruchelvam et al. 2011 looked at trends in supplier selection criteria and methods, including those for multi-sourcing strategies, and found technical capability, delivery, and quality most frequent criteria. The trends also noted that categorical weighting for selection, such as a score card, is popular in industry due to simplicity and quickness. [81]

Quote evaluation criteria are the factors that are used to assess the quotes received from suppliers in a procurement process. These criteria help to objectively assess the different quotes and determine which supplier is the best fit for the organization's needs.

Some common examples of quote evaluation criteria include:

- Price: The total cost of the goods or services being purchased, including any discounts or special offers.
- Delivery lead-time: The amount of time it will take for the supplier to deliver the goods or services.
- Quality of products or services: The level of quality or performance of the goods or services being purchased.
- Technical capabilities: The supplier's ability to meet any technical specifications or requirements for the goods or services being purchased.

- Service and support: The level of service and support that the supplier provides, including response times, training, and technical assistance.
- Payment terms: The terms of payment, including the payment schedule, any discounts for early payment, and any financing options offered by the supplier.

The results of the supplier quote evaluation can be used to rank the quotes and decide on which supplier to select. In some cases, the organization may request additional information or clarification from the suppliers before making a final decision.

5.2.1 Evaluation Scorecard

A supplier quote evaluation scorecard is a tool used to evaluate the quotes received from suppliers in a procurement process. It helps to objectively assess the different quotes based on a set of predetermined criteria, such as price, delivery lead-time, quality of products or services, and other factors. The scorecard assigns a score to each quote based on how well it meets the evaluation criteria, and the scores can be used to rank the quotes and decide on which supplier to select.

The specific criteria and weightings used in a supplier quote evaluation scorecard will depend on the needs of the organization and the procurement process. It is important to clearly define the evaluation criteria and how they will be measured before starting the evaluation process. This will help ensure a fair and transparent evaluation process and ensure that the chosen supplier is the best fit for the organization's needs.

5.3 Scorecard Case Study

To implement a threshold for the score card, the perfect score is determined and a percentage of that score is set as the threshold. This is the total, non-averaged, unweighted score. Logic is added to the score card to give each supplier a “1” if it does not meet the threshold and a “0” if it does. If no supplier meets the threshold, the score card will tell the user to select multiple suppliers. If at least one supplier meets the threshold, the score card will tell the supplier to select a single supplier. The individual weighted scores can then be reviewed in either case to determine which supplier(s) to select.

The updated scorecard and baseline score card is included in the dissertation attachments.

For this example, the perfect score is a sum of 130 and a threshold of 80% is set (104). The same vendor quotes from Table 3.1 Supplier Quotes are used. The same vendor information is also used from section, except where noted.

5.4 Multiple Supplier Selection

Using the same scoring from Chapter 3, no supplier's total score meets or exceeds the 80% threshold.

The weighted average scores in Table 5.1, show that Supplier 1 and Supplier 4 are the top two scoring suppliers with scores of 3.68 and 3.65, respectively.

These two suppliers will be chosen to place orders with. How to optimally split the order quantity among these two suppliers will be discussed in Chapter 6.

5.5 Single Supplier Selection

Although a multi-sourcing mitigation strategy may have been indicated to be effective in the risk assessment of Chapter 4, the actual quotes returned may indicate that a sole, reliable supplier can accomplish the requirements of the project.

To illustrate this, the scoring of Supplier 4 has been updated to reflect a now historically reliable supplier with no quality issues as shown in Table 5.2. The scores for Adherence to Instructions, Company Information, and Terms & Conditions have also improved as seen in Table 5.3.

- **Supplier 4:** Mid-range cost and lead-time, no minimum order quantity, historically reliable with no quality issues

The total Supplier 4 score is now 114, exceeding the 80% threshold. The same category weighting is used and now shows Supplier 4 with the best weighted average score.

This example also highlights one of the limitations of using an evaluation score card for quotes. The scoring can be subjective, especially for determining adherence to instructions and company information, unless detailed scoring rubrics are applied.

SUPPLIER SELECTION SCORECARD

Scores Available from 1-5. Basis for scoring must be listed with specific examples.

1. Adherence to RFP Instructions	Supplier 1	Supplier 2	Supplier 3	Supplier 4	BASIS FOR SCORE
Timeliness	4	2	3	4	
Completeness	4	2	3	4	
Overall Quality & Level of Professionalism	4	2	3	4	
Overall Response	4	2	3	4	
Average Score	4	2	3	4	
Subtotal	16	8	12	16	
2. Company Information	**Supplier 1**	**Supplier 2**	**Supplier 3**	**Supplier 4**	**BASIS FOR SCORE**
Financial Viability	5	3	4	4	
Organizational Structure	4	2	4	4	
Experience with Similar Companies	4	3	4	4	
Service Department	4	2	4	4	
References/Supplier History	1	2	4	4	
Average Score	4	2	4	4	
Subtotal	18	12	20	20	
3. Terms & Conditions	**Supplier 1**	**Supplier 2**	**Supplier 3**	**Supplier 4**	**BASIS FOR SCORE**
Minimum Order Quantity	5	1	1	5	5-No MOQ, 1-MOQ
Terms & Conditions	4	1	3	4	
Quote Availability/Length	4	1	3	2	Longer the quote is good for the better the score
Average Score	4	1	2	4	
Subtotal	13	3	7	11	
4. Requirements	**Supplier 1**	**Supplier 2**	**Supplier 3**	**Supplier 4**	**BASIS FOR SCORE**
Completeness of Vendor Response	4	2	3	4	
Overall Comprehension of Project/Design Objective	4	2	3	4	
Understanding of Requirements	5	2	4	5	
Vendor Ability to Meet Requirements	5	2	4	5	
Vendor Qualification	5	1	5	5	1-Requires additional qualification, 5-No additional qualifications
Average Score	5	2	4	5	
Subtotal	23	9	19	23	
5. Quality	**Supplier 1**	**Supplier 2**	**Supplier 3**	**Supplier 4**	**BASIS FOR SCORE**
Certifications	5	3	4	4	ISO certified, Mil-STD qualified
Quality Management System	5	3	4	4	FAIs, CoC, traceability, nonconformance documentation
History of Quality Issues	1	1	1	2	1-No/Poor History
Average Score	4	2	3	3	
Subtotal	11	7	9	10	
6. Delivery	**Supplier 1**	**Supplier 2**	**Supplier 3**	**Supplier 4**	**BASIS FOR SCORE**
Leadtime	5	3	1	2	+1-Lead time delays project or becomes critical path
History of On-time/Quoted Delivery	1	2	4	2	1-No/Poor History
Communication about delays	1	1	5	3	
Average Score	2	2	3	2	
Subtotal	7	6	10	7	
7. Financial	**Supplier 1**	**Supplier 2**	**Supplier 3**	**Supplier 4**	**BASIS FOR SCORE**
Price per Unit	4	2	1	3	
Other Fees	1	2	5	5	Additional fees—Tooling, documentation
Total Purchase Order Cost	4	2	1	3	
Average Score	3	2	2	4	
Subtotal	9	6	7	11	
TOTAL AVERAGE	26	14	22	26	
TOTAL	97	51	84	98	

Select Multiple Vendors

CRITERIA SCORES (AVG)	WEIGHT	Supplier 1 WEIGHTED SCORE	Supplier 2 WEIGHTED SCORE	Supplier 3 WEIGHTED SCORE	Supplier 4 WEIGHTED SCORE	NOTES
1. Adherence to RFP Instructions	0.05	0.20	0.10	0.15	0.20	
2. Company Information	0.05	0.18	0.12	0.20	0.20	
3. Terms & Conditions	0.10	0.43	0.10	0.23	0.37	
4. Requirements	0.25	1.15	0.45	0.95	1.15	
5. Quality	0.25	0.92	0.58	0.75	0.83	
6. Delivery	0.15	0.35	0.30	0.50	0.35	
7. Financial	0.15	0.45	0.30	0.35	0.55	
Total Score	1.00	3.68	1.95	3.13	3.65	

Figure 5.1 Supplier Evaluation Scorecard Example

Table 5.1 Supplier Quotes

	Supplier 1	Supplier 2	Supplier 3	Supplier 4
Total Quote Score	97	51	84	98

Table 5.2 Supplier Quotes-Total Score (Supplier 4 Update)

	Supplier 1	Supplier 2	Supplier 3	Supplier 4
Total Quote Score	97	51	84	114

Table 5.3 Supplier Quotes-Weighted Average Scores (Supplier 4 Update)

CRITERIA SCORES (AVG)	Supplier 1 WEIGHTED SCORE	Supplier 2 WEIGHTED SCORE	Supplier 3 WEIGHTED SCORE	Supplier 4 WEIGHTED SCORE
1. Adherence to Instructions	0.20	0.10	0.15	0.25
2. Company Information	0.18	0.12	0.20	0.25
3. Terms & Conditions	0.43	0.10	0.23	0.43
4. Requirements	1.15	0.45	0.95	1.15
5. Quality	0.92	0.58	0.75	1.00
6. Delivery	0.35	0.30	0.50	0.50
7. Financial	0.45	0.30	0.35	0.55
Total Score	3.68	1.95	3.13	4.13

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CHAPTER 6 ORDER SPLITTING

Once the multi-sourcing procurement strategy has been assessed and decided upon in the procurement process, the optimal order split among suppliers will need to be determined so that orders can be placed.

Modeling and simulation can be used to optimize the order sizes among multiple suppliers with uncertainty. This chapter starts with a mathematical description for optimizing orders in a multi-sourcing procurement strategy as shown in Figure 6.1. The chapter then uses simulation to explore two scenarios for optimization and analysis.

6.1 Mathematical Descriptions

The following subsections mathematically describe some of the key aspects of the simulation for implementing a multi-sourcing procurement strategy and splitting orders among multiple suppliers in a space industry project.

6.1.1 Chapter Nomenclature

The mathematical modeling nomenclature for this chapter is detailed Table 6.1.

6.1.2 Objectives

This model considers objectives based on two sides of the project management triangle, cost and schedule. The model seeks to minimize project cost and project schedule deviation through multiple supply tiers and project phases.

The third side, quality, is not set as its own objective, but could be considered within the schedule objective as it may be quality issues causing uncertainty and delays.

6.1.2.1 Objective 1: Minimizing Total Project Costs

Minimizing the Total Project Cost, *C*, to determine the optimal order sizes allows project managers to focus on this key project constraint with a multi-sourcing procurement strategy.

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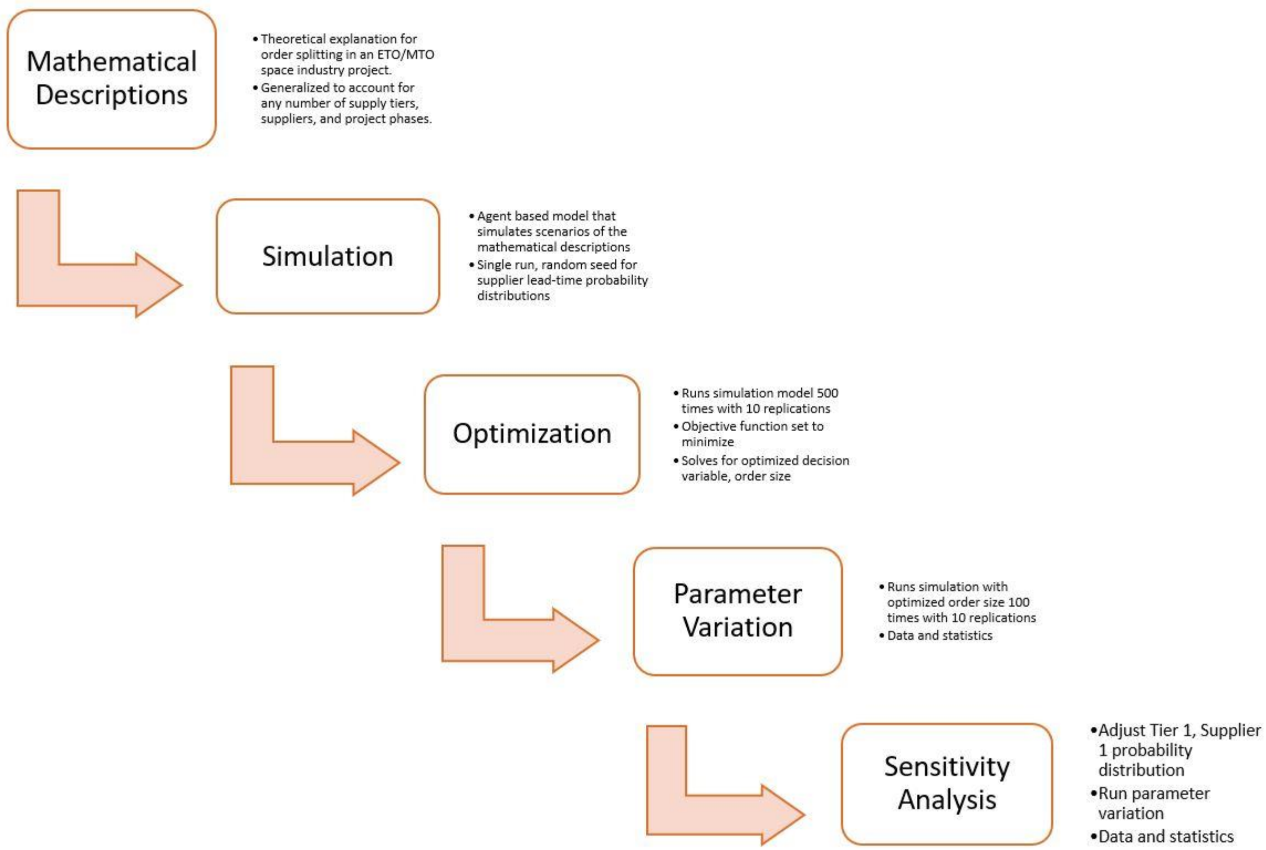


Figure 6.1 Chapter Modeling Flow

Table 6.1 Model Nomenclature

Symbol	Meaning
Time (t)	
β	Best-case schedule date/time
ϕ	Worst-case schedule date/time
μ	Most Probable schedule date/time
λ	Baseline schedule date/time
α	Actual schedule date/time
τ	Forecast schedule date/time
Counts and Limits	
j^k	j^{th} supplier in k^{th} tier (k=1, 2, …, K; j=1, 2, …, J))
J^k	Total number of suppliers in k^{th} tier
k	Number of supplier tiers
K	Total number of supplier tiers
n	Number of project phases
N	Total number of project phases
M	Project phase, M, used for forecasting at an actual phase M to the total project completion N, where $1 \leq M < N$
Decision variables	
s_{jk}	Order size of j^{th} supplier in tier k. For example: $s_{1,2}$ is the order size for the first supplier of the 2^{nd} tier.
Scheduling	
l_{jk}^{t}	Denotes lead-time at time (t) of the j^{th} supplier from supplier tier k. Leadtime includes manufacturing and shipping time. For example: $l_{1,2}^{\lambda}$ is the baseline lead-time for the first supplier of the 2^{nd} tier.
P_n^t	Project completion (project phases and suppliers)
h_n^t	Denotes the n^{th} project phase's completion in Time (t), not including supplier lead-times
δ	Schedule Deviation
Δ	Forecasted Schedule Deviation
Constraints: Order Size and Inventory	
q	Demand quantity
v	Inventory threshold for next phase to begin
Costs	
a_{jk}	Denotes the part unit price of the j^{th} supplier in k tier. For example: $a_{1,1}$ is the price per part for first supplier in the first supply tier.
b_n	Denotes cost of project phase n. For example: b_1 is the price to complete Project Phase 1.
x	Supplier Bonus/Penalty Constant
y	Project Phase Bonus/Penalty Constant
A	Supplier Total Costs
B	Project Phase Total Costs

Table 6.1Continued

Symbol	Meaning
C	Total Project Costs
Baseline Budgets and Constraints	
$\boldsymbol{A_\Lambda}$	Baseline Supplier Costs
$\boldsymbol{B_\Lambda}$	Baseline Project Phase Costs including contingency reserves
MR	Management Reserve
$\boldsymbol{\theta}$	Percentage of project baseline costs used for calculating management reserve
$\boldsymbol{\vartheta}$	Percentage of a baseline cost used to determine bonus/penalty constraints
$\boldsymbol{C_\Lambda}$	Baseline Total Project Costs
$\boldsymbol{\Psi}$	Project Budget

Total Project Cost, *C*, is the sum of the Total Supplier Costs, *A*, and the Total Project Phase Costs, *B*, which includes any bonuses for early completion or penalties for schedule delays.

$$C_{JKN} = A_{JK} + B_N \tag{6.1}$$

The previous equation can be set to a minimizing objective function of the Total Project Costs, *C*, for optimization.

$$\text{Minimize } C_{JKN} = A_{JK} + B_N \tag{6.2}$$

6.1.2.2 Objective 2: Minimizing Project Schedule Deviations

The absolute value of the project schedule deviation is considered in this model as the objective to minimize not only disruptions and delays, but also prevent a project or project phase from completing too early. A project manager may not want a project phase or project to be completed too early to avoid exceeding shelf-life requirements or having a gap in resource usage.

The following equation describes the objective function for minimizing schedule deviation at an actual project phase, *M*, before project completion.

$$\text{Minimize } |\delta| = \left|\mathrm{P}_{\mathrm{M}}^{\lambda} - \mathrm{P}_{\mathrm{M}}^{\alpha}\right| \tag{6.3}$$

The next equation describes the objective function to minimize the forecasted schedule deviation for the entire project to phase *N*.

$$\textit{Minimize } |\Delta| = \left|P_N^{\lambda} - P_N^{\tau}\right| \tag{6.4}$$

6.1.3 Constraints

Several constraints are considered throughout the model. Order constraints applicable to both model objectives are demand, supplier order size, and inventory thresholds. An overall project budget constraint is also applied to both models to make sure that the project does not exceed the project budget. Additional budget constraints are placed at the supplier level to set realistic bonus/penalties for supplier deliveries that do not exceed a specified amount of the total order.

6.1.3.1 Demand and Supplier Order Size

The orders sizes for each supplier in a tier, k, are a percentage, ϑ, of the total demand; therefore, the sum for all suppliers in tier, k, should equal the demand quantity, q^k.

$$\sum_{j=1}^{J} s_{j^k} = q^k, \;\; k = 1,2, \dots, K \tag{6.5}$$

For this model, it is assumed that that any attrition is included in the demand. Small batch MTO or ETO production does not follow the traditional safety stock model to minimize left over inventory and holding costs.

6.1.3.2 Inventory Threshold

This model assumes no partial deliveries are allowed from an individual supplier.

For the lower supplier tiers in the simulation solution, the total demand must be reached in inventory for Tier 1 to begin production; however, once the orders filled from Supply Tier 1 meet the Project Phase 1 inventory threshold, v^n where $n=1$, that project phase can start. Here it is assumed that project Phase 1 can start with a partial of the total demand. The threshold, v^n, should be a percentage of demand, q^k.

6.1.3.3 Project Budget Constraints

As an overall project budge constraint, the total project costs, C_{JKN}, should be less than or equal to the project budget, Ψ.

$$C_{JKN} \leq \Psi \tag{6.6}$$

This constraint limits the model bonus/penalties for all project phases so that a penalty would not exceed the baseline project phase costs. It also limits the bonus so that excessive bonuses are not given for early delivery.

$$\vartheta \sum_{n=1}^{N} b_n^{\lambda} \geq \left| \sum_{n=1}^{N} y_n \left(l_n^{\lambda} - l_n^{\alpha} \right) \right| \tag{6.7}$$

The baseline supplier costs for a tier, *k*, is the cost of a single supplier sourcing strategy*, j=1*, per tier, *k*.

$$\vartheta \sum_{k=1}^{K} a_k \, s_k \geq \left| \sum_{k=1}^{K} \sum_{j=1}^{J^k} x_{jk} \left(l_{jk}^{\lambda} - l_{jk}^{\alpha} \right) \right| \tag{6.8}$$

This constraint limits the model bonus/penalties for supplier, *j*, in supply tier, *k*, so that a penalty would not exceed the baseline supplier costs per tier, k. It also limits the bonus so that excessive bonuses are not given for early delivery.

6.1.4 Decision Variables

The decision variables in this model are the order sizes for each supplier, *j*, in supply tier, *k*, represented as, s_{jk}.

This is the decision that the simulations will seek to optimize through each objective. As the order sizes change, the costs and schedules change.

The simulations also use the part cost for each supplier in the first tier only, a_{j1}, as a decision variable. The lower tiers are set as a fixed as they would typically be included in the overall costs of the products in the first supply tier.

6.1.5 Baseline Project Costs

The project budget, Ψ, is the baseline project cost, C_{Λ}, plus management reserve, *MR*. Management reserve, *MR*, is a percentage, ϑ, of the project baseline for unknown risks that may incur costs. Typically, the Management Reserve is 5%-10% of the project baseline costs.

$$\Psi = C_\Lambda + MR = C_\Lambda + \theta C_\Lambda \tag{6.9}$$

The baseline project cost, C_Λ, is the baseline costs from both suppliers and project phases plus any contingency funds. For this model, the contingency funds are assumed to be included in the project phase costs, B_Λ, instead of a separate constant.

$$C_\Lambda = A_\Lambda + B_\Lambda \tag{6.10}$$

The baseline supplier costs, A_Λ, for the total supplier tiers, K, are calculated assuming a baseline of a single supplier, $j=1$, per supplier tier, k. For each tier, the order size multiplied by the cost per part is calculated and summed for all tiers. The order size will equal the demand, q^k. Since the baseline is based on a single supplier, $j=1$, per supplier tier, k, there is no summation of *j to J,* so it is dropped from the baseline cost equation.

$$A_\Lambda = \sum_{k=1}^{K} a_k s_k \tag{6.11}$$

The baseline project phase costs, B_Λ, for the total project in N phases are calculated as the cost for each project tier with contingency funds for known risks incorporated.

$$B_\Lambda = \sum_{n=1}^{N} b_n \tag{6.12}$$

6.1.6 Project Costs

A supplier's order cost is the price per part, a_{jk}, quoted from the supplier multiplied by the supplier's order size, s_{jk}. For this chapter, any additional fees or costs associated with supplier production are included in the price per part for the simulation.

The Total Supplier Costs, *A*, for *J* suppliers in *K* tiers adds all the suppler order costs with bonuses or penalties applied. The bonus or penalty is calculated by using the bonus/penalty constant rate, *x*, multiplied by the schedule deviation for the supplier.

This model and simulation calculate the bonus as a reduction of cost due to early delivery. The positive bonus is subtracted from a supplier order cost to reduce the order cost. The penalty is calculated as an increase in cost due to delivery delays. The negative bonus is subtracted from the supplier order cost, leading to a total cost for that supplier that is greater than their order cost.
The model is set up this way to view the supply chain and project together and to simulate negative impacts of delayed deliveries and project completion during optimization. In an industry project the bonus may be an award fee for extra funds given to the supplier that may come from the overall project budget or from other corporate funds. A penalty could be that no award fee is given and potentially no future orders.

$$A_{JK} = \left[\sum_{k=1}^{K}\sum_{j=1}^{J^k} a_{jk} s_{jk}\right] - \left[\sum_{k=1}^{K}\sum_{j=1}^{J^k} x_{jk}\left(l_{jk}^{\lambda} - l_{jk}^{\alpha}\right)\right] \tag{6.13}$$

The Total Project Phase Costs, *B*, for the total project in N phases are calculated similarly as the cost for each project tier with any bonus or penalties incorporated.

$$B_N = \sum_{n=1}^{N} b_n - \sum_{n=1}^{N} y\left(h_n^{\lambda} - h_n^{\alpha}\right) \tag{6.14}$$

Again, the bonus/penalty for each phase is calculated as project phase cost reductions or increases, respectively.

6.1.7 Project Schedule Baseline and Deviation

The other side of the project management triangle the model seeks to minimize as an objective is schedule. Minimizing schedule deviations in simulations will allow project managers to determine the best order split for minimizing schedule delays some of which may be caused by quality issues.

The total project time at any schedule time, *t*, can be calculated by the sum of the project phases complete plus the supplier lead-times for all tiers.

$$P_N^t = \sum_{n=1}^{N} h_n^t + \sum_{k=1}^{K} \sum_{j=1}^{J^k} l_{jk}^t \tag{6.15}$$

Schedule deviation for a project at phase, *n*, is calculated by the baseline, *λ*, minus the actual, *α*, times as shown in the following equation.

$$\delta_n = P_n^\lambda - P_n^\alpha \tag{6.16}$$

- Meeting the schedule will result in a deviation of zero.
- A negative deviation results in a schedule exceedance from the baseline
- A positive deviation results in a schedule that performs better than the baseline.

A baseline schedule for the project must first be determined for analysis at any future point. The project phase baseline to completion at time, *λ*, can be determined from historical data or subject-matter-experts The baseline time to completion, *λ*, from supplier to manufacturer is based on the case of only using one supplier instead of multiple suppliers and includes any scheduling buffers.

A generalized schedule shown in Figure 6.2 from supplier or completion of a project phase where schedule time, *t*, ranges from the best-case time to completion, *β*, to the worst-case time to completion, *φ*. These schedule bounds can again be determined from supplier quotes, historical data, or subject-matter-experts.

Another timeline parameter of note in this model, specifically for simulation parameters, is the most probable time to completion, *μ*. This parameter will be used for triangular distributions in simulations to show reliability and uncertainty in supplier deliveries.

For this model the baseline schedule and worst-case schedule times are not the same, the worst-case schedule will be greater than the baseline schedule to allow simulations to exceed the baseline schedule but also have an upper bound. In practical application the worst-case schedule may be the baseline schedule, or it may be unknown.

$$\varphi > \lambda \tag{6.17}$$

6.1.8 Forecasting Project Schedule Recovery

The project deviation can also be used to forecast recovery by minimizing the absolute value of the forecasted deviation as calculated as the baseline schedule time to completion minus the sum of the forecasted time to completion.

$$\Delta = P_M^{\lambda} - P_M^{\tau} \tag{6.18}$$

The forecast time to completion is the actual project schedule time at phase *M* plus the baseline time to completion of the remaining phases, *M+1 to N*. Assuming all suppliers have delivered at phase *M* where *1≤M<N*.

$$P_M^{\tau} = \left[\sum_{n=1}^{n=M} h_n^{\alpha} + \sum_{k=1}^{K}\sum_{j=1}^{J^k} l_{jk}^{\alpha}\right] + \sum_{n=M+1}^{N} h_n^{\lambda} \tag{6.19}$$

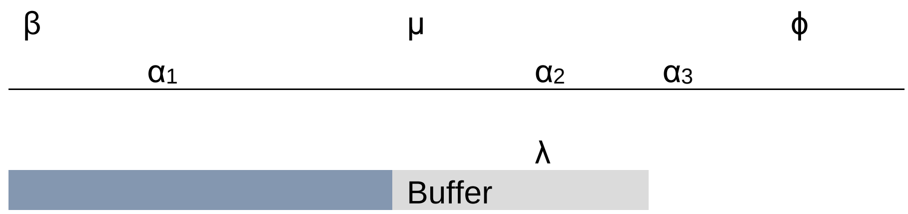


Figure 6.2.Schedule timeline

The baseline time to completion of the actual and future phases is the project baseline to *N* phases based on a single supplier in each supply tier.

$$P_N^\lambda = \sum_{n=1}^{N} h_n^\lambda + \sum_{k}^{K} l_k^\lambda \tag{6.20}$$

A comparison of the forecast time to completion to the baseline time to completion of *N* phases can show project managers if the project is recoverable in N phases, on target, or unrecoverable. An unrecoverable forecast may lead to additional migrations or a re-baselining of the project. Unfortunately, a spiral of delays and re-baselining of project schedules may occur in actual projects; however, for this research the project schedule will not be re-baselined.

The project is recoverable in *N* phases if:

$$P_N^\lambda > P_N^\tau \tag{6.21}$$

The project is not recoverable in *N* phases if:

$$P_N^\lambda < P_N^\tau \tag{6.22}$$

The project is on target to the baseline schedule if:

$$P_N^\lambda = P_N^\tau \tag{6.23}$$

From here the project manager can utilize the actual supply chain lead-times combined with the baseline project phase schedule to determine if the N^{th} project phase will complete on time or exceed the baseline schedule.

6.2 Modeling Uncertainty through Probability Distributions

Uncertainty in supplier deliveries or project phase completions due to disruptions or other risks can be modeled using the schedule time parameters in different probability distributions for each supplier or project phase.

Each supplier within each tier and each project phase may have different types of probability distributions for lead-time, manufacturing time, or testing. With compounding probability distributions for each supply tier and project phase, the overall project model and project success is too complex to solve without simulation.

To solve this problem, the uncertainty of disruption or delay for a supplier or project phase is simulated as randomness based on the probability distribution set for that supplier or phase using AnyLogic such as those shown in Table 6.2

6.2.1 Probability Distributions

A uniform distribution defines equal probability over the given range. For this model, the uniform distribution uses the best-case lead-time and worst-case lead-time. The Uniform 1 distribution ranges from the best-case lead-time up to the worst-case lead-time while Uniform 2 is inclusive of the worst-case lead-time in the simulation software. This distribution is useful for this model when lead-times occur over a short range of time. This distribution is also useful if the most-likely lead-time is unknown or unable to be determined.

The most-likely lead-time may be unknown or unable to be determined if there is a lack of historical data or if there is great supply chain uncertainty as in the case of supply disruptions due to Covid-19.

A triangular distribution can be used as an improvement over the uniform distributions. It allows for a lower probability of occurrence for range values less than the most likely and a higher probability of occurrence for range values greater than the most likely. This distribution is useful if the most-likely lead-time is known, or as in this model to describe supplier reliability.

6.2.2 Simulation Framework

Agent based simulations have been developed for this study from the model described earlier in this chapter to demonstrate the supply chain uncertainty in the space industry. Figure 6.3 shows the simulation model build, this flow chart along with additional model graphics are included in the dissertation attachments. These simulations use a random seed generator as pseudo-randomness for uncertainty bound by a probability distribution for the transition of each agent.

Table 6.2 Example Schedule Distributions

Distribution Type	**Boundaries**
Uniform1	$[\beta, \phi)$
Uniform2	$[\beta, \phi]$
Triangular	$[\beta, \phi, \mu]$

Simulations are developed using AnyLogic. This software uses a Linear Congruential Generator (LCG) used for both experimental and probability distributions.

6.2.2.1 Model Agents

The simulations models in this research use an Agent-Based model in AnyLogic to simulate the supplier-manufacturer relationship and forecast project completion. State charts are used in the model to describe the supply chain lead-times and project phase manufacturing times.

Model Agent

The main agent contains a simple dashboard of key project and forecasting metrics as well as links to the other agents. This agent also contains the main variables for time to supply, project completion, baselines, and schedule variances.

D-Tier

The D-Tier is the first-tier supply chain feeding directly to the project.
The probability distributions set for each D-Tier supplier represent the suppliers' lead-time or time to supply to the first project phase.

E-Tier

The E-Tier is the second tier of the supply chain, feeding the D-Tier. The probability distributions set for each E-Tier supplier represent the suppliers' lead-time or time to supply to the first tier of the supply chain. The E-tier time to supply is set to the maximum lead-time of the tier's suppliers, creating a pool of E-tier products for all the D-tier suppliers to pull from without experiencing shortages.

P1

The P1 agent represents the first project phase. A probability distribution represents the time to completion for this phase. This matches the actual project time at phase *M* in the mathematical model described earlier in this chapter. When the first-tier supplier deliveries meet a set threshold, Project Phase-1 can begin.

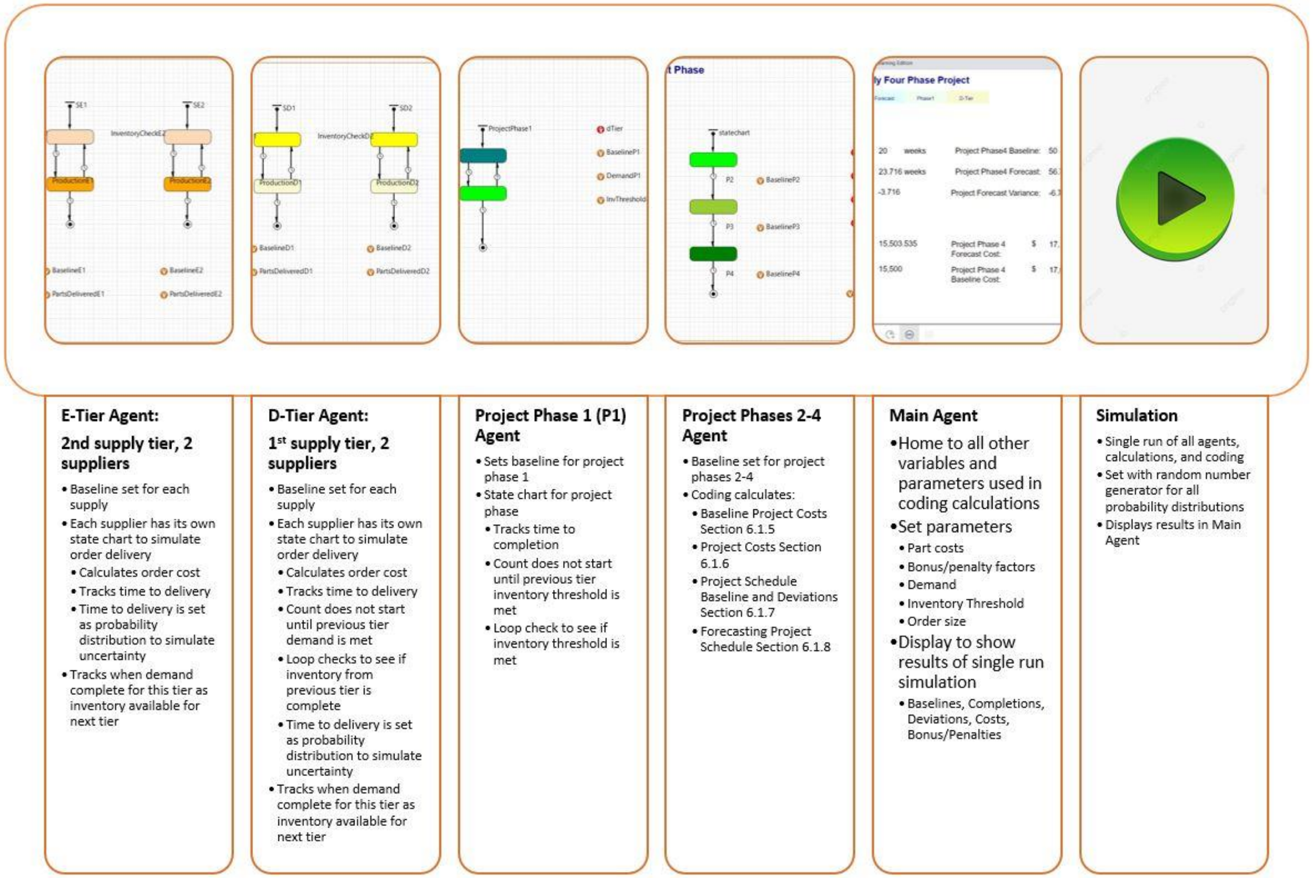


Figure 6.3 Simulation Model Build

ForecastP2_4

The Forecast agent consists of a chain of state charts connected by transitions using a probability distribution to represent the time to completion for project phases two through four, *M+1 to N*. The resulting time combined with the Project Phase 1 time, including time to supply, results in project forecast through four project phases.

Coding

The equations presented earlier in this chapter are used to develop the coding in the agents to calculate schedule deviations, total schedule length, baseline costs, bonus/penalty costs, and total project costs. These equations are included in the Appendix.

6.2.3 Optimization

The simulation runs a single, random case, calculating the time to supply and costs for each supplier in each supply tier. The time to completion and costs for each project phase are also calculated. The schedule is also calculated according to the baselines set for each supply tier and project phase. Total costs including bonus/penalties are also calculated.

6.2.3.1 Optimization Description

The optimization runs by varying the order size for each supplier to find the best order distribution to minimize either the schedule deviation or total project. Each run is based on a random number generator to simulate the uncertainty of the supply chain and project schedule. For the first supply tier, the supplier costs have also been varied based on the supplier quotes from Chapter 5.

The optimization runs 500 times with 10 iterations for each run to calculate the optimized order size.

Figure 6.4 describes the Anylogic optimization module and the parameter needed to run the simulation model for optimization.

6.2.3.2 Parameter Variation/Sensitivity Analysis Description

The best case from the optimization run for each objective is then run in a parameter variation 100 times with 10 iterations to gather data on how the best-case order sizes perform. Each run is based on a random number generator to simulate the uncertainty of the supply chain and project schedule.

The parameter variation (100x10) is then run several times changing the probability distribution for the first supplier in the first supplier tier by changing the most likely time delivery time. For this sensitivity analysis, the closer the most likely delivery time is to the worst-case delivery time simulates a less reliable supplier than the optimization run. The closer the most likely delivery time, the more reliable the supplier is from the optimization run.

The next section will build on the complexity of the mathematical model through simulation to minimize schedule variance and forecast schedule recovery through uncertainty in a variety of complex scenarios.

6.3 Simulation Scenarios

Continuing the baseline scenario in Section 3.1, the design and build of a circuit card assembly (CCA) for an avionics component for a space industry project, scenarios are examined from the perspective of the Phase-1 project manager.

Before placing orders, the project manager has followed the risk analysis tools previously presented and uses these two simulation scenarios to optimize the order split among suppliers and understand how a dual sourcing strategy can help mitigate the risk of cost increases and schedule delays from the baseline scenario.

The following scenarios examine the basic building block of the supplier-manufacturer relationship in this research where dual suppliers support one project phase. Like the problem studied by Tomlin and then Qi and Lee, one supplier is considered unreliable or experiences a disruption at random.[82], [83]

6.3.1 Scenario 1: Dual Sourcing Strategy for a Single Supply-Tier with Disruption

A supplier with a disruption is simulated with a larger probability distribution range than a known or undisrupted supplier due to the disruption causing a potentially longer lead-time than expected in the baseline schedule.

6.3.1.1 Parameters and Constraints

In this scenario, dual suppliers support manufacturing of the first project phase where Supplier-1 experiences a disruption or is less reliable than Supplier-2. Supplier-1 has quoted an earlier delivery and lower cost than Supplier-2, before experiencing the disruption. Supplier-1’s probability distribution has a wider range than Supplier-2 due to the disruption.

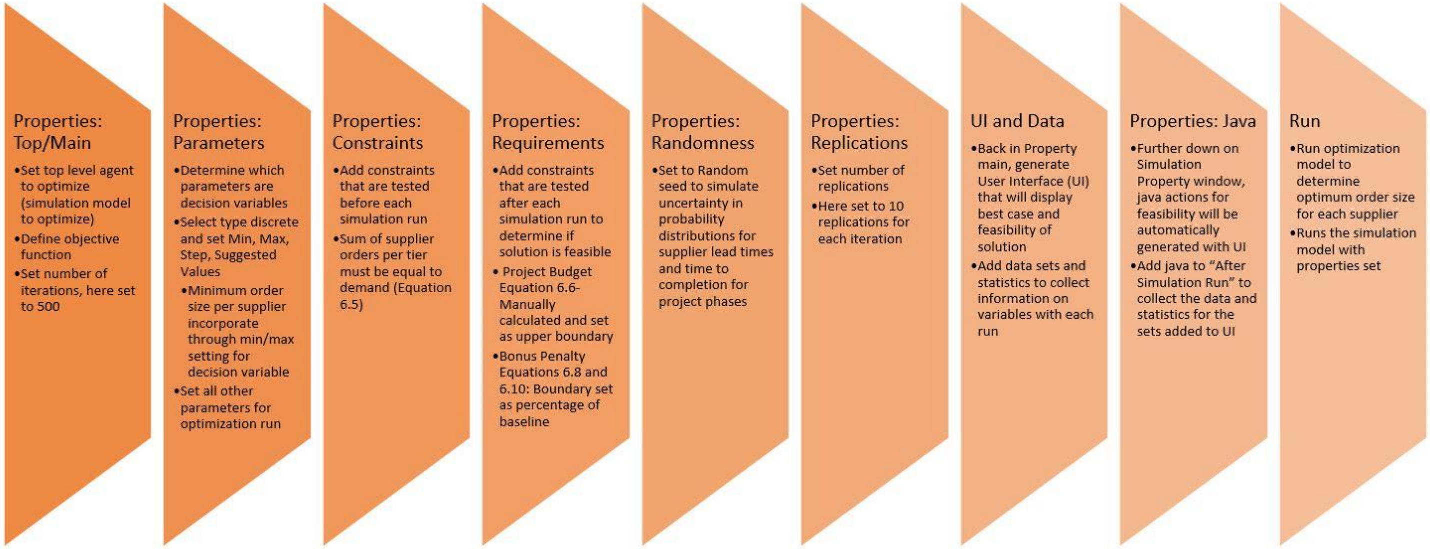


Figure 6.4 Anylogic Optimization Module

Supplier lead-times in the first supply tier are modeled as triangular probability distributions from best case to worst case with the mode set as the most likely lead-time.

- Supplier-1 Leadtime Probability Distribution: [β_{D1}, φ_{D1}, μ_{D1}]
- Supplier-2 Leadtime Probability Distribution: [β_{D2}, φ_{D2}, μ_{D2}]

The best-case time to delivery for Supplier-1 is less than the best-case delivery time of Supplier-2 to account for the early delivery quoted by Supplier-1. The worst-case time to delivery of Supplier-1 is greater than the worst-case time to delivery of Supplier-2 to account for a possible later delivery by Supplier-1 due to disruption and uncertainty.

- $B_{D1} < \beta_{D2}$
- $\Phi_{D1} > \phi_{D2}$

Each Project Phase time to completion is modeled on a discrete uniform distribution from best cast to worst case with the worst case included within the distribution.

- Project Phase Time to Completion Probability Distribution: [β_{Pn}, φ_{Pn}]

Scenario 1 parameters are listed in Table 6.3.

The optimization applies Equation 6.5 as a constraint so that the sum of the orders does not exceed the demand. The optimization is run with a random seed for 500 iterations, each with 10 replications with varied parameters. Each iteration also contains the following cost constraints to determine if the solution is feasible:

- Total Project Cost cannot exceed the project budget of $66,000.
- The absolute value of the D1 bonus/penalty cost cannot exceed 10% of baseline supplier cost, $2500.
- The absolute value of the D2 bonus/penalty cost cannot exceed 10% of baseline supplier cost, $2500.

The project budget is calculated as described in the mathematical
The simulation optimization is run.

6.3.1.2 Scenario 1, Optimization Objective 1-Minimize Schedule Deviation

The optimization simulation of this scenario varies supplier order size through varying the percentage of demand of each supplier order and supplier costs. Supplier minimum order size is considered in the simulation by limiting the range of variation of the demand percentage. The optimization uses decision variables in Table 6.4.

Table 6.3 Scenario 1 Simulation Model Parameters

Parameter	
Demand	50
D1 Baseline Lead-time	10 weeks
D1 Lead-time Probability Distribution	(8, 22, 16)
D2 Baseline Lead-time	16 weeks
D2 Lead-time Probability Distribution	(12, 18, 16)
Inventory Threshold	10
Project Phase Baseline Time to Completion	10 weeks
Project Phase Probability Distribution	[8, 12]
D-Tier Bonus/Penalty Factor, *x*	$150
Project Phase 1 Bonus/Penalty Factor, *y1*	$250
Project Phases 2-4 Bonus/Penalty Factor, *y2*	$750
Project Budget	
Project Phase 1 Baseline Cost	$5,000
Project Phases 2-4 Baseline Cost	$30,000
Baseline Supplier Costs	
Management Reserve (10% Baseline Costs)	

Table 6.4 Scenario 1 Decision Variables

Variable	**Min**	**Max**	**Step**
Order Size D1 (OrderSD1)	10	40	5
Order Size D2 (OrderSD2)	10	40	5
Part Cost D1	$500	$1200	$25
Part Cost D2	$600	$800	$25

The resulting best-case order size and part cost from the single tier, dual supplier model with a minimized schedule project schedule deviation is shown in the Table 6.5.

6.3.1.3 Scenario 1, Optimization Objective 2-Minimize Project Costs

Again, the optimization simulation of this model varies supplier order size through varying the percentage of demand of each supplier order and supplier costs. Supplier minimum order size is considered in the simulation by limiting the range of variation of the demand percentage. This optimization, however, seeks to minimize total project costs including any penalties for schedule delays. The optimization uses the same decision variables.

The resulting best-case order size and part cost from the single tier, dual supplier model with a minimized project cost objective is shown in Table 6.6.

6.3.1.4 Parameter Variation/Sensitivity Analysis

The best case for each objective is then run as a parameter variation, 1-100 runs, each with 10 replications to gather data and statistics for analysis and comparison. This is run several times for each objective varying the most likely parameter in the Supplier1 lead-time triangular distribution to simulate ~20% more/less reliability in the supplier lead-time from the optimization run.

6.3.1.4.1 Scenario 1, Objective 1 Sensitivity Analysis: Supplier D1 Reliability

Figure 6.5Figure 6.5 Scenario 1, Objective 1: Supplier 1 Bonus/Penalty Cost Sensitivity Analysis to Figure 6.8 show a summary of results for the Scenario 2, Objective 1 for this discussion. Data is recorded in the dissertation attachments.

As expected, the Supplier 1, D1, lead-time and bonus/penalty costs increase the less reliable the supplier’s most probable delivery.

Project costs also generally increase the less reliable the supplier’s most probable delivery; however, not uniformly or predictably for this scenario.

The mean lead-time for Supplier 1, D1, also increases the less reliable the supplier’s most probable delivery. Supplier 2’s, D2, lead-time remain relatively the same due to the shorter probability distribution range.

The project schedule deviation at project Phase 1 generally increases as the less reliable the supplier’s most probable delivery, but not linearly.

Table 6.5 Best Case Order Size and Part Cost Optimization for Scenario 1, Objective 1

Parameter	Optimum
Order Size D1 (OrderSD1)	35
Order Size D2 (OrderSD2)	15
Part Cost D1	$550
Part Cost D2	$600

Table 6.6 Best Case Order Size and Part Cost for Scenario 1, Objective 2

Parameter	Optimum
Order Size D1 (OrderSD1)	40
Order Size D2 (OrderSD2)	10
Part Cost D1	$500
Part Cost D2	$600

By optimizing the schedule deviation, the overall project schedule deviation shows that the later project phases are often able to make up some of the delays from Supplier-1 in this scenario.

6.3.1.4.2 Scenario 1, Objective 2 Sensitivity Analysis: Supplier D1 Reliability

Figure 6.9 to Figure 6.12 show a summary of results for the Scenario 2, Objective 1 for this discussion. Data is recorded in the dissertation attachments.

As expected, the Supplier 1, D1, lead-time and bonus/penalty costs increase the less reliable the supplier's most probable delivery. The range of penalty costs between the 19% less reliable and 19% more reliable for both objectives is about the same amount.

With the objective of minimizing the project costs, there is not a lot of variability in costs at project phase 1 and the total project costs.

The mean lead-time for Supplier 1, D1, also increases the less reliable the supplier's most probable delivery. Supplier 2's, D2, lead-time remain relatively the same.

The project schedule deviation trends toward a greater deviation the less reliable Supplier-1 is, but at times the later project phases make up for some of the supplier delays despite not optimizing for schedule. Schedule deviations optimizing for costs are in a similar range to the schedule optimization.

6.3.1.5 Management Insight and Discussion

The project manager in this scenario would be able to prioritize minimizing costs and without additional mitigations the schedule may still be recoverable. The project manager now can review additional mitigations to better maintain project schedule and cost.

6.3.2 Scenario 2: Dual Sourcing Strategy for Two Supply-tiers with Disruption

The simulation now expands the complexity of the scenario to two supplier tiers. For this scenario, the second-tier supplier costs remain fixed. In an industry project the lower supplier tier costs are incorporated into the first-tier supplier costs, but for this simulation scenario looks at them separately to assess a bonus/penalty for deliveries at all supplier tiers.

Table 6.7 Supplier 1 Reliability Sensitivity Analysis

β Best	ϕ Worst	μ Most Likely		
8	24	13	19%	more reliable
8	24	14	13%	more reliable
8	24	15	6%	more reliable
8	24	16	0%	base distribution
8	24	17	-6%	less reliable
8	24	18	-13%	less reliable
8	24	19	-19%	less reliable

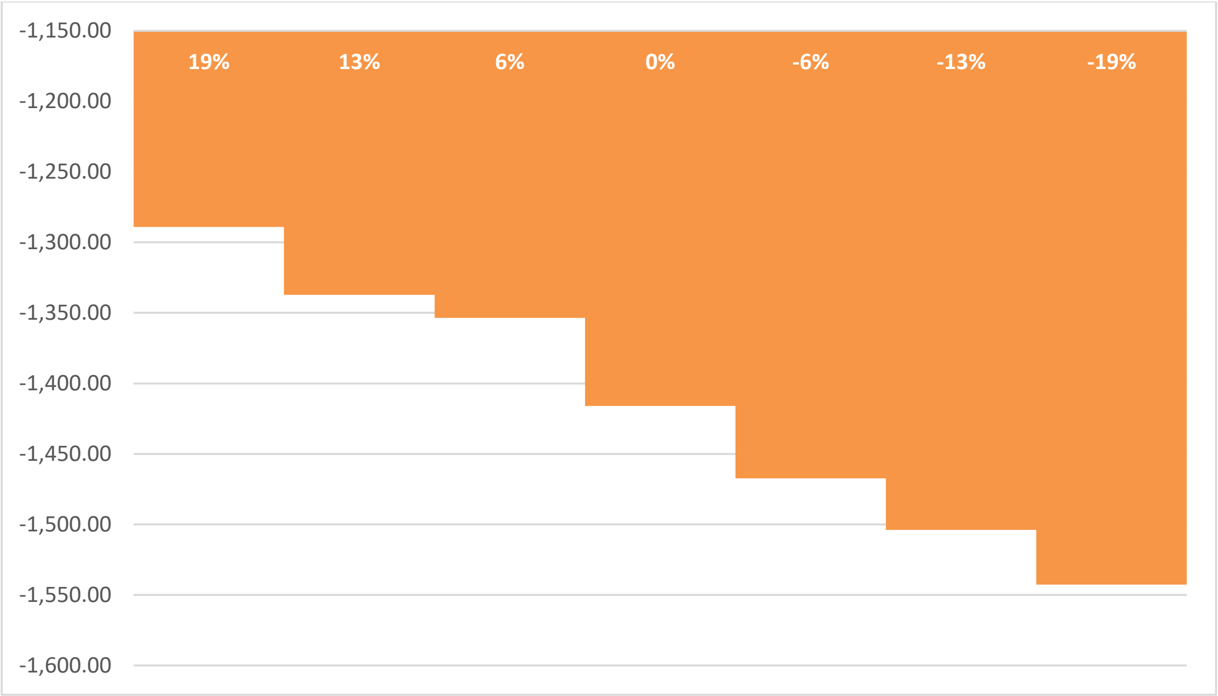
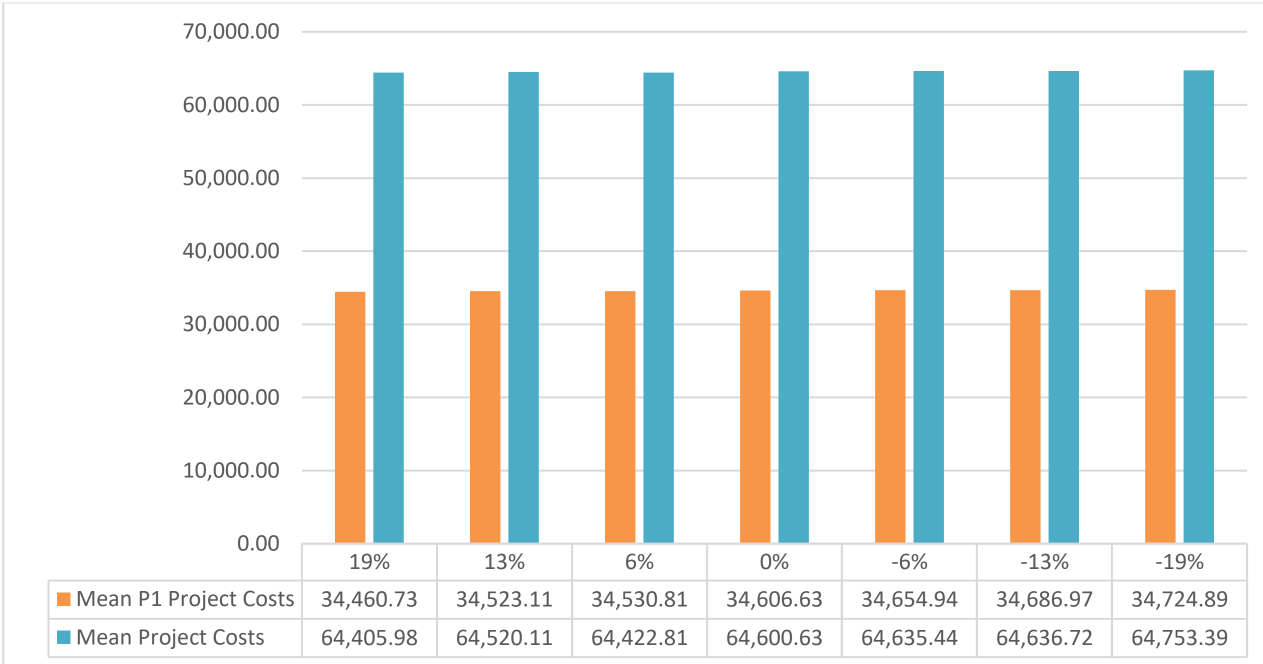


Figure 6.5 Scenario 1, Objective 1: Supplier 1 Bonus/Penalty Cost Sensitivity Analysis



	19%	13%	6%	0%	-6%	-13%	-19%
Mean P1 Project Costs	34,460.73	34,523.11	34,530.81	34,606.63	34,654.94	34,686.97	34,724.89
Mean Project Costs	64,405.98	64,520.11	64,422.81	64,600.63	64,635.44	64,636.72	64,753.39

Figure 6.6 Scenario 1, Objective 1: Project Costs Sensitivity Analysis

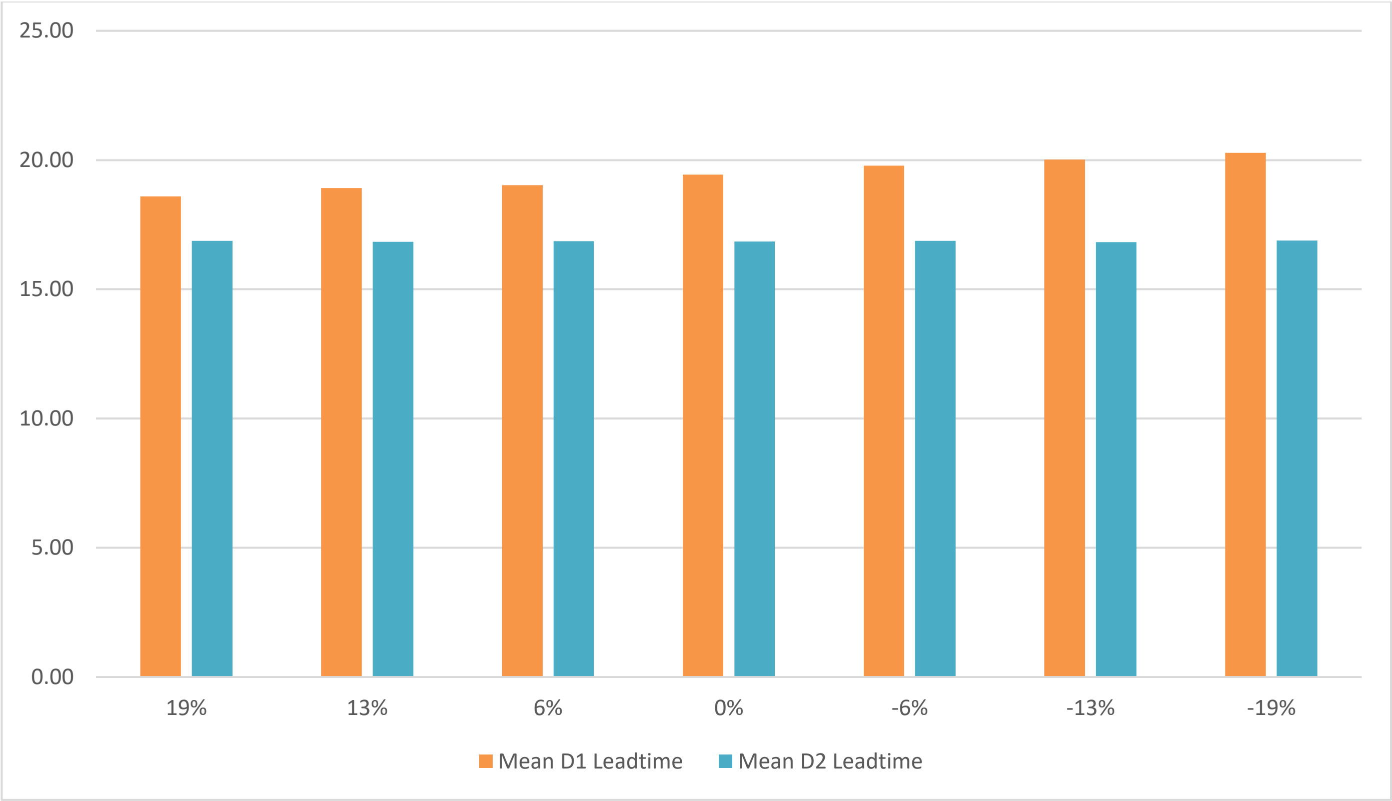


Figure 6.7 Scenario 1, Objective 1: Supplier Leadtime Sensitivity Analysis

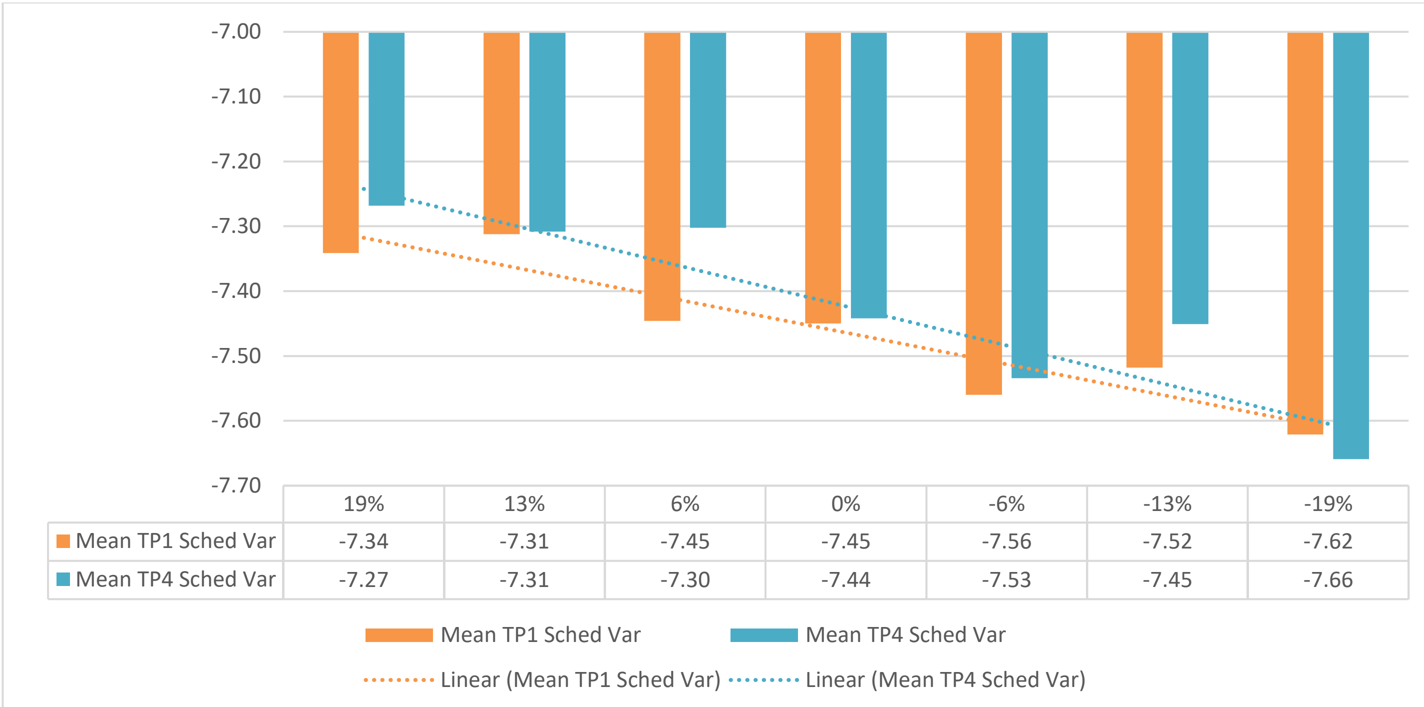


Figure 6.8 Scenario 1, Objective 1: Project Schedule Deviation Sensitivity Analysis

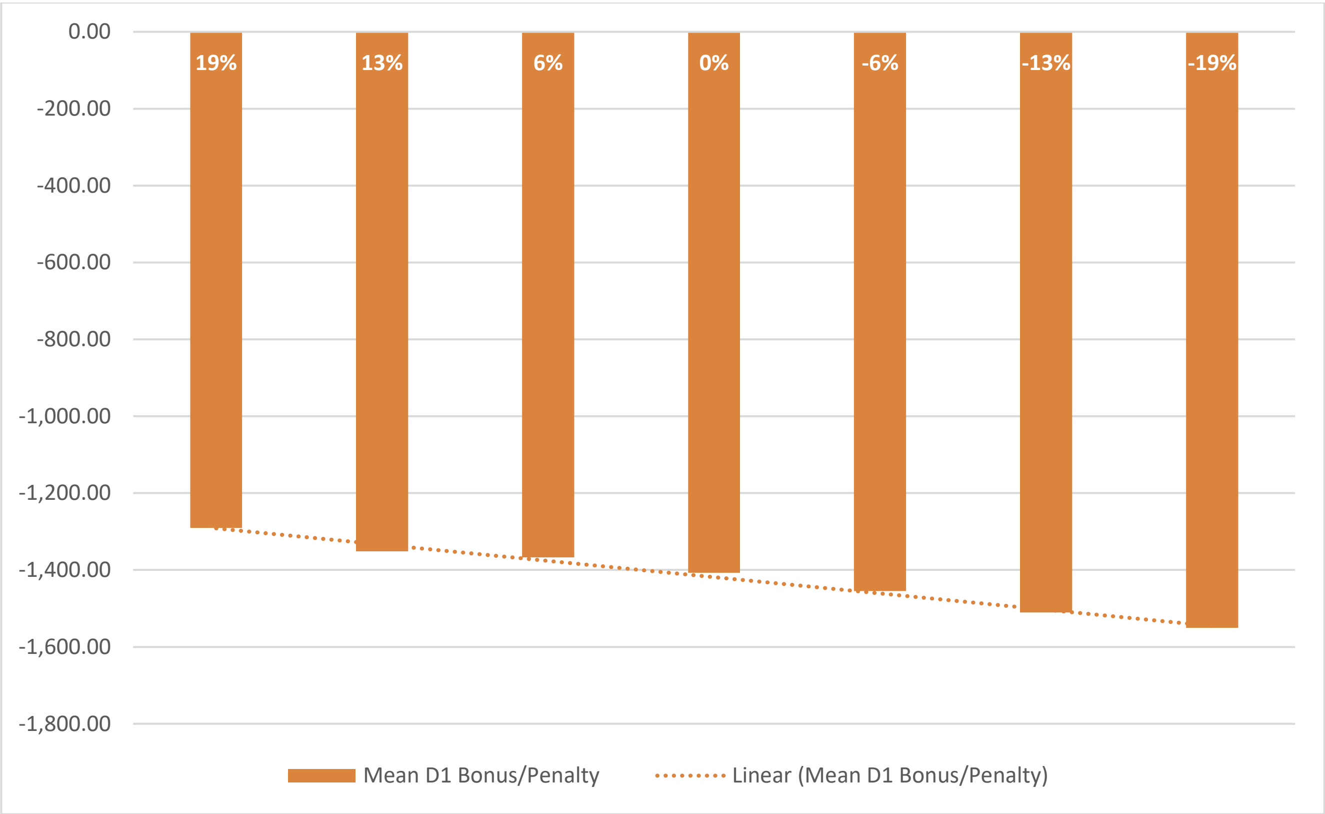
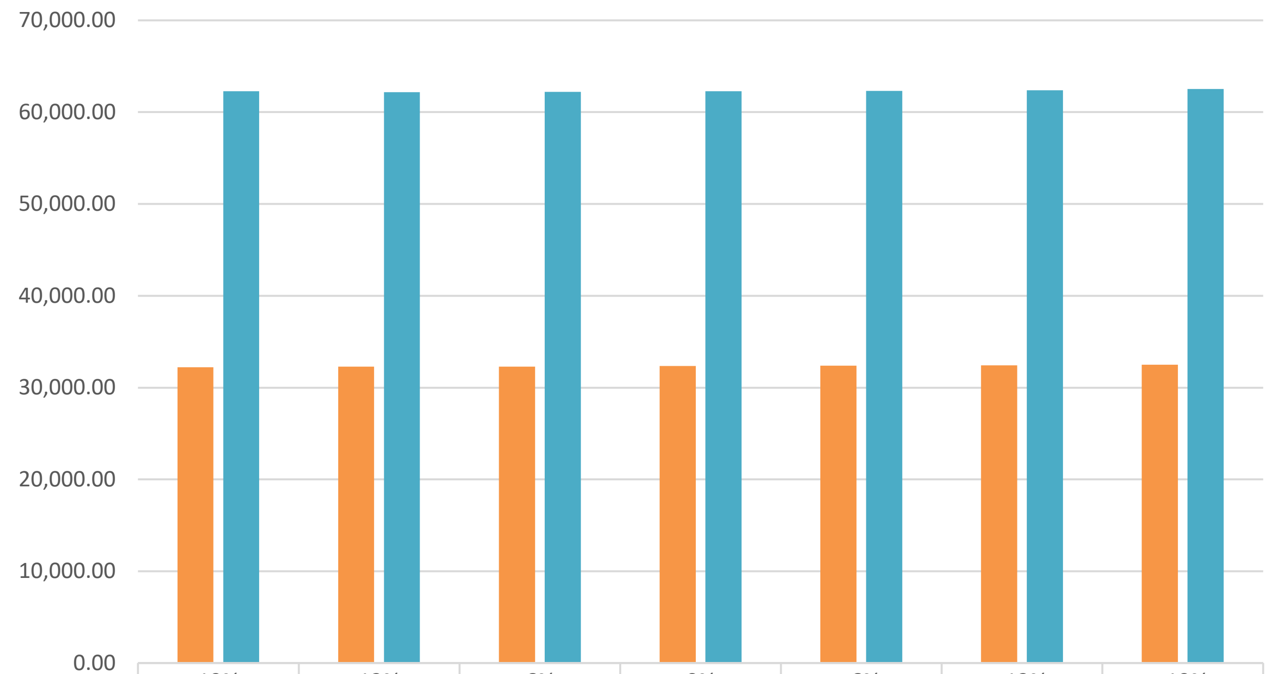


Figure 6.9 Scenario 1, Objective 2: Supplier 1 Bonus/Penalty Cost Sensitivity Analysis



	19%	13%	6%	0%	-6%	-13%	-19%
Mean P1 Project Costs	32,216.19	32,280.52	32,292.84	32,340.51	32,380.67	32,435.17	32,477.07
Mean Project Costs	62,267.94	62,178.52	62,211.84	62,267.76	62,324.42	62,372.92	62,518.32

Figure 6.10 Scenario 1, Objective 2: Project Costs Sensitivity Analysis

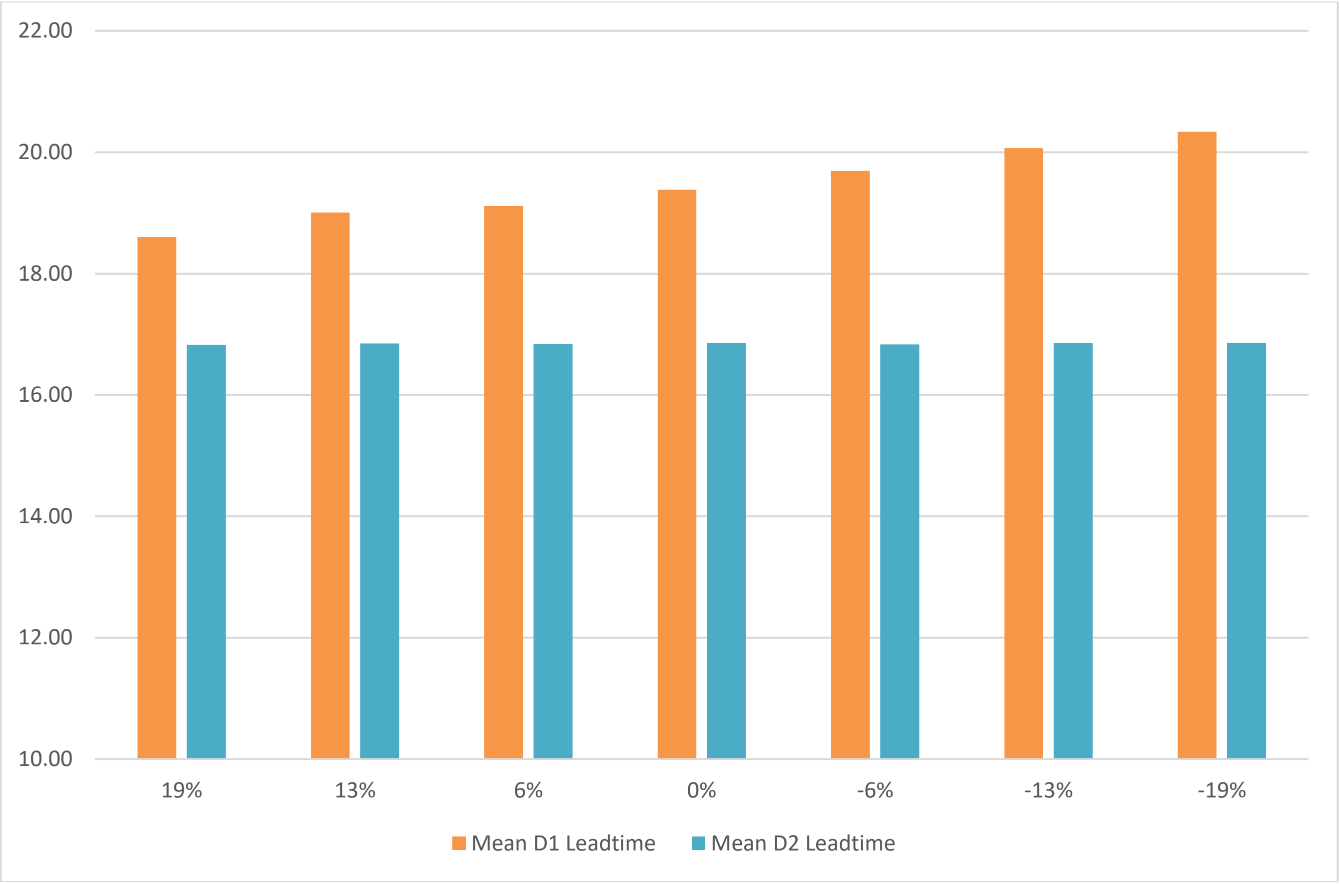
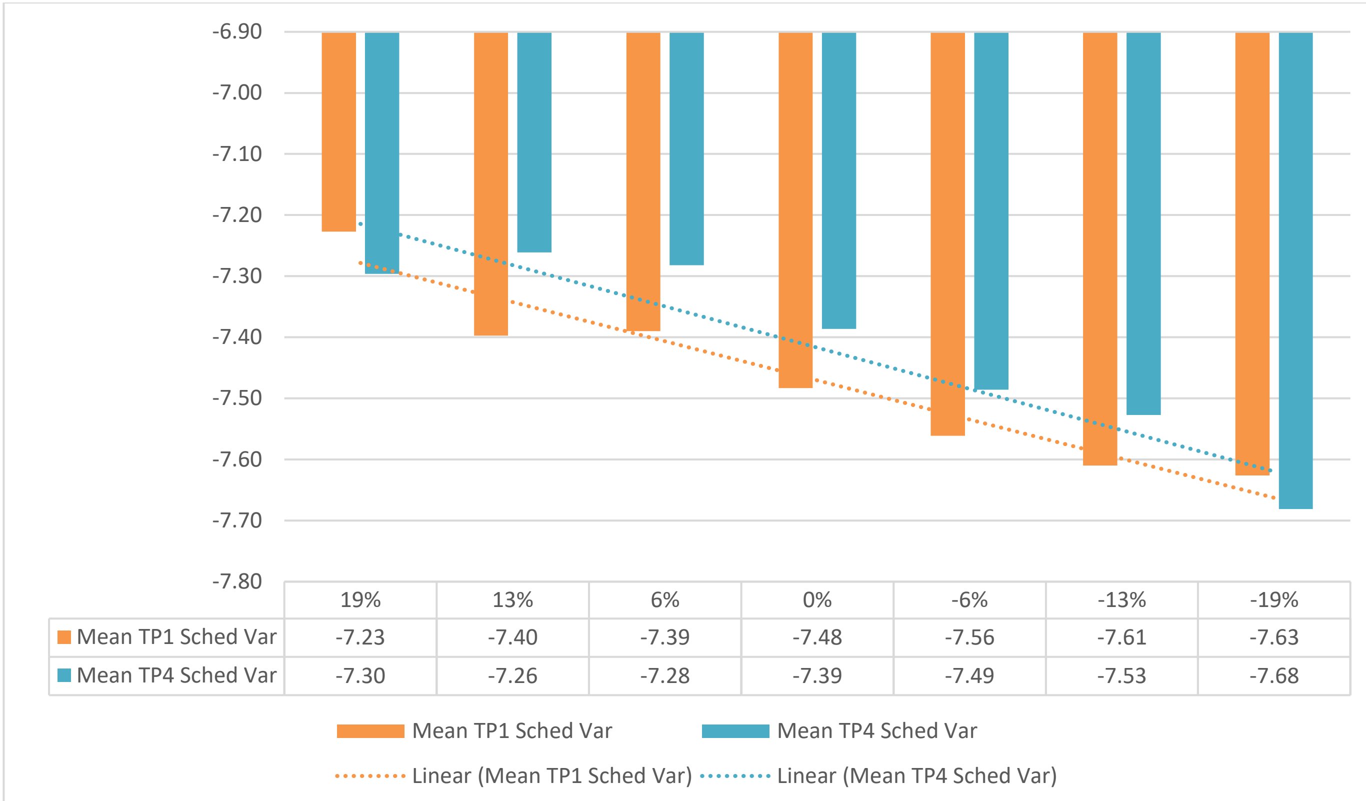


Figure 6.11 Scenario 1, Objective 2: Supplier Leadtime Sensitivity Analysis



	19%	13%	6%	0%	-6%	-13%	-19%
Mean TP1 Sched Var	-7.23	-7.40	-7.39	-7.48	-7.56	-7.61	-7.63
Mean TP4 Sched Var	-7.30	-7.26	-7.28	-7.39	-7.49	-7.53	-7.68

Figure 6.12 Scenario 1, Objective 2: Project Schedule Deviation Sensitivity Analysis

6.3.2.1 Parameters and Constraints

This simulation adds on the second supply tier, the E suppliers. This simulation uses the parameters as shown in Table 6.8.

The optimization applies Equation 6.5 as a constraint so that the sum of the orders in each tier do not exceed the demand. The optimization is run with a random seed for 500 iterations, each with 10 replications with varied parameters. Each iteration also contains the following cost constraints to determine if a solution is feasible:

- Total Project Cost cannot exceed the project budget of $79,750.
- The absolute value of the D1 bonus/penalty cost cannot exceed 10% of baseline supplier cost, $2500.
- The absolute value of the D2 bonus/penalty cost cannot exceed 10% of baseline supplier cost, $2500.
- The absolute value of the E1 bonus/penalty cost cannot exceed 10% of baseline supplier cost, $1250.
- The absolute value of the E2 bonus/penalty cost cannot exceed 10% of baseline supplier cost, $1250.

The orders from the second-tier suppliers must be completed before the first-tier suppliers begin to avoid a stockout situation in the first supply tier.

6.3.2.2 Scenario 2, Optimization Objective 1: Minimize Schedule Deviation

The optimization simulation of this model varies supplier order size through varying the percentage of demand of each supplier order. Supplier minimum order size is considered in the simulation by limiting the range of variation of the demand percentage in both supply tiers. The optimization uses decision variables in Table 6.9.

The resulting best-case order size for both tiers and part cost from first tier suppliers for this scenario with a minimized project cost objective is shown in Table 6.10.

6.3.2.3 Simulation Optimization Minimize Total Project Cost

The optimization simulation of this model varies supplier order size through varying the percentage of demand of each supplier order. Supplier minimum order size is considered in the simulation by limiting the range of variation of the demand percentage. The optimization uses the same decision variables.

Table 6.8 Scenario 2 Simulation Model Parameters

Parameter	
Demand	50
D1 Baseline Lead-time	10 weeks
D1 Lead-time Probability Distribution	(8, 22, 16)
D2 Baseline Lead-time	14 weeks
D2 Lead-time Probability Distribution	(12, 18, 16)
E1 Baseline Lead-time	10 weeks
E1 Lead-time Probability Distribution	[8, 12]
E2 Baseline Lead-time	12 weeks
E2 Lead-time Probability Distribution	[10, 14]
Inventory Threshold	10
Project Phase Baseline	10 weeks
Project Phase Probability Distribution	[8,12]
E-Tier Bonus/Penalty Factor, *x2*	$75
D-Tier Bonus/Penalty Factor, *x1*	$150
Project Phase 1 Bonus/Penalty Factor, *y1*	$250
Project Phases 2-4 Bonus/Penalty Factor, *y2*	$750
Project Budget	$79,750
Project Phase 1 Baseline Cost	$5,000
Project Phases 2-4 Baseline Cost	$30,000
Baseline Supplier Costs (Tiers D and E)	$37,500
Management Reserve (10% Baseline Costs)	$7,250

Table 6.9 Scenario 2 Decision Variables

Variable	Min	Max	Step
Order Size D1 (OrderSD1)	10	40	5
Order Size D2 (OrderSD21)	10	40	5
Part Cost D1	$500	$1200	$25
Part Cost D2	$600	$800	$25
Order Size E1 (OrderSE1)	10	40	5
Order Size E2 (OrderSE2)	10	40	5

Table 6.10 Best Case Order Size and Part Cost for Scenario 2, Objective 1

Parameter	Optimum
Order Size D1 (OrderSD1)	40
Order Size D2 (OrderSD2)	10
Part Cost D1	$600
Part Cost D2	$625
Order Size E1 (OrderSE1)	35
Order Size E2 (OrderSE2)	15

The resulting best-case order size for both tiers and part cost from first tier suppliers for this scenario with a minimized project cost objective is shown in the Table 6.11.

6.3.2.4 Parameter Variation/Sensitivity Analysis

The best case for each objective is then run as a parameter variation, 1-100 runs, each with 10 replications to gather statistics for analysis and comparison. This is run several times for each objective varying the most likely parameter in the First Tier, Supplier1, D1, lead-time triangular distribution to simulate ~20% more/less reliability in the supplier lead-time uncertainty.

6.3.2.4.1 Scenario 2, Objective 1 Sensitivity Analysis: Supplier D1 Reliability

Figure 6.13 to Figure 6.16 show a summary of results for the Scenario 2, Objective 1 for this discussion. Data is recorded in the dissertation attachments.

As expected, the Supplier 1, D1, lead-time and bonus/penalty costs increase the less reliable the supplier's most probable delivery.

Project costs also generally increase the less reliable the supplier's most probable delivery; however, not uniformly or predictable. As cost was not a focus, total project costs exceeded the project budget.

The mean lead-time for Supplier 1, D1, also increases the less reliable the supplier's most probable delivery. The other suppliers' lead-times remain relatively the same.

The project schedule deviation at project Phase 1 generally increases as the less reliable the supplier's most probable delivery, but not completely linearly. By optimizing the schedule deviation, the overall project schedule deviation shows that the later project phases are often able to make up some of the delays from Tier 1, Supplier-1, but not completely to meet the project schedule.

6.3.2.4.2 Scenario 2, Objective 2 Sensitivity Analysis: Supplier D1 Reliability

Figure 6.17 to Figure 6.20 show a summary of results for the Scenario 2, Objective 2 for this discussion. Data is recorded in the dissertation attachments.

In this scenario, the optimal order sizes were the same for both objectives. With objective one focused on schedule the overall costs are more than objective two as the part prices for the suppliers in the first supply tier are more than those in the second objective.

With the objective of minimizing the project costs, there is not a lot of variability in costs at project phase-1 and the total project costs; however, the variability was slightly larger by dollar amount than objective one. The mean project costs all exceeded the baseline project costs but remained within the project budget.

The mean lead-time for Supplier 1, D1, also increases the less reliable the supplier's most probable delivery. The other suppliers' lead-times remain relatively the same.

The project schedule deviation at project Phase 1 generally increases as the less reliable the supplier's most probable delivery, but not completely linearly. Even though schedule was not the objective, the overall project schedule deviation shows that the later project phases are often able to make up some the delays from Tier 1, Supplier-1, but not completely to meet the project schedule.

6.3.2.5 Management Insight and Scenario Discussion

Although both optimization objectives contained a project budget constraint, the parameter variation and sensitivity analysis show that focusing on schedule could exceed the project budget with supply chain uncertainty.

Both optimization objectives resulted in the same order split and contained in this scenario, but as the simulations are run with a random seed generator to simulate lead-time and project schedule uncertainty, rerunning the simulation may result in a different order split.

The project manager in this scenario can see that a delay in the lower supply tiers carries throughout the project and that the project schedule is not recoverable with a dual-supplier sourcing strategy alone. The dual sourcing strategy does mitigate some uncertainty as Table 6.13 shows the delays could have been worse with a sole supplier in the first tier. Other mitigations will be required to meet the project schedule.

Optimizing project costs allows this mitigation strategy to stay within the overall project budget, leaving funding for additional mitigations.

The project manager in this scenario should optimize with a cost objective and explore additional mitigations such as partial orders for lower-tier suppliers.

Table 6.11 Best Case Order Size and Part Cost for Scenario 2, Objective 1

Parameter	Optimum
Order Size D1 (OrderSD1)	40
Order Size D2 (OrderSD2)	10
Part Cost D1	$500
Part Cost D2	$600
Order Size E1 (OrderSE1)	35
Order Size E2 (OrderSE2)	15

Table 6.12 Supplier 1 Reliability Sensitivity Analysis

β Best	ϕ Worst	μ Most Likely		
8	24	13	19%	more reliable
8	24	14	13%	more reliable
8	24	15	6%	more reliable
8	24	16	0%	base distribution
8	24	17	-6%	less reliable
8	24	18	-13%	less reliable
8	24	19	-19%	less reliable

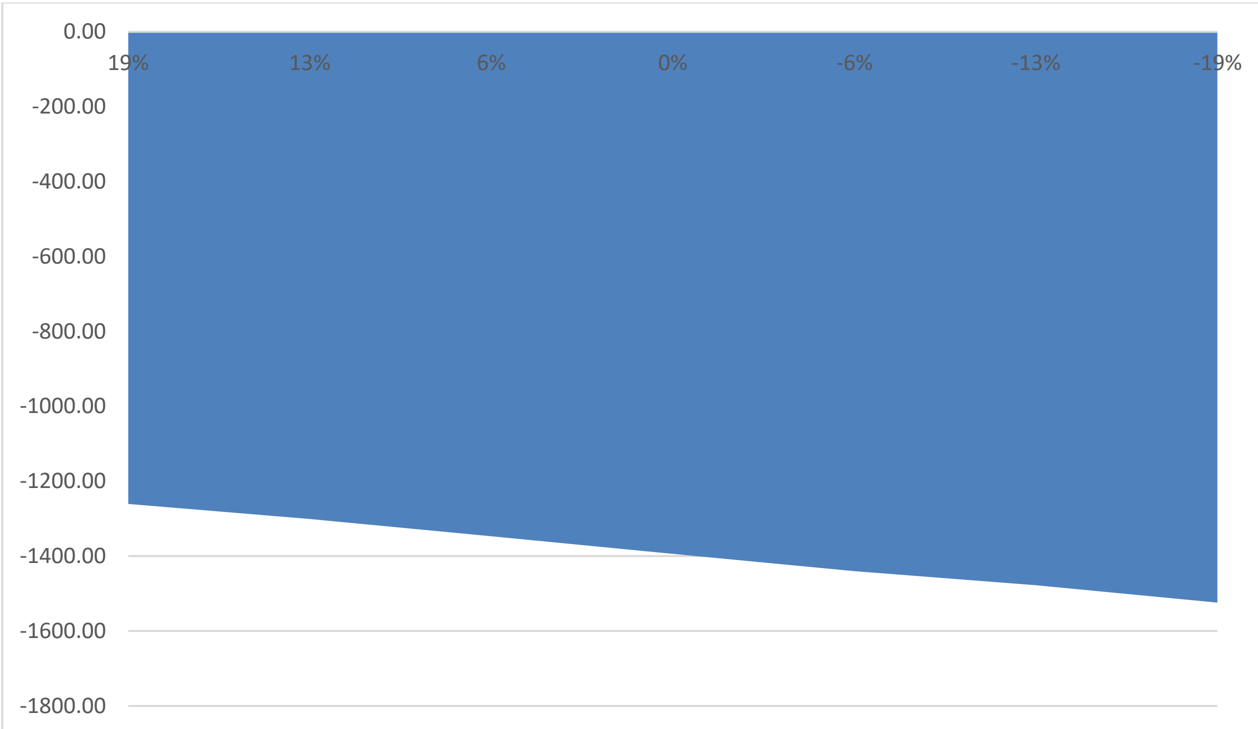
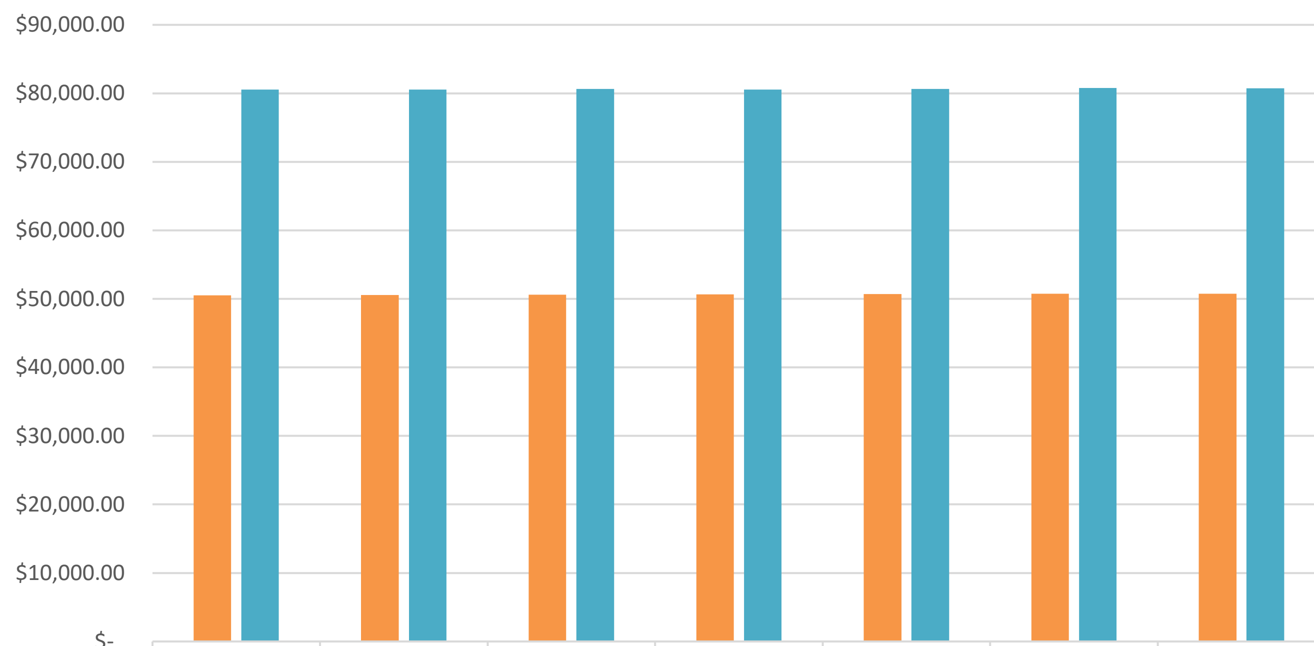


Figure 6.13 Scenario 2, Objective 1: Tier 1,Supplier 1 Bonus/Penalty Cost Sensitivity Analysis



	19%	13%	6%	0%	-6%	-13%	-19%
Mean P1 Project Costs	$50,517.74	$50,560.20	$50,607.04	$50,650.67	$50,701.55	$50,736.78	$50,741.72
Mean Project Costs	$80,555.74	$80,536.20	$80,656.04	$80,572.67	$80,664.05	$80,770.78	$80,753.98

Figure 6.14 Scenario 2, Objective 1: Project Costs Sensitivity Analysis

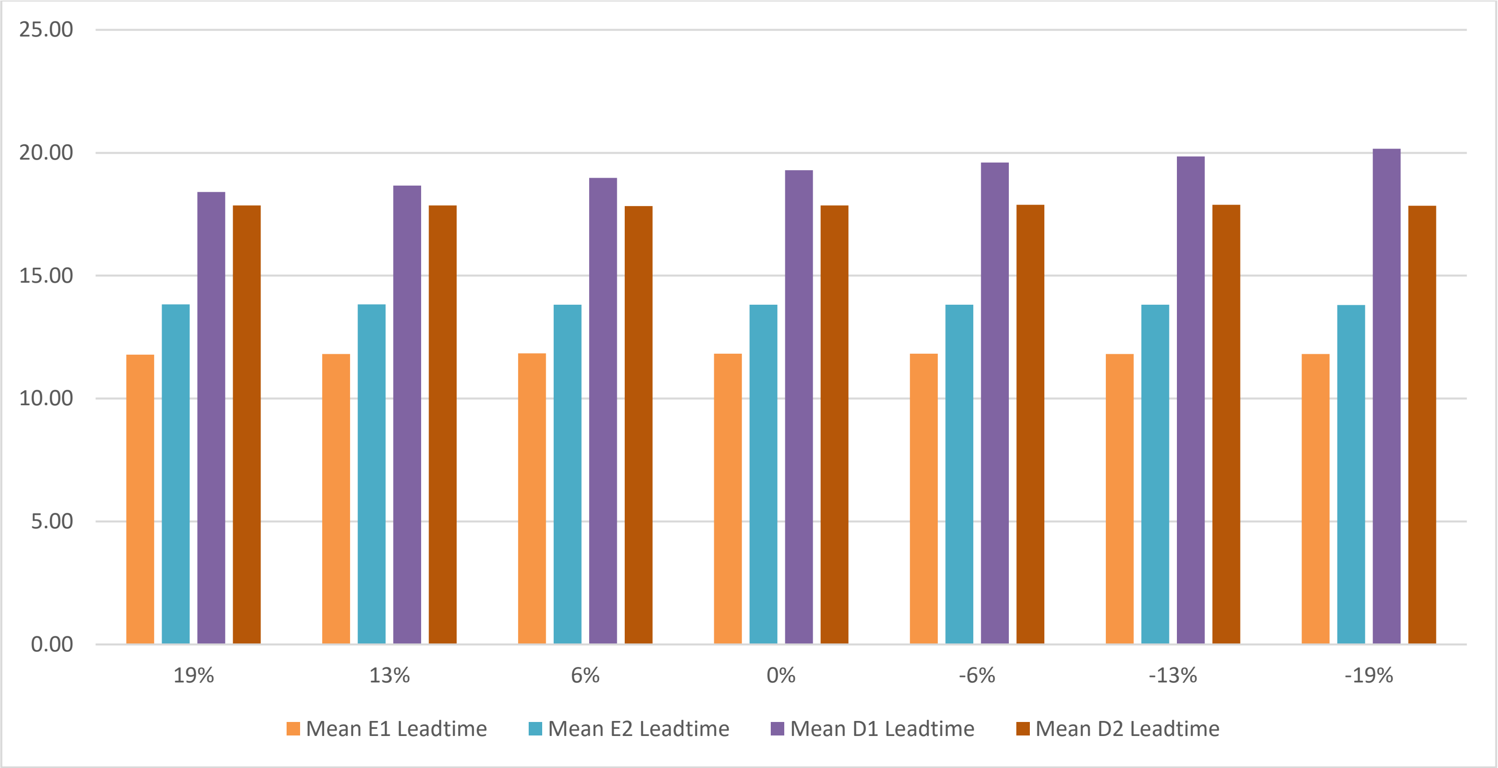
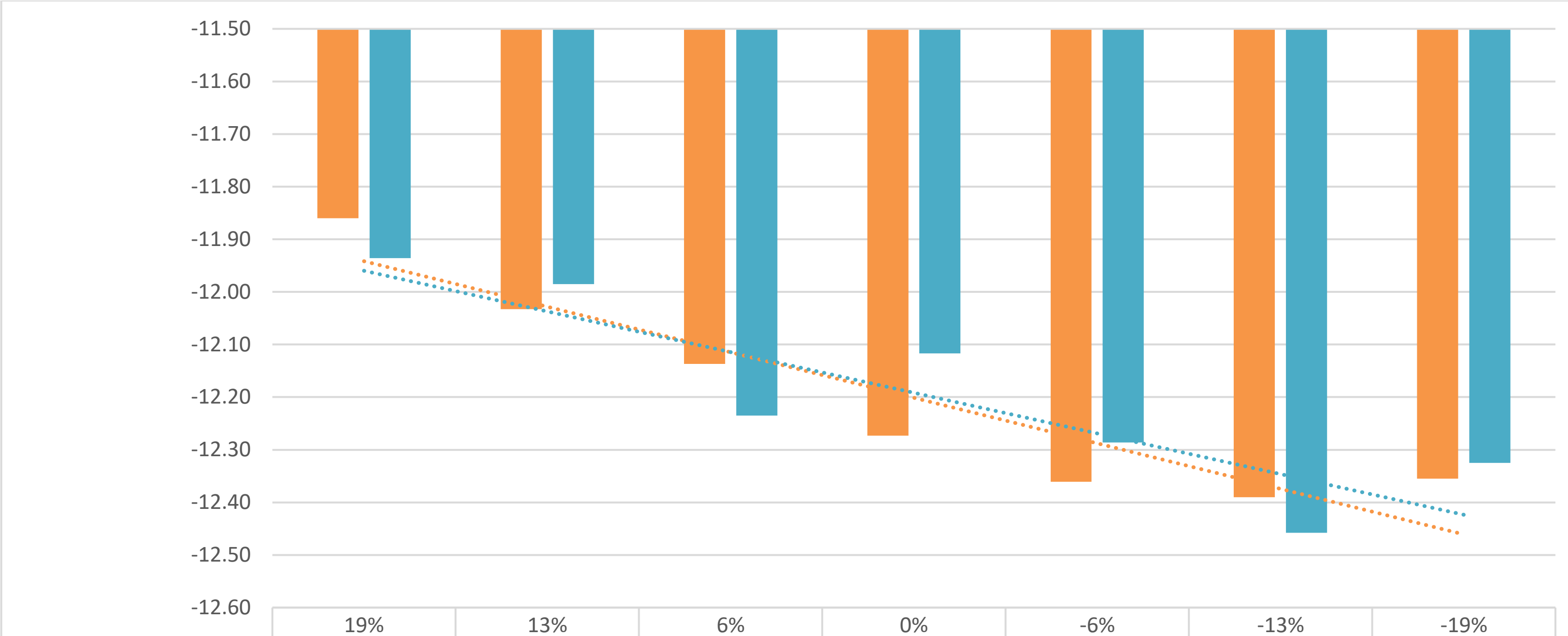


Figure 6.15 Scenario 2, Objective 1: Supplier Leadtime Sensitivity Analysis



	19%	13%	6%	0%	-6%	-13%	-19%
Mean TP1 Sched Var	-11.86	-12.03	-12.14	-12.27	-12.36	-12.39	-12.36
Mean TP4 Sched Var	-11.94	-11.99	-12.24	-12.12	-12.29	-12.46	-12.33

Figure 6.16 Scenario 2, Objective 1: Project Schedule Deviation Sensitivity Analysis

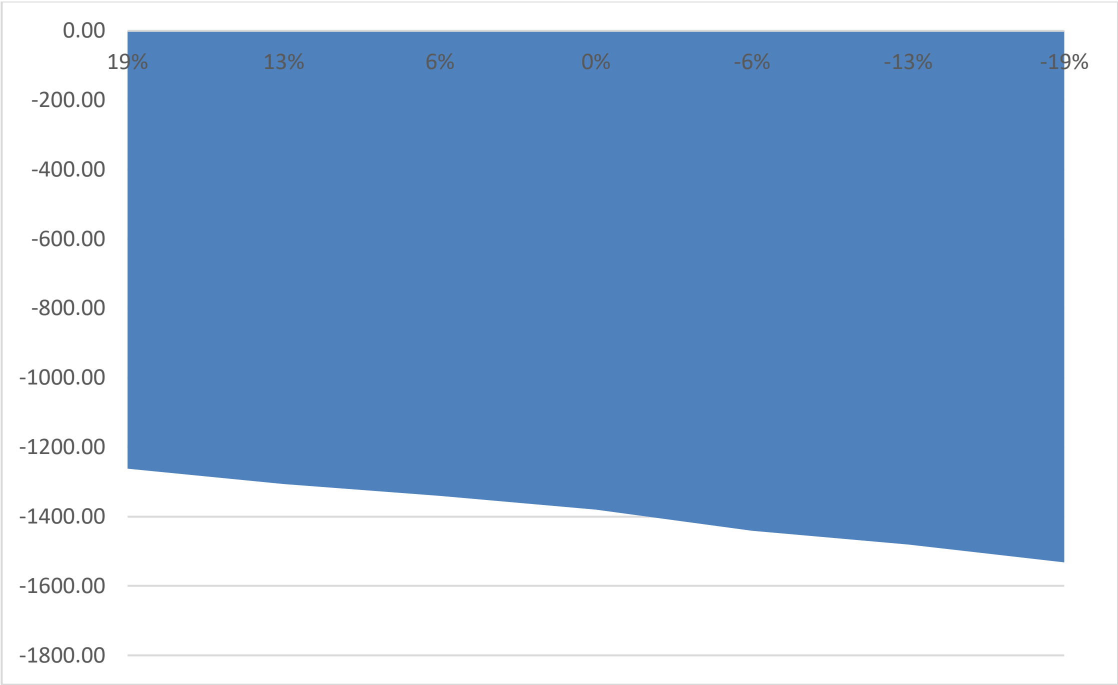


Figure 6.17 Scenario 2, Objective 2: Tier 1, Supplier 1 Bonus/Penalty Cost Sensitivity Analysis

	19%	13%	6%	0%	-6%	-13%	-19%
Mean P1 Project Costs	$46,260.29	$46,291.98	$46,347.79	$46,387.70	$46,422.98	$46,469.48	$46,534.51
Mean Project Costs	$76,247.79	$76,260.98	$76,337.79	$76,398.70	$76,428.48	$76,528.48	$76,572.01

Figure 6.18 Scenario 2, Objective 2: Project Costs Sensitivity Analysis

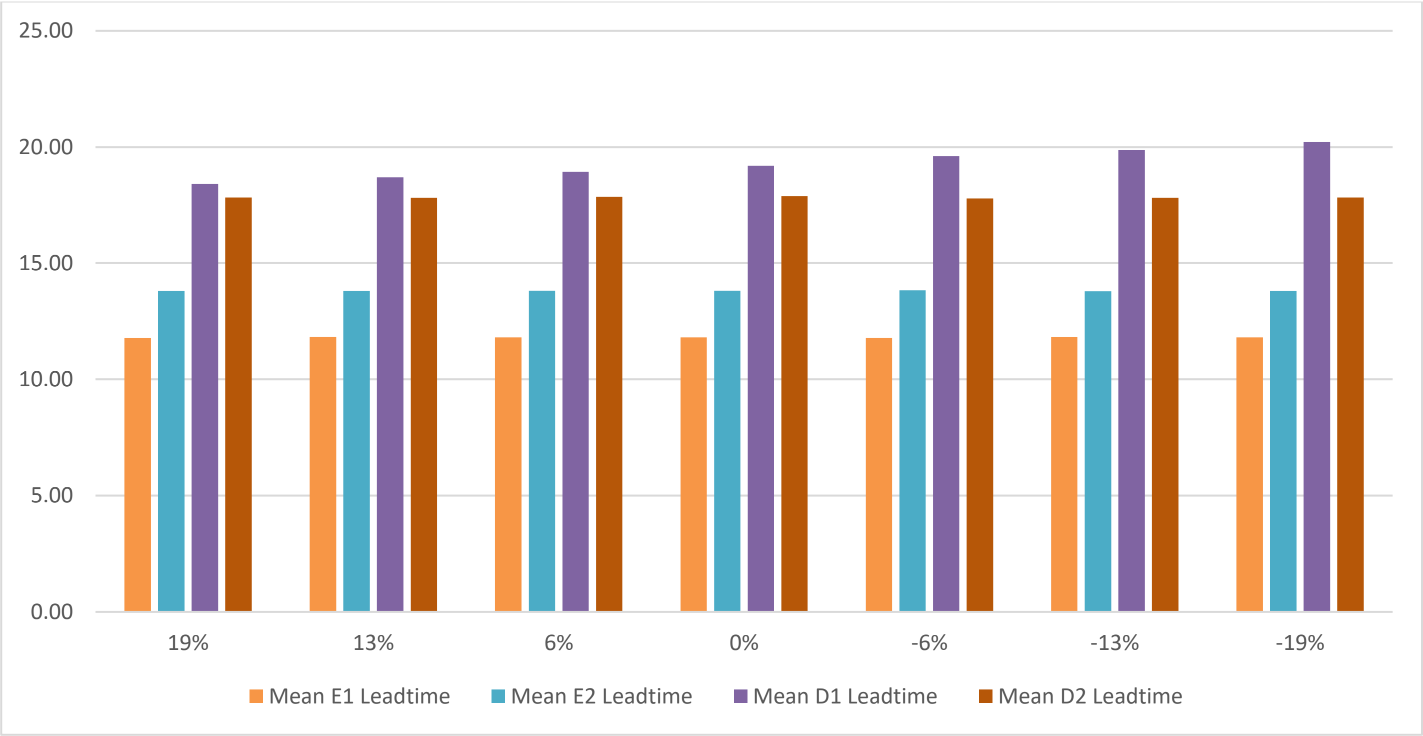


Figure 6.19 Scenario 2, Objective 2: Supplier Leadtime Sensitivity Analysis

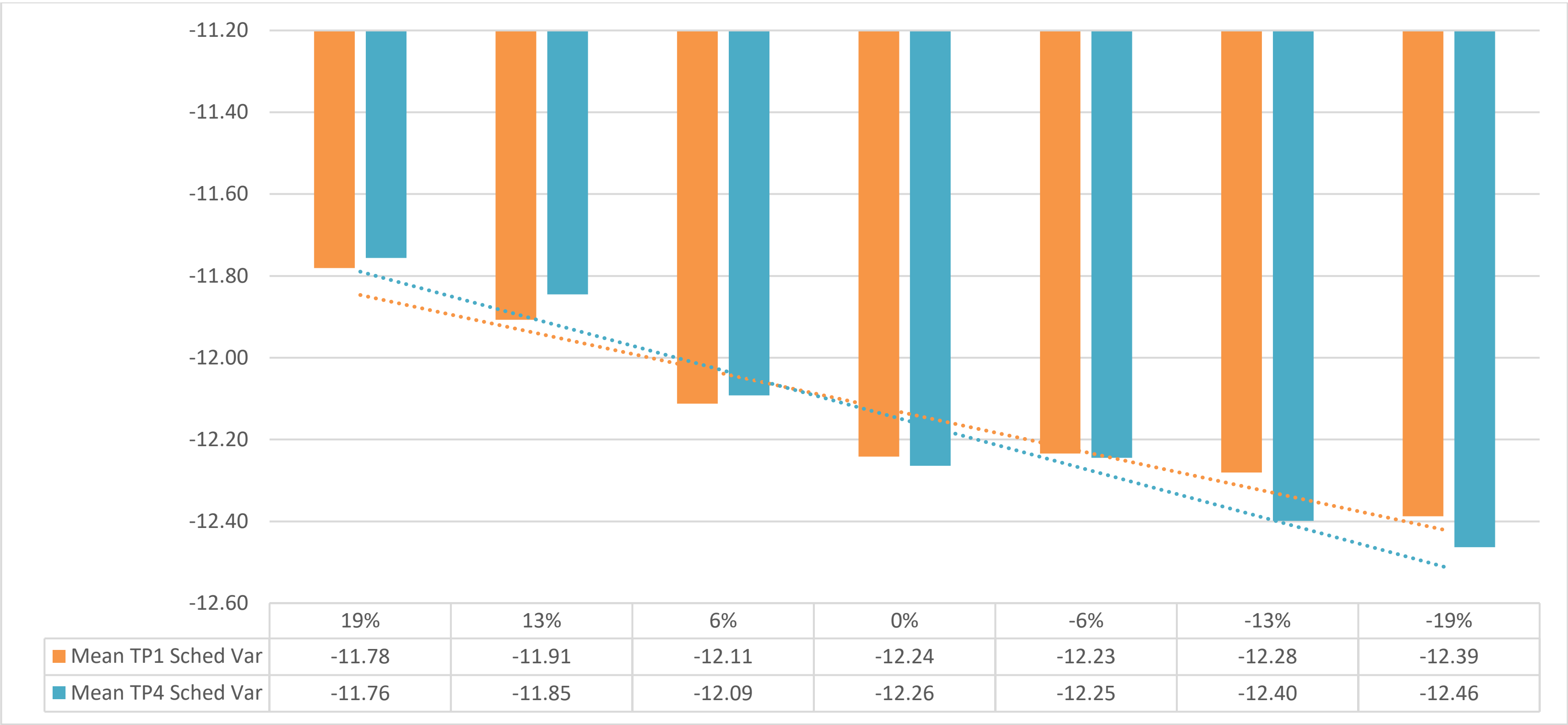


Figure 6.20 Scenario 2, Objective 2: Project Schedule Deviation Sensitivity Analysis

Table 6.13 Scenario 2 Time to Supply Sensitivity Analysis

	Objective 1		Objective 2	
	Mean D1 Lead-time	**Mean D2 Lead-time**	**Mean D1 Lead-time**	**Mean D2 Lead-time**
19%	18.40	17.86	18.42	17.83
13%	18.67	17.85	18.71	17.81
6%	18.98	17.83	18.94	17.86
0%	19.29	17.86	19.20	17.88
-6%	19.60	17.88	19.61	17.79
-13%	19.85	17.88	19.87	17.82
-19%	20.16	17.84	20.21	17.83

CHAPTER 7 DISCUSSION, CONCLUSIONS, AND RECOMMENDATIONS

As the space industry continues to grow and becomes more competitive, supply chain disruptions and uncertainty will increasingly affect project management and execution.

The risk-based process presented in this research to better understand and mitigate supply chain disruptions and uncertainty will hopefully improve the project management of space industry projects to successful completions.

The tools presented in this research can be adapted to various situations that will help project managers better plan for and mitigate supply chain risk and uncertainty for space industry projects and further human exploration of space.

7.1 Discussion and Conclusions

By assessing supply chain risks proactively, early in project development milestones, mitigation strategies can be identified and implemented early, including the multi-sourcing strategy studied in this research.

Using supplier quote evaluation scorecards with scoring thresholds for a multi-sourcing strategy can help implement this strategy if it was not assessed in earlier project milestones. This tool can also be used to confirm the mutli-sourcing strategy if it was identified earlier in project development.

Implementation of the multi-sourcing strategy is perhaps the most difficult aspect of this process. The mathematical framework provided in this research for determining an optimal order split amongst suppliers is not discretely solvable when considering the supply chain uncertainty and disruption this strategy is seeking to mitigate.

Specific project scenarios can be studied, and optimal order sizes determined utilizing simulation tools. For the scenarios studied in this research, minimizing project cost instead of schedule deviations still allowed for some schedule recovery and maintained some management reserve for additional risk and mitigations. The scenarios show that the multi-sourcing strategy can be beneficial in mitigating some of the supply chain risk and uncertainty for space industry projects; however, additional mitigations may be needed to achieve overall project goals when the project experiences a supply chain disruption.

7.2 Future Work

This research excluded the step of supplier qualifications. Investigating risk-based supplier selection and including qualification in the overall process is one area for future work.

This research presents a framework for risk-based analysis and procurement to mitigate space industry supply chain risk. This framework is presented through a theoretical case study scenario. Future research should utilize these tools and methods in industry practice to study the results of industry and project implementation.

Expanded simulations and scenarios, perhaps with real industry data, would be another area for future research. Including additional mitigation strategies and studying how different migrations relate to one another could also be an interesting topic for future research.

Expanding the tools presented in this research to other make-to-order industries could offer comparisons and further help the understanding of supply chain risk and offer potential improvements to multiple industries.

Lastly, as human habitation expands beyond earth’s atmosphere, extraplanetary supply chain risks and sustainability will become growing areas of research.

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APPENDIX: SIMULATION MODEL

Simulation Models

Simulation models are included in a zip file with the dissertation attachments.

Coding

Examples of Supplier Coding

```
PartsDeliveredD1=main.OrderSD1;
main.TSD1=time();
main.CostD1=main.PartCostD1*main.OrderSD1;

main.TSD= min(main.TSD1, main.TSD2);

PartsDeliveredF1=main.OrderSF1;
main.TSF1=time();
main.CostF1=main.PartCostF1*main.OrderSF1;

InventoryAvailE=PartsDeliveredE1+PartsDeliveredE2;
main.TSE= max(main.TSDE, main.TSDE);
```

Project Metrics Coding

```
//Project Scheduling

//Supplier Schedule Variance
SchedVarE1=eTier.BaselineE1-main.TSE1;
SchedVarE2=eTier.BaselineE2-main.TSE2;
SchedVarD1=dTier.BaselineD1-main.TSD1;
SchedVarD2=dTier.BaselineD2-main.TSD2;

//Project Phase 1 Actuals
main.ProjectBaselineP1= eTier.BaselineE1+dTier.BaselineD1+p1.BaselineP1;
main.SchedVarP1=main.ProjectBaselineP1-(main.TP1+main.TSD+main.TSE);

//Project Phase 4 Forecast
main.FTP4=main.TP1+main.TSD+main.TSE+main.TP4;
main.ProjectBaseline=eTier.BaselineE2+dTier.BaselineD2+p1.BaselineP1+Pro
jectBaseline2_4;
main.SchedVarFP4=main.ProjectBaseline-main.FTP4;

//Project Costs

//Baseline Costs
main.BLDC=main.PartCostD1*main.DemandP1 + main.PartCostE1*main.DemandP1;
main.BLCP4=main.CP2_4+main.CP1+main.BLDC;
```

```
//Supplier Bonus/Penalty Costs
main.BPD1=SchedVarD1*(main.x);
main.BPD2=SchedVarD2*(main.x);
main.BPE1=SchedVarE1*(main.x);
main.BPE2=SchedVarE2*(main.x);

//Project Costs
main.BPP1=(p1.BaselineP1-main.TP1)*(main.y1);
main.P1Cost=main.CP1-main.BPP1;

main.BPP2_4F=(ProjectBaseline2_4-main.TP4)*(main.y2);
main.P2_4CostF=main.CP2_4-main.BPP2_4F;

main.P1TotalCost=main.P1Cost+(main.CostD1-main.BPD1)+(main.CostD2-
main.BPD2)+(main.CostE1-main.BPE1)+(main.CostE2-main.BPE2;
main.P4TotalCostF=main.P1TotalCost+main.P2_4CostF;
```

Data Files

Data files are included in a zip file with the dissertation attachments.

VITA

Jennifer Seals Cooper, PE received her Bachelor of Science in Engineering from the University of Tennessee-Martin in 2009. Jennifer started her career in plastics manufacturing before moving to oil and gas consulting. Along the way she became a licensed professional engineer and earned Masters of Science in Engineering Management (2014) and Environmental Engineering (2016) from the Missouri University of Science and Technology.

Jennifer made a career transition in 2018 to work for Boeing on the NASA Space Launch Program as part of the Avionics Electrical Power Systems team. She took advantage of Boeing's Learning Together program to pursue her Doctor of Philosophy in Industrial Engineering specializing in Engineering Management though the University of Tennessee. After graduation, Jennifer will continue to apply her engineering management expertise at Boeing as a Flight Systems Project Engineer.

Research and lecturing interests include project management, supply chain risk mitigation, supply chain sustainability, batch manufacturing, and life-cycle management.